China Steel Technical Report, No. 37, pp.74－78, (2024)

The Development of 6061 Aluminum Plate for Semiconductor Manufacturing Equipment

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To meet the standards of semiconductor manufacturing, this study clarifies the related mechanisms via the scanning electrochemical microscopy (SECM), the scanning electron microscope/energy-dispersive X-ray spectroscopy (SEM/EDS), the in-situ electrical continuous cooling transformation (CCT) phase diagram, and the quenching simulation in the small-scaled experimental pool. To achieve a good anodized surface, we can avoid the appearance of the anodizing stripe, which is caused by the continuous Al-Fe-Si eutectics in the aluminum plate. By means of optimizing the casting and the hot rolling parameters using the Taguchi methods and the Gleeble machine, respectively, the morphology of the eutectics was transformed from a reticular arrangement to a linear arrangement, effectively eliminating the anodizing stripe. For high strength, a two-step quenching path is employed. First, the solution soaking temperature is increased by 30ºC, followed by air-cooling, and finally, the material is quenched in a water tank at a moderate temperature. This approach enhances solid solution strengthening and reduces residual stress caused by temperature differences during the quenching process. For improved flatness, increasing the dropping speed during the quenching process helps the aluminum plate pass quickly through the film boiling zone, in the achievement of avoiding inhomogeneous thermal conduction and shape distortion. Finally, the 6061 aluminum alloy plate meets the high standards for vacuum chambers in semiconductor manufacturing equipment, has been certified by several international companies, and supports local production within the semiconductor manufacturing supply chain.

Keywords: 6061 aluminum alloy, Vacuum chamber, Two-step quenching, Anodizing surface, Residual stress, In-situ electrical continuous cooling transformation phase diagram

1. INTRODUCTION

For use in the vacuum chamber of the semiconductor manufacturing process, materials must demonstrate characteristics such as lightweight, high thermal conductivity, and workability. Aluminum alloys are therefore the ideal candidate materials due to the properties mentioned above. Given the adequate strength, good weldability, and reasonable price, the 6061 aluminum alloy is the mainstream material in the current market. However, standard 6061 aluminum alloy plates cannot meet the critical requirements of ultra-high vacuum applications unless they achieve the high standards of a good anodized surface, high strength, and high flatness factors essential for a good appearance, resistance to high pressure, and precise machining tolerances in advanced semiconductor manufacturing processes. However, the rolling reduction of the thick aluminum alloy plate (12 mm< t < 80 mm) is lower than that of the thin sheet (t < 7 mm), so the eutectics of the slab are not well dispersed during the rolling process. In this case, the gathered eutectics tend to produce defects after the anodizing treatment. For this reason, the international aluminum alloy mills have adopted a new generation casting system to improve slab homogeneity. To achieve high strength and flatness, increasing the cooling rate of the aluminum plate in the drop-bottom quenching furnace can preserve a high concentration of alloying elements during solution treatment, the inhomogeneous thermal conduction can also lead to shape distortion and residual stress, which are detrimental to the high flatness. To ensure a homogeneous cooling environment, international aluminum alloy mills use horizontal quenching furnaces to produce aluminum plates. On the other hand, the horizontal quenching furnace still has disadvantages, including long processing time and high cost. From metallurgical and mechanical perspectives, this study aims to develop several technologies for producing 6061 aluminum alloy plates that meet the high standards required for vacuum chambers in the semiconductor manufacturing field utilizing existing vertical quenching equipment. This approach will also support local production within the semiconductor manufacturing supply chain.

2. EXPERIMENTAL METHOD

This study produces a slab of 6061 aluminum alloy via direct chill casting, with its composition listed in Table 1. The slab is homogenized at 520℃ for 12 hours, then rolled starting from an initial temperature of 480℃, resulting in a final aluminum alloy plate with a thickness of 35mm. After the final rolling pass, the aluminum alloy plate was immediately cooled using sprayed rolling oil to retain the mechanical stress. The 35-mm aluminum plate is cut into dimensions of 5mm x 20 mm x 0.2 mm for preparation of the in-situ electrical resistivity measurement system, which was designed to establish the CCT curve. The system heats the sample above the solution temperature and then cools it down using natural cooling, fan cooling, and dry-ice cooling. The CCT curve is Subsequently obtained from the inflection points in the resistivity vs. temperature plot at various time intervals. Based on the CCT curve, we designed the parameters for the two-step quenching process and applied them to the production line of the drop-bottom quenching furnace. After the solution treatment and quenching, the aluminum plate was firstly artificially aged at 180ºC for 8 hours, then cut to the standard JIS-No.5 sample, for preparation for the tensile test. The tensile testing machine used was the Zwick/Roell Z050, and the testing followed the JIS Z 2241 standard. The microstructure was identified using a CHI-9200 scanning electrochemical microscopy (SECM). A JEOL JSM-7000 scanning electron microscope (SEM) equipped with an Oxford energy-dispersive X-ray spectroscopy (EDS), and a Leica MZ-16A optical microscope were also used. The flatness and the residual stress were measured using the RESOLUTE optical linear encoder, and the slitting method(1), respectively.

3. RESULTS AND DISCUSSION

3.1. The Modulation of the Eutectics

The technology in this section is aimed at eliminating the defect of the anodizing stripe and improving the surface quality of the aluminum plate. Figure 1 shows the results obtained from the SECM analysis, one can see that the anodizing stripe(2) is caused by selective corrosion as evidenced by the different redox potentials between the Al-Fe-Si eutectics(3-5) and the Al matrix (Figure 1(a)). The existence of the Al-Fe-Si eutectics is associated with the parameters of the solidification during the casting process. Therefore, the casting parameters including the weight percentage of Fe, the weight percentage of Si, the liquid level, and the casting speed for the slab, are optimized using the Taguchi method. In this case, the average size of the eutectics is reduced from 85 to 38 μm (Figure 1(b)), additionally, their morphology changes from a reticular arrangement to a linear one. Subsequently, controlling the temperature of the sprayed rolling oil during the hot rolling process helps preserve mechanical stress, preparing the material for

Table 1 The composition (wt%) of the 6061 aluminum alloy.

code	Si	Fe	Cu	Mn	Mg	Al
6061	0.60	0.60	0.20	0.12	1.10	Bal.

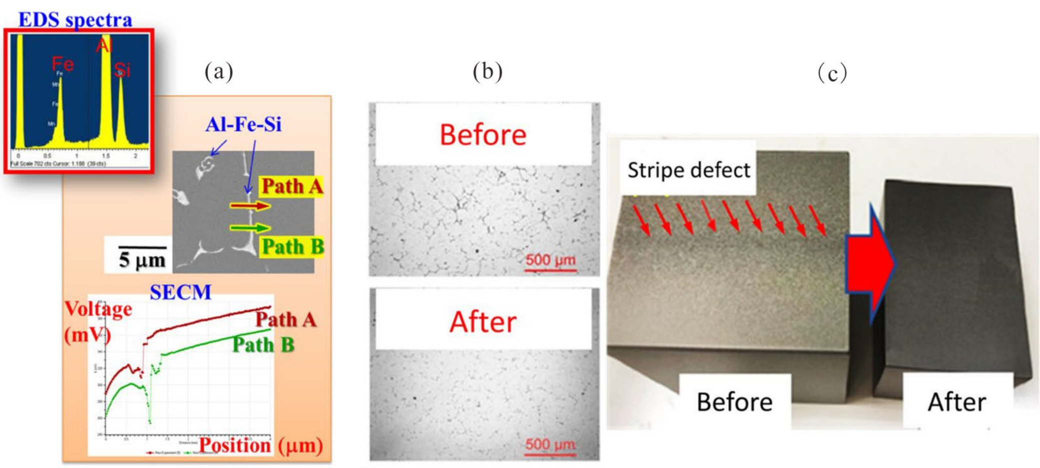

Fig.1. (a) Line scan of the redox potential around the site of the anodizing stripe. (b) Optical images of the slabs in the conditions before and after the manufacturing improvement. (c) Macrographs of the aluminum plates in the conditions before and after the manufacturing improvement.

the recrystallization stage in the subsequent solution treatment. After the solution treatment, the expansion of grain boundaries in the well-recrystallized aluminum alloy plate further disperses the eutectics, transforming their morphology from a linear arrangement to a punctiform one. As a result, the likelihood of anodizing stripes caused by continuous Al-Fe-Si eutectics is reduced, and the quality of the anodized surface for the aluminum alloy plate meets the US military standard of Mil8625 (Figure 1(c)).

3.2. THE TWO-STEP QUENCHING

The technology in this section is aimed at reducing the residual stress while maintaining the high strength of the aluminum alloy plate. When the aluminum alloy plate is immediately quenched after the high-temperature solution treatment (Figure 2(a)-path 1), the solid solubility of the aluminum matrix increases. However, the enhanced strength of the aluminum alloy plate is accompanied by the side effect of high residual stress [6-7]; If the aluminum ally plate is not immediately quenched after the solution treatment followed by an air cooling step (Figure 2(a)-path 2), the temperature difference between the edge and the center for the aluminum alloy plate will is reduced. However, this cooling path passes through the precipitation zone of the equilibrium β phase (Figure 2(a)-pink area). The aforementioned cooling path (path 2) will mitigate insufficient strength in the aluminum plate after the artificial aging process. Hence, precise control of the cooling path is crucial for managing residual stress. This study establishes an in-situ continuous cooling transformation (CCT) curve for the aluminum alloy plate on our production line, using an in-situ electrical resistivity measurement system. Compared to the CCT curve measured via the hardness, the in-situ electrical resistivity CCT curve shows smoother transitions at both the forehead and the nose regions (Figure 2(b)). Based on this information, this study develops a two-step quenching process: first, increasing the solution soaking temperature by 30^{o}C, then applying an air cooling step, and finally quenching the plate into a water tank from a mild temperature (Figure 2(a)-path 3). By avoiding penetration of the precipitation zone, this approach establishes a cooling path that precisely passes near the equilibrium β phase zone on the CCT curve. This ensures a sufficient concentration of saturated Mg or Si atoms in the aluminum alloy plate lattice, whilst also reducing the temperature difference (ΔT) between the edge and the center of the aluminum alloy plate. As shown in Figure 2(c), ΔT in the two-step

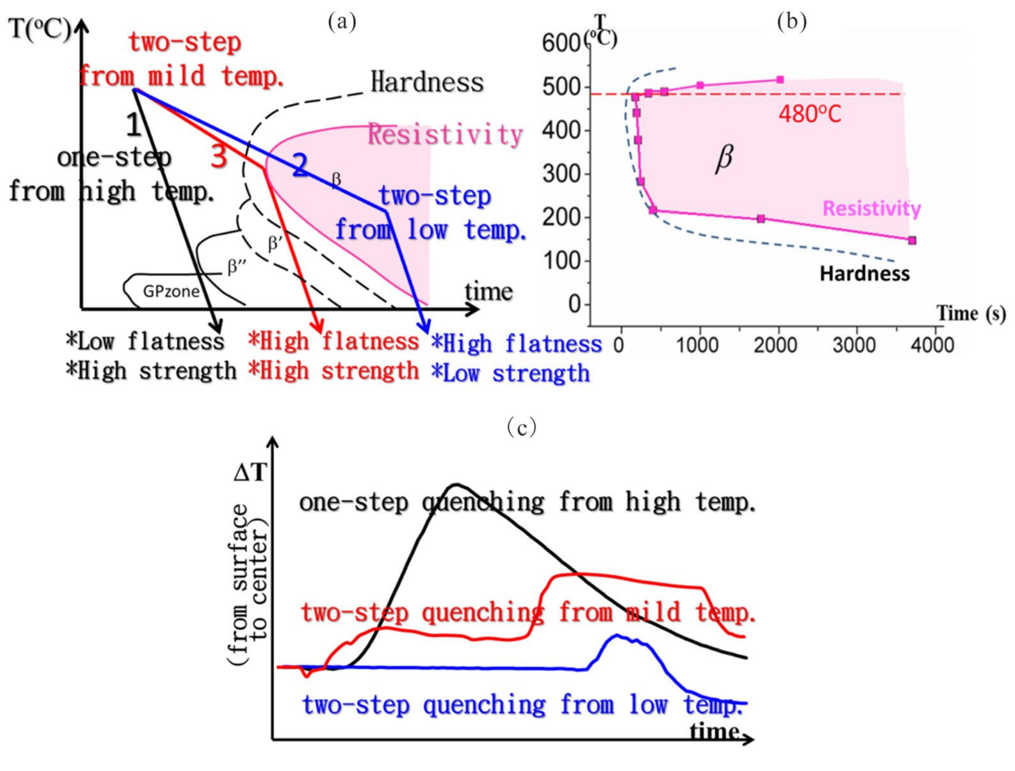

Fig.2. (a) Various quenching paths follow the solution treatment. (b) Continuous cooling transformation (CCT) phase diagram obtained from electrical resistivity and hardness measurements, respectively. (c) Temperature differences for the different quenching paths.

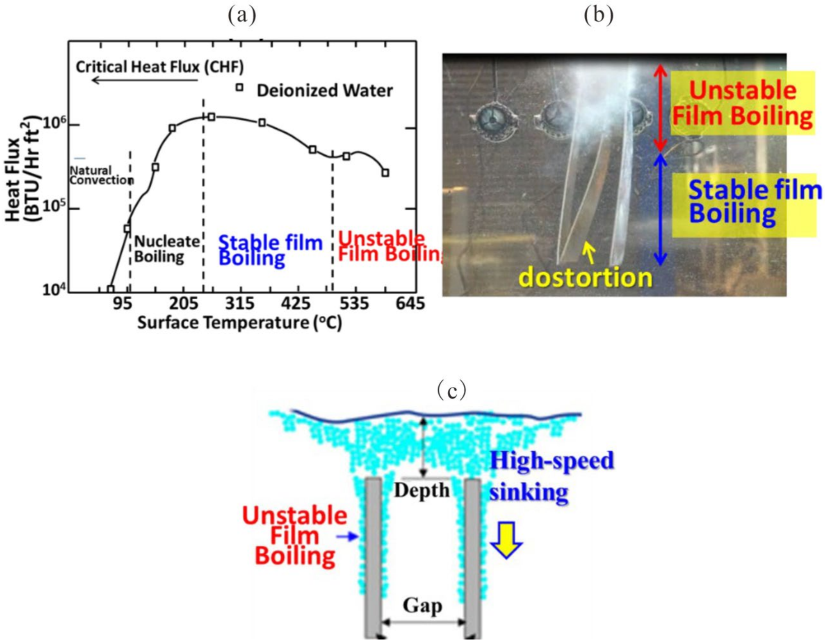

Fig.3. (a) Plot of boiling conditions vs. temperature obtained from the quenching process of the aluminum plate(8). (b) Small-scaled quenching experiment conducted in a pool with transparent walls. (c) The aluminum plate sinking through the film boiling area during the quenching process.

quenching process is smaller than that of the one-step process, resulting in reduced residual stress. Ultimately, the residual stress and strength of the aluminum alloy plate are improved to <10 MPa and >310 Mpa, respectively.

3.3 The High-Speed Sinking

The technology in this section aims to reduce the penetrating time of the aluminum alloy plate through unstable film boiling and improve its flatness. During the initial stage of the quenching process in the drop-bottom quenching furnace, shape distortion occurs in the aluminum alloy plate, due to the formation of unstable film boiling in the shallow area of the quenching liquid (Figure 3(a) and 3(b)). The effect of the residual stress on the aluminum alloy plate exacerbates shape distortion after machining, This phenomenon is primarily caused by the disturbance of the inhomogeneous thermal conduction between the shallow and deep areas of the quenching liquid. To overcome this issue, the small-scaled quenching experimental pool in this study demonstrates that the high-speed sinking technology allows the aluminum alloy plate to pass through the unstable film boiling in a short time (Figure 3(c)), as a result, the alleviated residual stress reduces both vertical and horizontal shape distortion of the aluminum alloy plate. Based on the final sinking speed, acceleration, and braking reaction time of old production equipment, the high-speed sinking technology is optimized using the V-T plot. After overclocking the motor and Structurally strengthening the drop-bottom quenching furnace. The sinking time is successfully reduced from 7 to 0.768 seconds. Additionally, the vertical and horizontal shape distortion was limited to 1 mm/m, achieving a precise grade for the aluminum alloy plate.

4. CONCLUSIONS

(1) Through the modulation of eutectics, two-step quenching, and high-speed sinking technologies, this study overcomes the physical limitations of the old drop-bottom quenching furnace and successfully produces high-quality aluminum alloy plates with good surface properties, high strength, and high flatness. These plates meet the standards for good appearance, high-pressure resistance, and precise machining tolerances, while also supporting local production within the semiconductor manufacturing supply chain.

(2) The two-step quenching process develops a unique cooling path that precisely passes through the β–Mg_2Si region on the electrical CCT curve, ensuring a sufficient concentration of saturated Mg or Si atoms in the aluminum alloy lattice. This approach effectively overcomes the interference between high strength and high flatness in these plates.

(3) The 6061 aluminum alloy plate successfully meets

the US military standard of Mil8625 and satisfies several semiconductor manufacturing grade requirements including high strength (>310 MPa), low residual stress (<10MPa), and high flatness (<1 mm/m).

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