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Two-Step Quench Process for the 6061 Aluminum Alloy

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In order to ensure that the quality of the 6061-aluminum alloy plate is good enough for the application of advanced semiconductor manufacturing, this study proposed a two-stage quenching path which was firstly initialized by increasing the solution soaking temperature by 30°C, secondarily stopped by an air-cooling step, and finally quenched into the water tank from a lower temperature. This policy promoted the spheroidization of eutectic phases which favored the surface anodizing quality of the aluminum plate. The key point of this technology was developing a cooling path which precisely passed by the region of β–Mg_2Si in the continuous cooling transformation (CCT), in accordance to the sufficient saturated Mg or Si atomic lattice concentration for the aluminum alloy. Finally, this study successfully created a novel method associated with the solution treatment and the quench process, overcame the interference between the manufacturing processes, and produced high-quality aluminum plate; which showed low residual stress, high hardness and great uniformity during the eutectic phase.

Keywords: 6061 aluminum plate; Low residual stress; Quench process

1. INTRODUCTION

Aluminum alloys were suggested for the application of the ultra-high vacuum system because of their several advantages, including a lightweight property, a fair price, excellent thermal conductivity, and workability. Unfortunately, aluminum alloys have not been extensively used for the commercial vacuum system owing to the outgassing and the weldability issues. However, the above issues were recently overcome after the emergence of methods for manufacturing hollow elements and the surface finish. On the other hand, the semiconductor manufacturing processes are developing at a tremendous pace. Therefore, aluminum alloys have naturally become the candidate for the ultra-high vacuum system. For example, the surfaces of the aluminum alloys are usually completed with the anodizing treatment in order to avoid the adsorption of moisture. In addition, the thermal stability and the abrasion resistance of the anodizing oxidation layer also extend the life cycle of the vacuum components. In accordance with the technology node of the semiconductor below the 10 nm level, the impure elements of the film on the wafer should be limited in concentrations within the ppt (=10^{-12}) range. In order to prevent the unexpected elements from mixing into the sputtering plasma which plays an important role in the electrical property of the semiconductor film, the impurities of the film should meet the standards of the low concentration and the high repeatability. Thus, the anodizing oxidation layer on the surface of the aluminum alloy plate should reveal great uniformity. This study is aimed to invent a novel method associated with the solution treatment and the quench process, overcome the interference between the manufacturing process, and finally produce the high-quality aluminum plate which shows great uniformity during the eutectic phase, low residual stress, and high hardness. As a result, this product also seeks to penetrate into the supply chain of the vacuum system for the advanced semiconductor manufacturing industry.

2. EXPERIMENTAL METHOD

The AA6061 slab with a composition of Al-0.65Si-0.58Fe-0.10Mn-0.98Mg-0.31Cu-0.14Ti (wt%) is preheated at 550°C for 2h, and then passed repeatedly through the hot rolled mill until the required plate thickness of 35mm is obtained. The 35-mm aluminum plate is then cut to the following dimensions of 1800 mm x 800 mm x 35 mm, and a K-type thermal couple is embedded into the edge of the aluminum plate which is designed to record the temperature history during the overall quench process from 570 to 540°C. The first and second steps of the quench process are applied for this experiment. After these procedures, the aluminum plate is sliced into several pieces for the purpose of the metallurgical analysis, the anodizing treatment, the residual stress measurement, and the hardness test (HRB). Note that the slitting method which was still establishing itself as a standard engineering method over the last few years is the most promising technique for obtaining through-thickness residual stress distribution[1-2]. Given the analysis mentioned above, it is possible to figure out the correlation between the quality of the aluminum plate and the quench process of the mill.

3. RESULTS AND DISCUSSION

3.1. Two-step solution treatment and quenching process

If the aluminum plate is fabricated by the traditional process, i.e., high-temperature solution treatment and quenched into water immediately, the ascending Mg and Si saturated lattice concentration will benefit the strength of the aluminum plate after the artificial aging. The high strength of the material takes advantage of the micromachining for the vacuum chamber. On the other hand, the high temperature of the solution treatment also promotes the spheroidization and discontinuity for the Al-Fe-Si eutectic[3-5] phase and Mg-Si precipitation[6-7] of the aluminum alloy, respectively. The spheroidization and discontinuity of the heterogeneous phase will prevent the effect of local cell reaction during the anodizing treatment, and assist the uniformity for the surface oxidation layer of the vacuum components. However, the high-temperature solution treatment is usually accompanied with a high initial temperature before the aluminum plate is quenched into the water. The high initial quenching temperature will result in the side effect of thermal residual stress for the aluminum plate. On the contrary, the low-temperature solution treatment is applied for the manufacture of the aluminum plate (Fig.1 (path 3)), and the residual stress is reduced on coexistence with a different side effect. Based on the low initial quench temperature, the cooling path penetrates into the region of β-Mg_2Si in the continuous cooling transformation (CCT) phase while the coarse Mg_2Si phase participates in the matrix of the aluminum alloy. As a result, the saturated Mg or Si atomic lattice concentration is not sufficient, and the mechanical strength of the artificially aged aluminum alloy failed for the reason of lacking the β'-Mg_2Si precipitation hardening phase. Meanwhile, the low-temperature solution treatment also causes the defect in the anodized stripe which is subjected to the insufficient spheroidization of the Al-Fe-Si eutectic phase. It is worth mentioning that the surface anodized stripe of the aluminum alloy is the main issue for the disqualification of the vacuum components in the field of semiconductor manufacturing. In order to produce the aluminum plate which performs a high anodizing surface quality, high hardness, and low residual stress, this study proposed a two-stage quenching path (Fig.1 (path 2)) which was firstly initialized with a high-temperature solution treatment, secondarily stopped by an air cooling step, and finally quenched into the water tank from a lower temperature. The key point of this technology is developing a cooling path which precisely passes by the region of β-Mg_2Si in the continuous cooling transformation (CCT), in accordance to the sufficient saturated Mg or Si atomic lattice concentration for the aluminum alloy.

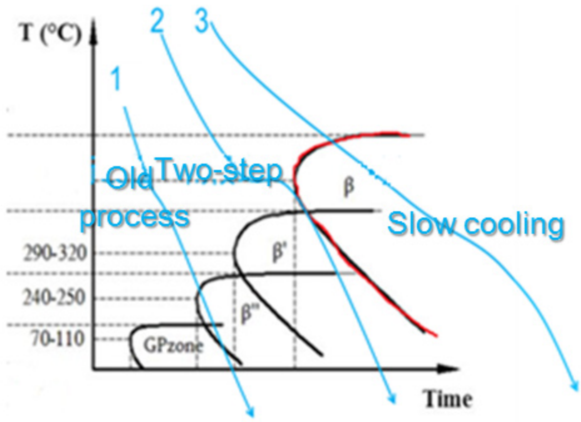

Fig.1. Aluminum plates are quenched with (1) one-step (old process), (2) two-step, and (3) one-step (slow cooling rate) paths, respectively.

3.2. Improvement of the surface anodizing quality

The products of aluminum alloy are called plates, and rolls when the thicknesses are >6 mm and < 6mm, respectively. By means of hot rolling, the plates are made from an aluminum slab of an initial thickness of 530 mm and reduced downstream to 150~6 mm. Attributed to the reduction ratio of a plate smaller than that of a roll, the special density of the eutectic phase of the final plate product varying from the surface to the center remains from the casting process because of the different cooling rates of the slab. The selective corrosion makes the inhomogeneous microstructure feature of the plate obvious in the thickness direction, so the anodizing stripe appears after the anodizing treatment[8]. As mentioned in Section 3.1, the two-stage quenching proposed in this study consists of several sequences. First, the temperature of the solution treatment is raised about 30°C to achieve the goals of the spheroidization of eutectic phases for the purpose of reducing the inhomogeneous microstructure feature of the plate obvious in the thickness direction. Second, the aluminum plate is dropped into the water tank at a lower temperature in order to minimize the temperature difference within the aluminum plate to reduce the residual stress after the quenching process. Finally, the 6061-aluminum plate with both the high anodizing surface quality and the low residual stress were successfully fabricated in the production line.

If the aluminum plate is made from the one-stage quenching path, the spheroidization of eutectic phases in the thickness direction will not be sufficient because of the temperature of the solution treatment being relatively low. As shown in the Figure 2 (right), one can see that the special densities of the eutectic phase on the surface of the aluminum subjected to the 0% (Label: 0t) and 12.5% (Label: 1/8t) depth in the thickness direction are higher than those done to the 25% (Label: 1/4t) and 50% (Lable: 1/2t) ones. For this reason, one can see that there is a surface anodized stripe defect found in the aluminum plate after the anodizing treatment (Fig.2 (left)). However, this defect of the anodized stripe is modified due to the temperature of the solution treatment being revised by 30°C higher than the original one. For the special density of the eutectic phase, the difference between the 0% (Label: 0t), 12.5% (Label: 1/8t), 25% (Label: 1/4t), and 50% (Label: 1/2t) depths in the thickness direction becomes unobvious (Fig.3 (right)). The anodized stripe no longer exists, and the anodized surface quality is much better.

3.3. Diminution of the temperature difference, residual stress, and hardness

As demonstrated in Figure 4, the aluminum plate is quenched immediately after the high-temperature

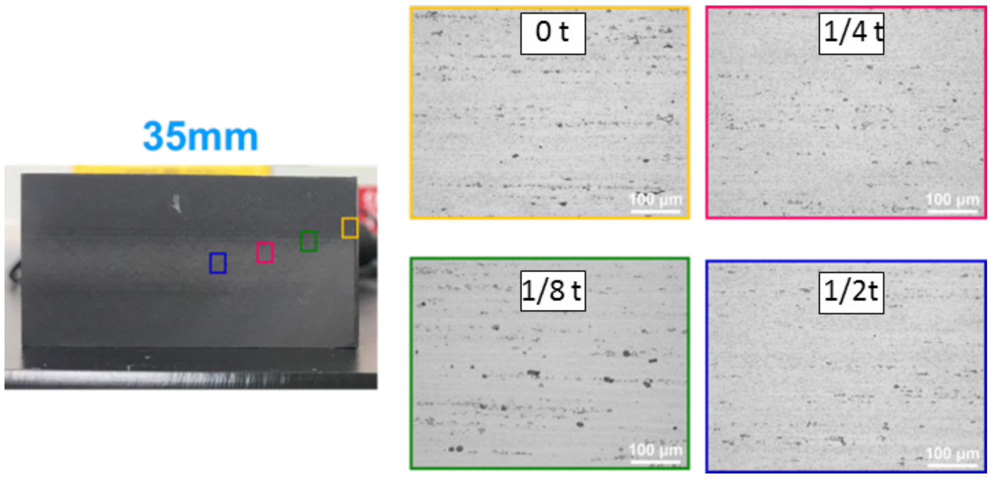

Fig.2. The microstructural eutectic phase (right) and anodized surface quality (left) for the aluminum plate fabricated via 1-step quench path.

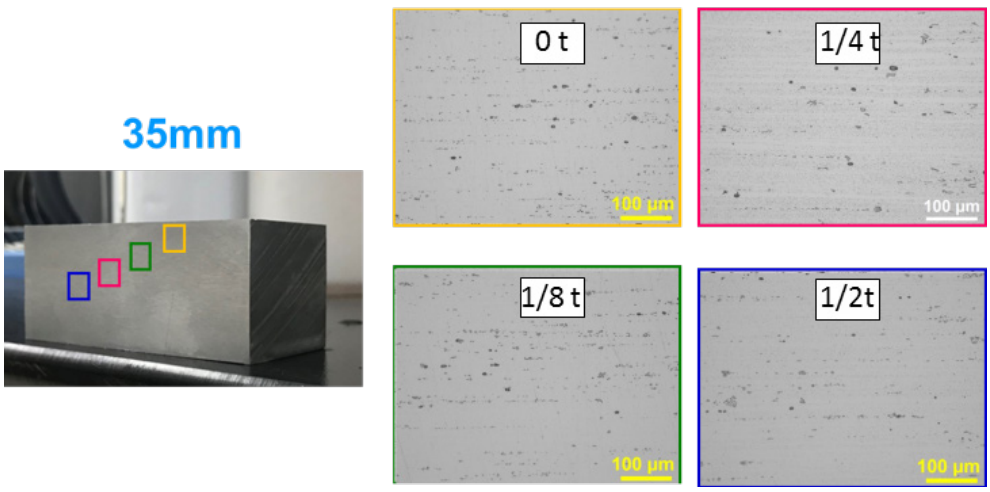

Fig.3. The microstructural eutectic phase (right) and anodized surface quality (left) for the aluminum plate fabricated via 2-step quench path.

solution treatment via the one-stage quenching path (Fig.4 (red line)), the temperature difference between the former and later part of the plate sunken into the water is about 250°C. The final product of the aluminum plate undoubtedly retains the residual stress. The novel two-stage quenching path which was firstly initialized with a high-temperature solution treatment, secondarily stopped by an air-cooling step, and finally quenched into the water tank from a lower temperature (Fig.4 (green line)), can spheroidize the eutectic phases, increase the sustainability of the Mg/Si atomic lattice concentration, and decrease the temperature difference between the hot and cold point. Consequently, one can obtain an aluminum plate which shows high anodizing surface quality, high hardness, and low residual stress. However, the process of the one-stage quenching path (Fig.4 (orange line)) reduces both the hot-to-cold temperature difference and the residual stress, but the insufficient Mg/Si atomic lattice concentration harms the mechanical stress of the aluminum plate. Figure 5 and Figure 6 identify the distribution of thickness-direction residual stresses which are measured from the high-temperature two-stage quenching path and the high-temperature one-stage path, respectively. One can see that the residual stress

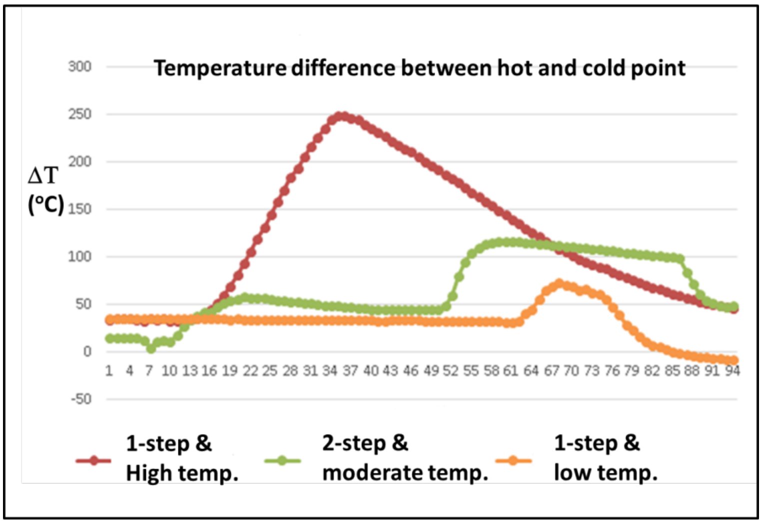

Fig.4. The ΔT between hot and cold point of the aluminum plates which were fabricated via 1-step quench path consisted of high-temperature solution treatment (red line), 2-step quench path consisted of high-temperature solution treatment and medium-temperature quenching (green line), and 1-step quench path consisted of low-temperature solution treatment (orange line), respectively.

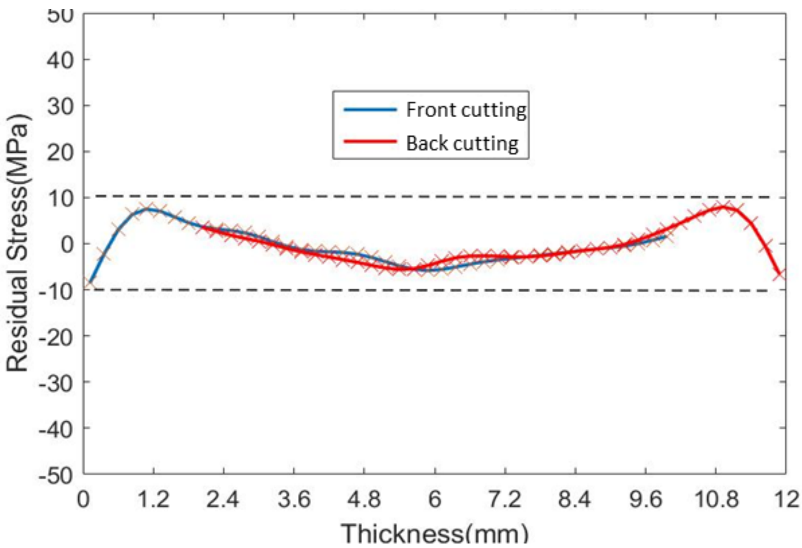

Fig.5. The residual stress of the NDxRD plane for the aluminum plate fabricated via 2-step quench path.

acquired from the moderate initial quenching temperature (two-stage quenching) is twice lower than the high initial one (one-stage quenching). For the two-stage quenching sample, the distribution of residual stress in the thickness direction is quite symmetrical. In this way, the rebound after mechanical finishing is not found in our aluminum plate anymore. Figure 7 displays the 170°C artificial hardness curves for the aluminum plates which are produced via the two-stage high-temperature and the one-stage low-temperature quenching processes, respectively. One can see that the hardness of the former process is higher than that of the later one. It is proved that the two-stage high-temperature quenching is a total solution for achieving the high anodizing quality, the low residual stress, and the high hardness for the aluminum plate.

4. CONCLUSION

In order to enhance the solution effect and reduce the quenching stress during the continuous manufacturing procedures of 6061-aluminum alloy, this study proposed a two-stage quenching path which was firstly

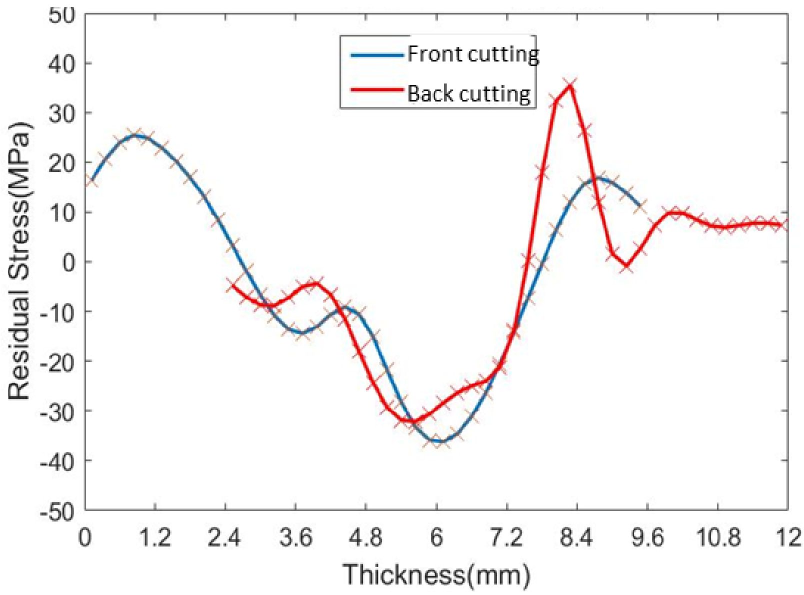

Fig.6. The residual stress of the NDxRD plane for the aluminum plate fabricated via 1-step quench path (high-temperature solution treatment).

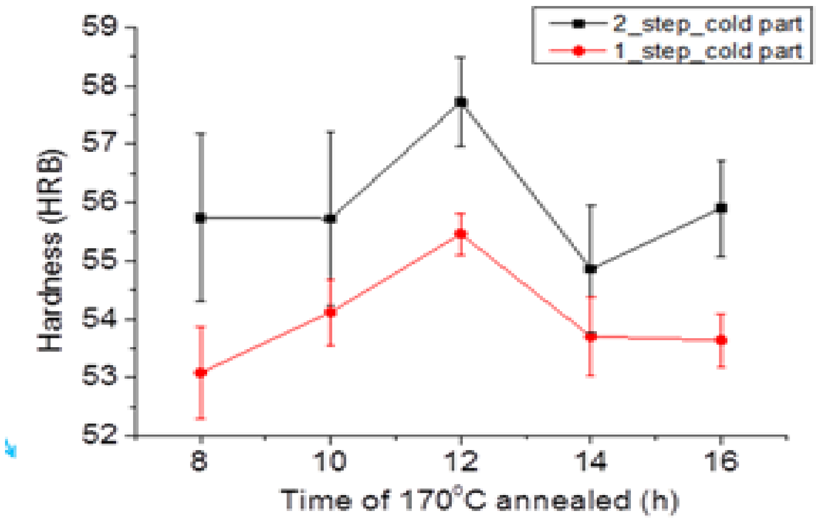

Fig.7. The aging curves of the hardness for the aluminum plates fabricated via 2-step quench path consisted of high-temperature solution treatment and medium-temperature quenching (black line) and 1-step quench path consisted of low-temperature solution treatment (red line), respectively.

initialized with a high-temperature solution treatment, secondarily stopped by an air-cooling step, and finally quenched into the water tank from a lower temperature. This invention successfully overcame the disadvantage of the drop-quench furnace as well as achieving the goals of the spheroidization of eutectic phases, the diminution of the temperature difference within the aluminum plate, and the sustainability of the Mg/Si atomic lattice concentration. The 6061-aluminum plate which revealed the high anodizing surface quality, the high hardness, and the low residual stress successfully penetrated into the supply chain of the ultra-high vacuum system for the advanced semiconductor manufacturing industry, whilst also being a profitable product for CSC.

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