Research on Solid Solution Process of High Strength Casting Al-5.0Cu-0.5Mn Alloy

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Abstract. In this paper, hardness testing, metallographic analysis, scanning electron microscope, X-ray diffraction and other methods are used to study the solid solution behavior of Al-5.0Cu-0.5Mn alloy in the range of 0-24h at 500°C-550°C. After different solid solution processes, the micro-structure and mechanical properties of the change law, the following conclusions are obtained: the as-cast alloy mainly consists of aluminum matrix and non-equilibrium eutectic composition, and the non-equilibrium eutectic is distributed in the grain boundary of the alloy in a discontinuous network. So, we get the following conclusions: The non-equilibrium eutectic in the alloy is rich in Cu elements, and its main chemical composition is Al2Cu. The formation of this structure is due to the rapid cooling of the ingot during the solidification process and insufficient atom diffusion.

1. Introduction
Al-5.0Cu-0.5Mn alloy is a kind of high-strength cast aluminum alloy researched by our country. It uses high-purity raw materials, controls the influence of harmful impurities, and adds various trace alloying elements such as titanium, zirconium, vanadium, and boron. It is made by refining crystal grains, adding cadmium to control its aging process, and applying strict heat treatment. It is currently the highest tensile strength aluminum alloy in the world[1-3]. It can be used to replace steel with aluminum, replace forging with casting, reduce weight, improve product performance, reduce production costs, shorten production cycles, promote high-quality casting technology, and produce difficult castings. At present, the alloy has been included in the Ministry and National Standards and has become an important structural material for military and civilian products. In this paper, the solid solution behavior of Al-5.0Cu-0.5Mn alloy is studied, and the micro-structure and mechanical properties of the alloy through different solid solution processes are investigated[4-6].

2. Experiments
The experimental material is a high-strength cast Al-5.0Cu-0.5Mn alloy with a block shape, and its chemical composition is shown in Table 1. The Al-5.0Cu-0.5Mn alloy was solid-solution processed, and the metallographic structure of the alloy was observed by metallographic microscope and scanning electron microscope. The hardness value of the Vickers hardness machine and X-ray diffraction were tested and analyzed.
Table 1. The chemical composition of Al-5.0Cu-0.5Mn (unit: %)

| alloy composition | Cu   | Mn   | Ti   | B    | V    | Cd   | Zr   |
|-------------------|------|------|------|------|------|------|------|
| proportion        | 5.14 | 0.48 | 0.23 | 0.01 | 0.09 | 0.05 | 0.06 |

3. Test results and analysis

3.1. As-cast micro-structure

The as-cast structure of the test alloy is shown in Figure 1. It can be seen from the figure that the grain size of the alloy is relatively small. The grain size of the alloy is calculated by the cross-section method, and it is measured to be about 60μm; There are also a large number of discontinuous network black second phase structures distributed there. The size of the black second phase is coarse, about 50-100μm, which is extremely unfavorable to the mechanical properties of the alloy and must be eliminated by heat treatment. In order to further understand the basic morphology and chemical composition of the second phase of the grain boundary, we carried out scanning electron microscopy analysis on it, as is shown in Figure 2.

![Figure 1. As-cast micro-structure (a) 200 times (b) 100 times.](image)

![Figure 2. Scanning electron micro-graph of as-cast alloy (a) 500 times (b) 1000 times (c) 2000 times (d) 5000 times](image)

It can be seen from Figure 2 that the white structure is a non-equilibrium eutectic. From the area of the non-equilibrium eutectic, there are more equilibrium ones, mainly because the cooling rate of the ingot is faster during the cooling process, and it is too late for the solute atoms in the alloy to diffuse. The solute atom concentration in the local area reaches the concentration of the eutectic alloy, thus forming a non-equilibrium eutectic. In order to detect the chemical composition of the non-equilibrium eutectic, we performed an energy spectrum analysis of the non-equilibrium eutectic, as is shown in Figure 3.
Figure 3. Scanning electron microscopy and energy spectrum analysis photos of alloy non-equilibrium eutectic structure (a) scanning electron microscopy photos (b) A energy spectrum analysis photos

Table 2. Energy spectrum analysis results of point A

| Element | Wt% | At% |
|---------|-----|-----|
| BK      | 08.41 | 23.09 |
| CK      | 04.62 | 11.43 |
| AlK     | 40.15 | 44.18 |
| ZrL     | 06.50 | 02.11 |
| CdL     | 01.64 | 00.43 |
| TiK     | 00.29 | 00.18 |
| VK      | 01.29 | 00.75 |
| MnK     | 06.71 | 03.62 |
| CuK     | 30.39 | 14.20 |
| Matrix  | Correction | ZAF |

It can be seen from Figure 3 that the non-equilibrium eutectic presents a typical lamellar structure. The main elements of the non-equilibrium eutectic (point A) are Al and Cu. The content of Cu is extremely high, indicating that the white structure is a non-equilibrium co-crystal. The possibility of crystalline Al2Cu is very high. In order to further verify it, we conducted X-ray diffraction analysis, as is shown in Figure 4.

Figure 4. X-ray diffraction pattern of as-cast al
It can be seen from Figure 4 that in addition to the diffraction peaks corresponding to the matrix α-Al, there are diffraction peaks at the 2θ angles of 20°, 30°, 42° and 47°, and the substances corresponding to these diffraction peaks are all Al2Cu. The alloy contains a large amount of Al2Cu phases, and the white Cu-rich phase on the grain boundary is the non-equilibrium eutectic. Al2Cu is formed during the solidification of the ingot. Since more non-equilibrium eutectic is detrimental to the mechanical properties of the alloy, we have to solid-solution treatment to improve the mechanical properties of the alloy.

3.2. The effect of solution treatment process on alloy structure

Figures 5-8 show the alloy metallographic structure: when the solid solution temperature is 500 °C, the black line structure of the alloy is very obvious, indicating that the degree of non-equilibrium eutectic dissolution is not high, a large amount of supersaturated solid solution is not formed, and the mechanical properties are not obviously improved. When the solution temperature is 520 °C, there are more black lines in the alloy, indicating that the degree of non-equilibrium eutectic dissolution is moderate, but a large amount of supersaturated solid solution is still not formed, and the mechanical properties are not improved significantly. When the solution temperature is 535 °C, the black line structure of the alloy is not obvious, indicating that the degree of non-equilibrium eutectic dissolution is high, there is almost no non-equilibrium eutectic, a large amount of supersaturated solid solution is formed, and the mechanical properties are improved significantly. When the solution temperature is 550 °C, although the alloy has no black line structure, a large amount of black block structure appears, indicating that the non-equilibrium eutectic has a high degree of dissolution, resulting in over-burning and unstable performance.

Figure 5. Metallographic diagram of alloy when the solution temperature is 500 °C
(a) 500 °C/2h (b) 500 °C/12h (c) 500 °C/24h

Figure 6. Metallographic diagram of alloy when the solution temperature is 520 °C
(a) 500 °C/2h (b) 500 °C/12h (c) 500 °C/24h
3.3. The effect of solution treatment process on grain size

Figure 9 is a diagram of the grain size of different solution treatment processes. It can be seen from the figure that at four different solution treatment temperatures of 500°C, 520°C, 535°C, and 550°C, as the solution time increases, the alloy’s grain size keeps increasing. With the same solution time, the grain size of the alloy gradually increases when the temperature becomes higher. Among them, when...
the solid solution temperature is 550°C, the change in the grain size of the alloy is the most obvious. But due to the over-heating, the grain size changes irregularly, which is not suitable for research as a standard solid solution process. So the other three temperatures are more suitable to be the best solution treatment temperature for this experiment.

3.4. The effect of solution treatment process on alloy micro-hardness

Figure 10. Hardness micro-graphs of different solution treatment processes

Figure 10 is the micro-hardness diagram of different solution treatment processes. It can be seen from the diagram that when the solution temperature is 550°C, the micro-hardness of the alloy first increases and then decreases, which is mainly due to the dissolution of the non-equilibrium eutectic into the matrix. It increases the solid solution strengthening effect of the alloy and also the hardness. As the grain size of the alloy increases, the grain boundary strengthening effect of the alloy is reduced.

We can know from the results of the effect of the solution treatment process on the grain size and micro-hardness of the alloy that the optimal solution treatment temperature of the alloy is 535°C because the non-equilibrium eutectic of the alloy can fully dissolve into the matrix at this temperature, and the crystal The grain size will not grow too much.

3.5. X-ray diffraction analysis of solid solution alloy

Figure 11. X-ray diffraction pattern of solid solution alloy
In order to further analyze the solid solution effect of the alloy, we performed X-ray diffraction analysis on the sample after 535 °C/8h solution treatment. As is shown in Figure 11, in the X-ray diffraction pattern, the as-cast alloy has a 2θ angle of 20°. The diffraction peaks existing at, 30°, 42° and 47° positions have disappeared, which means that the Al2Cu structure is greatly reduced, that is, the non-equilibrium eutectic is reduced, and the supersaturated solid solution is formed, which is fully prepared for the subsequent aging. Therefore, the best solution treatment process for this alloy is 535°C/8h.

4. Conclusion
(1) There is aluminium matrix and non-equilibrium eutectic in the cast alloy, and the non-equilibrium eutectic is not continuously distributed at the grain boundaries.

(2) The non-equilibrium eutectic was mainly containing Cu element, and the composition of the eutectic was determined as Al2Cu. The forming mechanism was attributed to the high cooling rate and the Cu atoms were unable to diffuse sufficiently.

(3) The superior solid solution treatment method is 535/8h, after which the non-equilibrium eutectic can be mostly dissolved into the matrix formation of supersaturated solid solution, while the grain size has not fully grown, still maintained below 100 μm.

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