

Article

Synergistic Effects of Nd Content and Cooling Rate on the Organization and Properties of Al-Nd Alloys

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Abstract: This research focuses on the synergistic effect of the cooling rate and solute neodymium (Nd) content on the microstructure and physical properties of aluminum-neodymium (Al-Nd) alloys. The results indicate that the cooling rate has a significant impact on the grain morphology, size, and morphology of eutectic Al₁₁Nd₃ in the alloy. As the cooling rate decreases, the grains transform from columnar crystals to equiaxed crystals, exhibiting different distribution characteristics in various regions, and the eutectic transforms from skeletal to lamellar and then to acicular. The Nd content affects the eutectic growth and solubility, reaching the maximum solubility at 11 wt.% Nd. Due to the longer diffusion time of Nd atoms in the slow-cooling region and the formation of compounds, the lattice constant in the slow-cooling region is larger. In terms of physical properties, the hardness and electrical conductivity of the alloy are inversely related. The hardness increases with an increase of the cooling rate and Nd content, which is attributed to grain refinement and solid solution strengthening, while the electrical conductivity decreases. These findings are of important theoretical and practical significance for optimizing the performance and application of Al-Nd alloys.



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Keywords: Al-Nd alloy; microstructure; hardness and conductivity; Nd content; synergistic effect

1. Introduction

Aluminum alloys are widely used in various fields, such as in the electronics, aerospace, and automotive industries, due to their excellent corrosion resistance, electrical conductivity, relatively high hardness, and low cost [1–3]. The performance of aluminum alloys can be significantly improved by doping with rare earth elements, particularly in terms of mechanical properties, which can greatly enhance key indicators such as electrical conductivity, strength, toughness, and ductility [4–6]. Binary rare earth alloys also show considerable potential in applications, as the introduction of rare earth elements has a notable impact on the performance of aluminum alloys, especially in terms of enhancing their mechanical properties, with improvements in corrosion resistance being particularly outstanding [7,8].

Rare earth elements can effectively refine the grain structure of aluminum alloys and reduce internal defects in the crystal, thereby significantly improving the mechanical

properties of the material [9–11]. With the continuous advancement of materials science, the application of rare earth elements in aluminum alloys has become a key research area. Among the numerous binary rare earth alloys, Al-Ce, Al-Sc, and Al-Nd alloys have been widely applied due to their unique performance advantages [12,13]. Specifically, Al-Ce alloys are extensively used in shipbuilding due to their excellent corrosion resistance [14]; Al-Sc alloys, by significantly improving the strength and heat resistance of aluminum alloys, exhibit outstanding performance in high-temperature, high-pressure environments or engineering applications requiring extremely high strength [15–17]; Aluminum-neodymium alloys are widely used in aerospace materials and TFT-LCD panels, owing to their excellent physical properties, such as low electrical resistivity and high hardness [18–20]. In the manufacturing process of TFT-LCD panels, Al-Nd alloys are primarily used to produce sputtering targets. Through the sputtering process, aluminum-neodymium alloy targets form electrode layers on the glass substrate. The main function of the electrode layer is to provide an electric field for the liquid crystal molecules, thereby controlling their alignment direction and adjusting the transmission and blocking of light, achieving image display effects. Compared with pure aluminum targets, aluminum-neodymium alloy targets exhibit superior performance in terms of electrical conductivity, corrosion resistance, and other properties, which help to improve the quality and stability of the electrode layer [19,21–24].

The main eutectic phase present in Al-Nd alloys is $\text{Al}_{11}\text{Nd}_3$. This eutectic phase can act as a heterogeneous nucleation core during the solidification process of Al-Nd alloys, effectively promoting the nucleation of the aluminum matrix and thus refining the grain structure. Grain refinement increases the number of grain boundaries within a unit volume, and grain boundaries can effectively hinder the motion of dislocations, thereby improving the alloy's strength and hardness while simultaneously enhancing its plasticity and toughness. Moreover, the presence of the eutectic phase can also enhance the alloy's hardness [20,24].

As the neodymium content increases, the Al-Nd binary phase diagram shows that $\text{Al}_{11}\text{Nd}_3$ exists in both high-temperature β -phase and low-temperature α -phase crystal structures, with a phase transition temperature of approximately 950 °C [25]. The addition of neodymium significantly affects the tensile properties and corrosion resistance of the aluminum alloy [24,26]. Qitao Lv and colleagues found that the addition of neodymium to 6082 aluminum alloy enhances the interfacial bonding strength between the precipitates and the matrix, thereby further improving the strength and toughness of 6000 series aluminum alloys [27]. Additionally, Wanwu Ding and his team discovered that adding neodymium to 6063 aluminum alloy significantly increased its elongation [28]. These studies demonstrate that the incorporation of neodymium has a positive effect on both the mechanical properties and corrosion resistance of aluminum alloys.

The Nd content and cooling rate have a significant impact on the grain size, grain morphology, secondary dendrite arm spacing, formation of the eutectic $\text{Al}_{11}\text{Nd}_3$ phase, and the physical properties of the alloy. However, related research remains relatively scarce. Particularly in binary Al-Nd alloy systems, studies on the performance characteristics of the eutectic $\text{Al}_{11}\text{Nd}_3$ phase and its microstructural evolution are still insufficient. This study investigates aluminum-neodymium alloys with three different Nd contents (0.78%, 2%, and 11%) across four different temperature intervals (A to D) to explore the microstructure and mechanical property variations of the cast alloys. The results of this study will lay the foundation for subsequent process optimization and practical applications of aluminum-neodymium alloys.

2. Materials and Methods

2.1. Sample Preparation

In order to obtain Al-Nd alloys solidified at different cooling rates, high-purity aluminum ingots with a purity of 99.99 wt.% and neodymium ingots were selected to prepare the alloy, and casting was carried out using a wedge-shaped copper mold. First, pure aluminum and pure neodymium were mixed in a specified ratio and placed in a high-purity graphite crucible. The crucible was then fixed in an intermediate frequency induction furnace in a vacuum environment and heated to a temperature of 1000–1200 °C for 20 min. Afterward, the frequency was reduced, and the temperature was lowered to 800–1000 °C. The temperature was maintained for 15 min before the molten metal was cast into the pre-designed, wedge-shaped copper mold. The alloy was then cooled in a vacuum for more than 3 h before being removed. After removal, the ingot was cut along its midpoint, and the sample was sectioned according to the designed A–D regions. The sampling arrangement is shown in Figure 1.

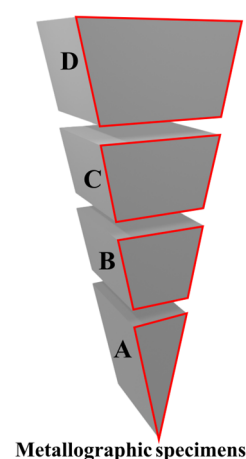


Figure 1. Specimens with different cooling rates, the cooling rate from A to D decreases gradually.

2.2. Microstructure Analysis

The specimens were polished, the metallographic structure of the alloys was examined using an optical microscope (OM, OLYMPUS, Tokyo, Japan). The specimens were then anodized with 2.5 vol% HBF_4 solution at 20 V and 0.5–1.0 mA for about 45 s. The microstructures were then visualized with cross-polarized light using an optical microscope with a polarization imaging system, and analyzed by Image-Pro Plus (6.0, Media Cybernetics, Rockville, MD, USA) to calculate the area fraction of the eutectic structure in the orthogonally polarized image, and the area fraction of the eutectic phase in at least fifty different positions of the alloys with three different Nd compositions was selected at different positions and averaged to minimize the statistical error and make the experimental results representative. the microstructure was studied using a scanning electron microscope (SEM, TESCAN MIRA3, Brno, Czech Republic), and the composition was analyzed qualitatively and quantitatively using an energy-dispersive X-ray spectrometer (EDS, TESCAN MIRA3, Brno, Czech Republic). The elemental composition of the cast phase in the four samples was characterized using an X-ray diffractometer (XRD, Smart Lab 9kw, Tokyo, Japan) with Cu targets to determine the lattice parameters of the alloys, with diffraction angles ranging from 20 to 100 in steps of 5 /min. During the sample processing, the samples were etched with aqua regia for 45 s. Subsequently, the phase micro-morphology of the samples was observed using a scanning electron microscope (SEM, model TESCAN MIRA3, Brno, Czech Republic).

2.3. Performance Analysis

The electrical conductivity of the materials was measured using a Sigmascope conductivity meter (Xiamen Tianyan Instrument Co., Ltd., Xiamen, China). Each sample was evaluated at multiple points (with an average of eight points), and the average value was recorded. Prior to testing, the sample surfaces were polished using sandpaper, and calibration was performed using a standard copper block before each measurement. The probe was rotated 90° for each reading. The hardness of the three alloy compositions was tested using a microhardness tester (FUTURE-TECH, Kawasaki, Japan). For each sample, five points were evaluated, and the average hardness value was recorded.

2.4. Analysis of Synergistic Effects

For samples with three different compositions, X-ray diffraction (XRD) tests were first carried out to obtain the corresponding spectral data. According to Bragg's law:

$$n\lambda = 2d\sin\theta \quad (1)$$

where n is the diffraction order, λ is the X-ray wavelength, d is the interplanar spacing, and θ is the diffraction angle. Characteristic diffraction peaks that are distinct and free from interference were precisely selected from the XRD patterns to determine the inter-planar spacing d . For the cubic crystal system, the relationship between the inter-planar spacing d and the lattice constant a was used.

$$d = \frac{a}{\sqrt{h^2 + k^2 + l^2}} \quad (2)$$

where h , k , and l are the Miller indices. This was done to calculate lattice constant a_0 of α -Al in the sample. The solubility of Nd in Al was roughly estimated according to Vegard's law [29]

$$a = a_0(1 - x) + a_1x \quad (3)$$

where a is the actual lattice constant of the alloy $\text{Al}_{11}\text{Nd}_3$, a_0 is the lattice constant of pure aluminum, a_1 is the standard lattice constant of pure neodymium, and x is the solid solubility of Al-Nd. x was used to represent the solubility of Nd in Al.

On this basis, the synergistic effect of the cooling rate and Nd content on the properties of Al-Nd alloys were explored in-depth. The variation laws of the alloy's microstructure, mechanical properties, and physical properties with the change of Nd content under different cooling rates were compared. Through systematic data analysis and evaluation of experimental results, the synergistic relationship between the two in the process of affecting alloy properties was clarified.

3. Results

3.1. Effect of Cooling Rate on Grain Morphology and Size

For the Al-0.78 wt.% Nd alloy, four samples (A, B, C, and D) exhibited specific microstructural grain morphology distribution patterns, as shown in Figure 2. Near the mold wall, columnar grains dominated, whereas in the central region, equiaxed grains were the predominant morphology. From the perspective of cooling rate, as the cooling rate decreased from sample A to D, the grain structure showed a gradual refinement trend. This indicated that lower cooling rates (such as the cooling conditions corresponding to sample D) were favorable for grain refinement. Specifically, the growth direction of the columnar grains was perpendicular to the mold wall and extended outward along the mold wall. The dendrite growth rate in this direction was significantly higher than in other directions. This preferential rapid growth mode is referred to as preferential growth. During this process,

the latent heat released by the preferentially growing dendrites inhibited the growth of dendrites in other directions, thereby affecting the overall grain growth morphology [30–32]. As the cooling rate gradually decreased, a noticeable transition in grain morphology occurred, from columnar grains to equiaxed grains. In sample A, columnar grains were the dominant grain morphology. Samples B and C contained both columnar and equiaxed grains, with the proportion of equiaxed grains in the central region gradually increasing. In sample C, the region where columnar grains transitioned to equiaxed grains can be clearly observed. Finally, in sample D, equiaxed grains became the primary component, and the overall grain size was noticeably smaller compared to those of the other samples.

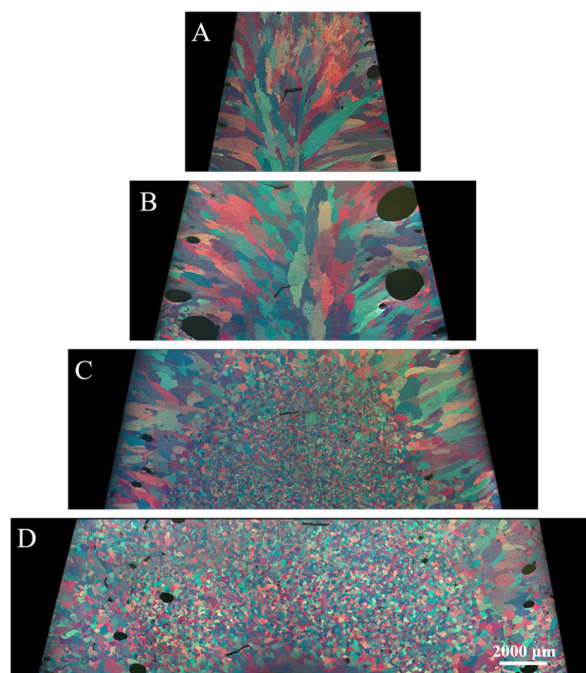


Figure 2. Grain morphology of Al-0.78 wt.% Nd at different cooling rates. (A) is columnar crystal, (B,C) are a mixture of columnar crystals and equiaxed crystals; (D) is equiaxed crystal.

3.2. Effect of Different Nd Content and Cooling Rate on Grain Size and Distance Between Secondary Dendrites

Figure 3 clearly demonstrates the microstructural changes of the Al-Nd alloy under different cooling rates. It can be clearly observed that with the gradual decrease in cooling rate, the microstructure of the alloy exhibited a significant coarsening phenomenon. At the lowest Nd content, the distribution of the eutectic structure was not significant. However, as the cooling rate continuously decreased, the dendrite arms gradually became thicker and larger, while the eutectic structure became more pronounced. By comparing the A–D regions in Figure 3, it is evident that with the decreasing cooling rate, the primary dendrite arm spacing progressively increased. Additionally, changes in Nd content also influenced the alloy's microstructure. Specifically, as the Nd content increased, the dendrites gradually became coarser and more robust.

For the Al-11 wt.% Nd alloy, the eutectic phase $\text{Al}_{11}\text{Nd}_3$ predominated in its microstructure. At positions A and B, the eutectic phase primarily exhibited a feather-like morphology, while at positions C3 and D3 in the figure, spherical crystals appeared. At position D, rod-shaped crystals emerged. It is important to note that for alloys with high Nd content, the grain boundaries between crystals became difficult to distinguish clearly. In such cases, when measuring dendrite arm spacing and grain size, statistical operations were no longer performed to ensure the accuracy and validity of the statistical data.

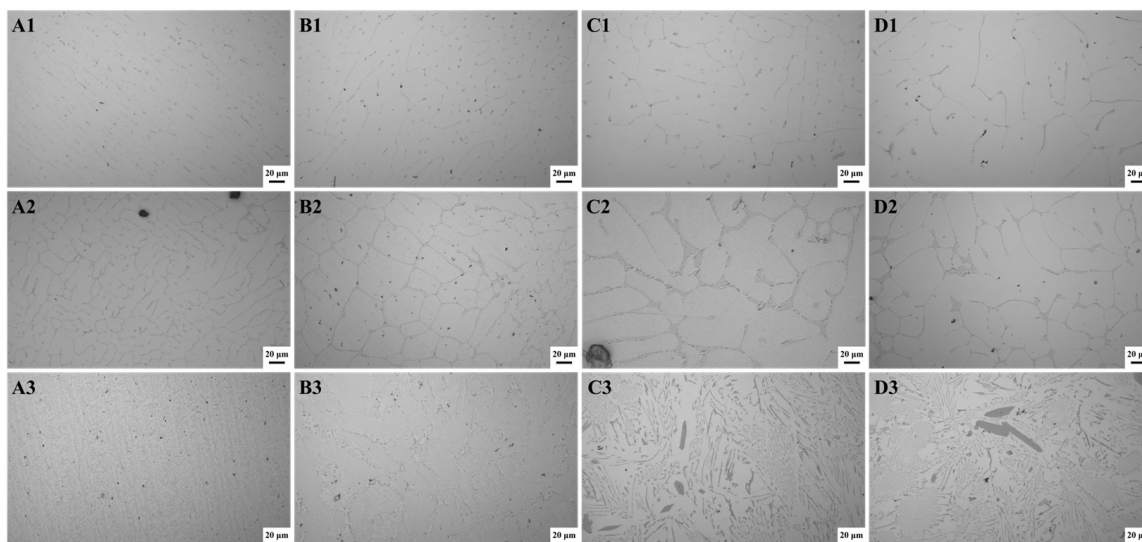


Figure 3. Microstructures of the three alloys at different cooling rates, (A1–D1) for Al-0.78 wt.% Nd, (A2–D2) for Al-2 wt.% Nd, (A3–D3) for Al-11 wt.% Nd.

Figure 4 presents a systematic and precise statistical analysis of the grain width in regions A, B, C, and D, revealing a close correlation between the cooling rate and the dendrite arm spacing, as well as the grain size of the alloy. The study shows that as the cooling rate increased, the dendrite arm spacing of the alloy decreased, while the grain size of both alloys increased. Specifically, for the Al-0.78 wt.% Nd sample, the dendrite arm spacing decreased from 36.12 μm to 18.41 μm , while the grain size increased significantly from 606.74 μm to 1070.47 μm . For the Al-2 wt.% Nd sample, the dendrite arm spacing decreased from 42.72 μm to 20.21 μm , and the grain size increased from 535.23 μm to 798.63 μm .

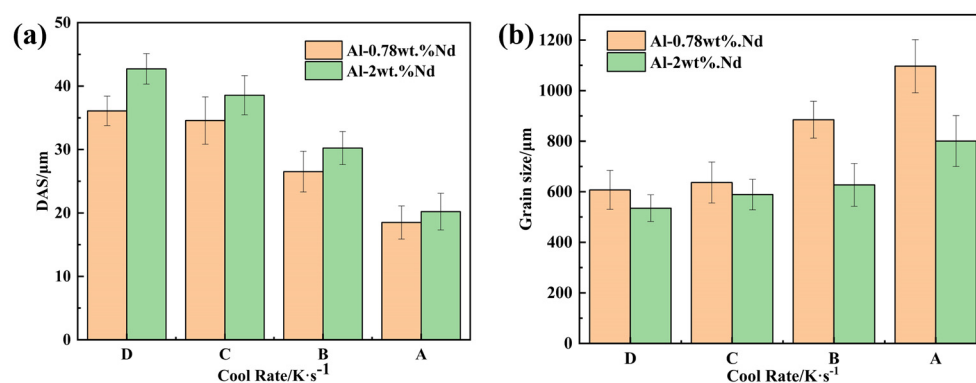


Figure 4. (a) DAS variation of Al-Nd alloys at different cooling rates, (b) grain size of Al-Nd alloys at different cooling rates.

A further comparison of the data between the two samples revealed that the grain size of Al-0.78 wt.% Nd was always larger than that of Al-2 wt.% Nd, while the dendrite arm spacing of Al-2 wt.% Nd was consistently greater than that of Al-0.78 wt.% Nd. As the solute Nd content increased, the grain size of the alloy decreased, and the dendrite arm spacing increased. This indicated that the Nd content played a crucial role in the alloy's grain refinement process.

3.3. Microstructure of Al-Nd Alloys with Different Nd Contents

An in-depth analysis of the SEM images in Figure 5 reveals that under conditions of continuously decreasing cooling rate, the microstructure of the alloy exhibited a regular

evolution. The growth of the lamellar eutectic structure showed a trend of gradual enlargement, with its features becoming increasingly pronounced. The spatial distribution of the structure tended to become more uniform, while the network-like structure formed by the interwoven grain boundaries became tighter and more complex. Notably, in the D region under the same cooling rate conditions, the lamellar crystals of the Al-11 wt.% Nd alloy (as shown in Figure 3D) had a size that was significantly larger than the corresponding structures in the Al-0.78 wt.% Nd and Al-2 wt.% Nd alloys. From a phase distribution perspective, the eutectic phase in the Al-0.78 wt.% Nd and Al-2 wt.% Nd alloys were concentrated in the α -Al matrix, occupying a substantial area. Furthermore, energy dispersive spectroscopy (EDS) analysis revealed that the Nd element was primarily enriched in the eutectic region.

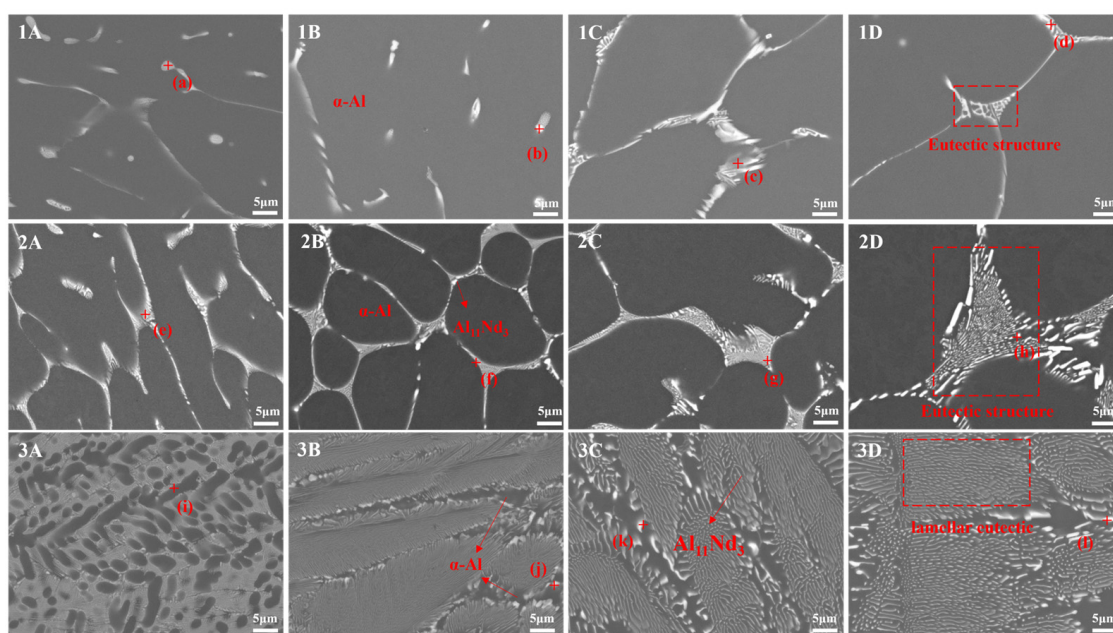


Figure 5. Microstructure of alloys with different Nd contents at cooling rates in A, B, C and D zones, (1A–1D) is Al-0.78 wt.% Nd, (2A–2D) is Al-2 wt.% Nd, (3A–3D) is Al-11 wt.% Nd.

Combining the EDS analysis, the main phase of the Al-0.78 wt.% Nd and Al-2 wt.% Nd alloys was α -Al, whereas the main phase of the Al-11 wt.% Nd alloy was the Nd-rich $\text{Al}_{11}\text{Nd}_3$ phase.

Based on a comprehensive analysis of XRD and EDS, as shown in Figure 6 and Table 1, it can be observed that in the three alloys with different Nd contents, the primary phases were α -Al and $\text{Al}_{11}\text{Nd}_3$. The lamellar eutectic composition was primarily $\text{Al}_{11}\text{Nd}_3$, with Nd elements being significantly enriched in the eutectic region. The eutectic morphology in all three alloys was predominantly lamellar, with the key eutectic phase being $\text{Al}_{11}\text{Nd}_3$, which was embedded in the α -Al matrix. This structure arose from the alternating lamellar arrangement of the aluminum matrix and the Nd-rich eutectic phase. This lamellar eutectic structure typically forms under moderate cooling rates, and its formation mechanism is primarily driven by the differences in diffusion rates of aluminum and neodymium during solidification, as well as the combined effect of interfacial energy. The interplay of these factors promoted the eutectic to form in a lamellar distribution, thereby reducing the system's total energy [33].

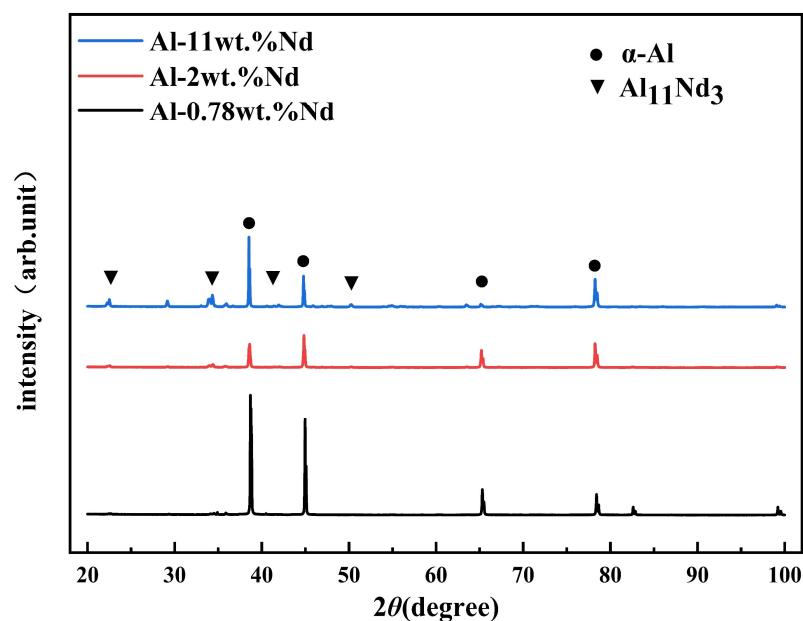


Figure 6. XRD analysis of three alloys with different Nd content compositions.

Table 1. EDS analysis results for the locations marked.

Sample	Point	Composition (Weight Percent, wt.%)	
		Al	Nd
Al-0.78 wt.% Nd	(a)	87.55	12.45
	(b)	77.12	22.88
	(c)	71.91	28.09
	(d)	70.03	29.97
Al-2 wt.% Nd	(e)	84.59	15.41
	(f)	78.61	21.39
	(g)	78.81	21.19
	(h)	73.18	26.82
Al-11 wt.% Nd	(i)	83.47	16.53
	(j)	74.76	25.24
	(k)	72.21	27.79
	(l)	65.48	34.52

3.4. Morphology of $Al_{11}Nd_3$ in Al-Nd Alloys

Figure 7 shows the microstructures of the Al-0.78% Nd and Al-2% Nd alloys. The eutectic $Al_{11}Nd_3$ morphology, presented in the upper left corner after deep etching, reveals the impact of the cooling rate. For the Al-0.78% Nd alloy, the eutectic in the A region, where the cooling rate was high, was dendritic, while in the D region, where the cooling rate was low, it took on a skeletal form and was embedded in the α -Al matrix. In the case of the Al-2 wt.% Nd alloy, the eutectic $Al_{11}Nd_3$ was primarily lamellar, embedded in the α -Al matrix, and the eutectic area in the D region was larger than in the A region. Additionally, with increasing Nd content, the alloy structure became finer, and the eutectic morphology became coarser and clearer. For the Al-11% Nd alloy, in the A region with a high cooling rate, the eutectic formed feather-like crystals, with α -Al embedded in $Al_{11}Nd_3$ and transforming from a fibrous to a lamellar structure. In the D region, where the cooling rate was low, the eutectic primarily exhibited a needle-like morphology.

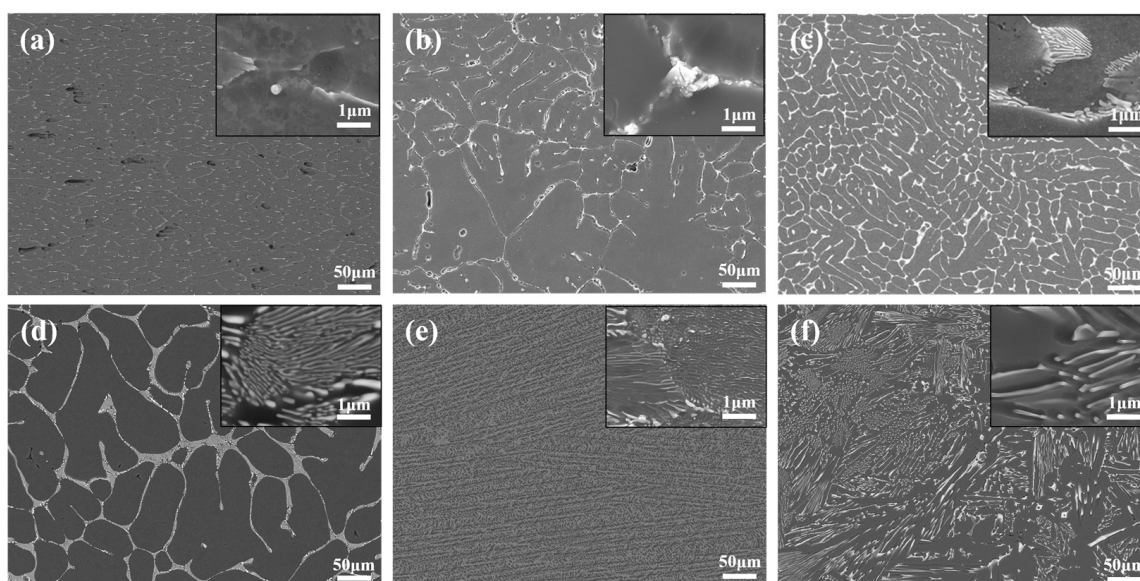


Figure 7. Eutectic morphology of aluminum-neodymium alloys with different contents in A and D zones at various cooling rates. (a,b) are Al-0.78 wt.% Nd, (c,d) are Al-2 wt.% Nd, (e,f) are Al-11 wt.% Nd.

3.5. Effect of Cooling Rate on Solid Solubility

The lattice constant variation of α -Al and the solubility X were calculated in Section 2.4 and recorded.

As can be seen from Figures 8 and 9, when the Nd content was relatively low, such as in Al-0.78 wt.% Nd and Al-2 wt.% Nd alloys, the diffraction angle θ of the α -Al crystal mainly shifted toward the right. This rightward shift led to a decrease in the interplanar spacing d . According to the relevant formula, the lattice constant also decreased accordingly. When the content was high, the diffraction angle shifted toward the left, which caused the interplanar spacing d to increase, and the lattice constant also increased. As the Nd content increased, the interplanar spacing d increased, as did the lattice constant.

It can be clearly observed from Figure 10 that, in the case of a relatively low Nd content, taking the Al-0.78 wt.% Nd and Al-2 wt.% Nd alloys as examples, the diffraction angle θ of the α -Al crystal showed an obvious tendency to shift to the right. According to Formula (2), when the diffraction angle θ shifted to the right, it inevitably resulted in a corresponding decrease in the interplanar spacing d . Through accurate calculations using the relevant formula, it can be known that the lattice constant also decreased at this time. When the Nd content increased, the crystal diffraction angle θ showed a shift toward the left. Again, according to Formula (2), this leftward shift caused the interplanar spacing d to increase, and then the lattice constant also increased. With the gradual increase of the Nd content, the interplanar spacing d showed a corresponding increasing trend, thus making the lattice constant increase continuously, which fully demonstrates that the Nd content has a significant impact on the lattice structure of the Al-Nd alloy.

According to Table 2, as the cooling rate increased, the lattice constant first increased and then decreased, reaching its maximum value in Zone C. Since solubility is closely related to the lattice constant, the solubility also increased accordingly, and the solubility in Zone C was also the maximum.

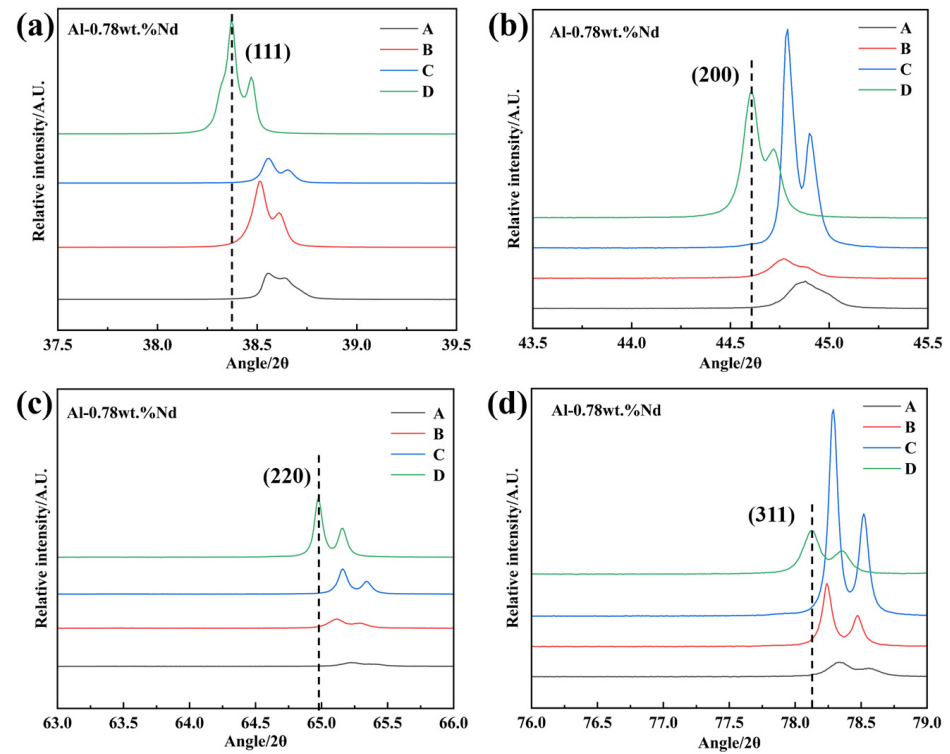


Figure 8. Diffraction peak changes of different crystal planes of α -Al in Al-0.78 wt.% Nd. (a) The (111) crystal plane of α -Al, (b) the (200) crystal plane of α -Al, (c) the (220) crystal plane of α -Al, (d) the (311) crystal plane of α -Al.

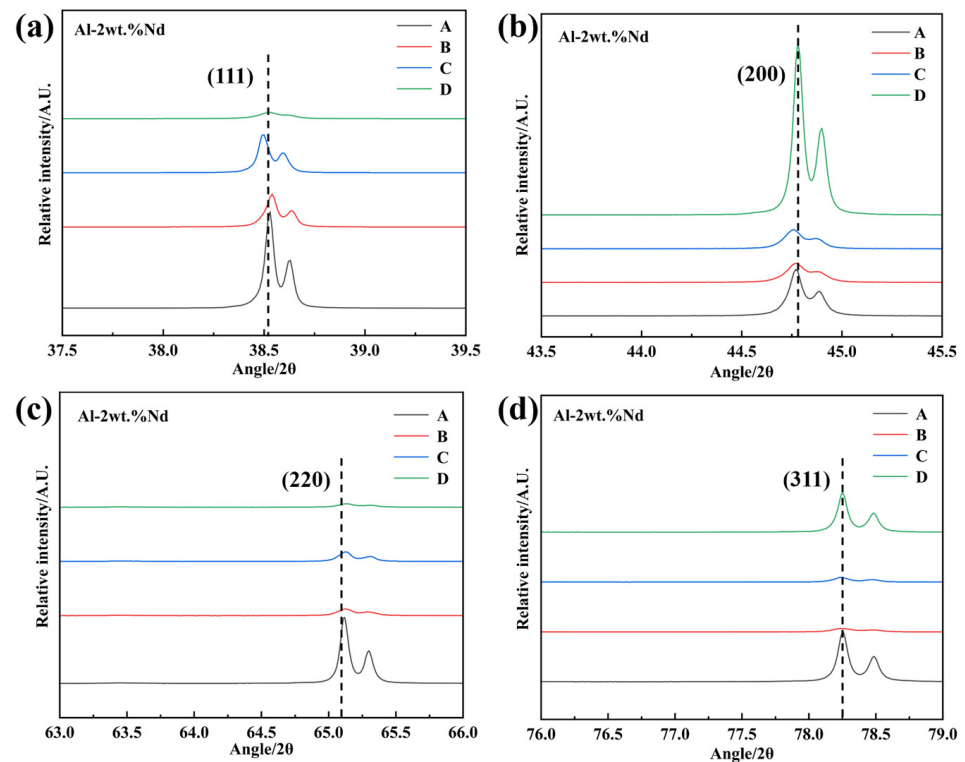


Figure 9. Diffraction peak changes of different crystal planes of α -Al in Al-2 wt.% Nd. (a) The (111) crystal plane of α -Al, (b) the (200) crystal plane of α -Al, (c) the (220) crystal plane of α -Al, (d) the (311) crystal plane of α -Al.

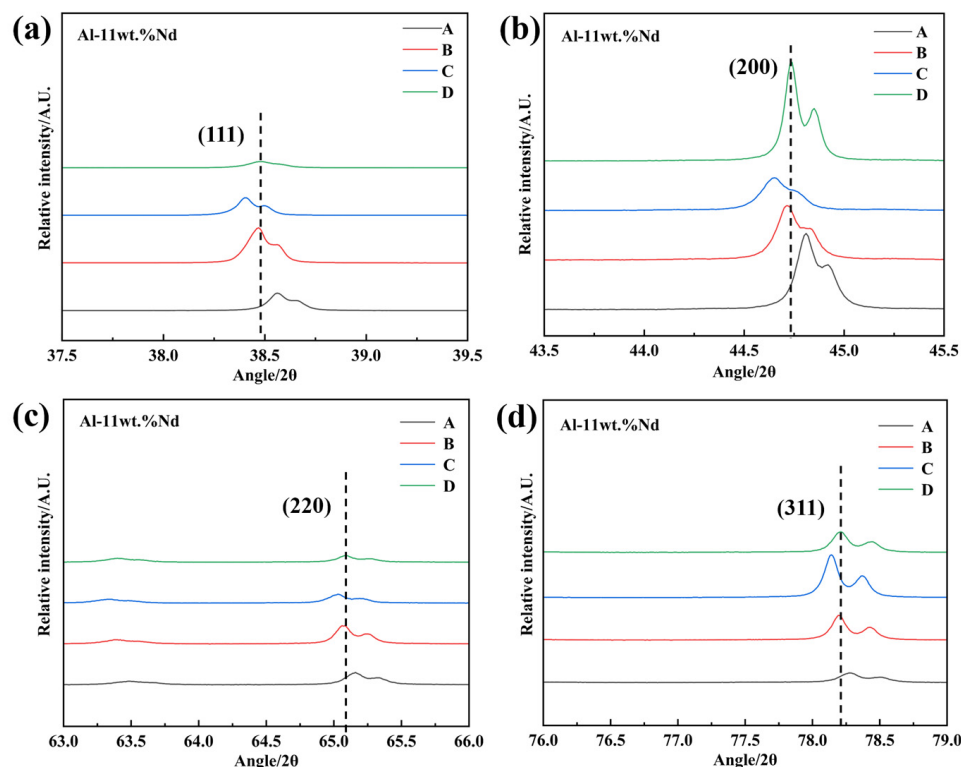


Figure 10. Diffraction peak changes of different crystal planes of α -Al in Al-11 wt.% Nd. (a) The (111) crystal plane of α -Al, (b) the (200) crystal plane of α -Al, (c) the (220) crystal plane of α -Al, (d) the (311) crystal plane of α -Al.

Table 2. Variation of the lattice parameter of α -Al and matrix solid solubility of Al-Nd alloy at different cooling rates.

Sample	Cool Rate, K·s ^{−1}	Average Lattice Constant of α -Al	The Matrix Solid Solubility, %
Al-0.78 wt.% Nd	A	4.0452	18.96
	B	4.0462	19.17
	C	4.0466	19.25
	D	4.0455	19.02
Al-2 wt.% Nd	A	4.0462	19.17
	B	4.0477	19.49
	C	4.0464	19.20
	D	4.0464	19.22
Al-11 wt.% Nd	A	4.0522	20.56
	B	4.0544	21.14
	C	4.0477	19.51
	D	4.0469	19.32

3.6. Effect of Cooling Rate on the Properties of Three Different Content Alloys

By analyzing the changes in electrical conductivity and hardness of the three alloys with different compositions under different cooling rates shown in Figure 11, it can be observed that, in terms of electrical conductivity, as the cooling rate increased, the electrical conductivity of the alloys gradually decreased. This phenomenon is related to the grain size. Referring to Figure 4b, the grain size increased with the cooling rate. Specifically, the D region primarily consisted of equiaxed grains, which had the smallest grain size and many grain boundaries, while the A region consisted mostly of columnar grains, which had the largest grain size and fewer grain boundaries, reducing the probability of electron

scattering. As the cooling rate increased, the grains gradually coarsened, the grain size increased, and the number of grain boundaries decreased, resulting in a gradual decrease in electrical conductivity [34,35]. Specifically, the electrical conductivity of Al-0.78 wt.% Nd decreased by 5.9%, Al-2 wt.% Nd decreased by 9.6%, and Al-11 wt.% Nd decreased by 3.4%. In the Al-Nd alloy system, with increasing Nd solute content, the electrical conductivity decreased. Al-11 wt.% Nd has a significantly lower electrical conductivity compared to Al-0.78 wt.% Nd and Al-2 wt.% Nd. When comparing the electrical conductivity of the A and D regions under the same cooling rate, the electrical conductivity of Al-11 wt.% Nd was 19.3% and 21.4% lower than that of Al-0.78 wt.% Nd in the A and D regions, respectively.

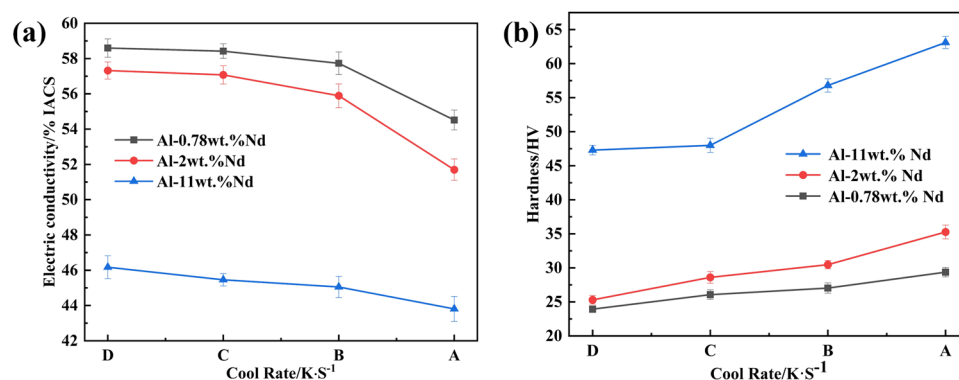


Figure 11. (a) Variation of electrical conductivity of three-component alloys at different cooling rates, (b) Variation of hardness of three-component alloys at different cooling rates.

Regarding hardness, the hardness of all three alloys increased gradually with increasing cooling rate. The hardness of Al-0.78 wt.% Nd increased by 12.6%, Al-2 wt.% Nd increased by 32.4%, and Al-11 wt.% Nd increased by 32.7%. Among them, the Al-11 wt.% Nd alloy had the highest hardness, while Al-0.78 wt.% Nd had the lowest. When comparing the hardness in the A and D regions under the same cooling rate, the hardness of Al-11 wt.% Nd was 116.4% and 83.6% higher than that of Al-0.78 wt.% Nd in the A and D regions, respectively. When the Nd content was low, its effect on the hardness of the binary alloy was not significant, and the trend was not obvious. However, when the Nd content was high, the effect on the hardness of the binary alloy was more pronounced, and the trend was clearer. For example, in the C-A phase, the hardness change slope for Al-11 wt.% Nd was the largest. When the Nd content was low, the hardness of the alloy was close to that of pure aluminum, but overall, the hardness increased with the cooling rate. This was mainly due to the fact that hardness is closely related to grain size, intermetallic compounds, and grain boundaries. When the Nd content is higher, the grain size is smaller, the number of grain boundaries is larger, and the hardness is correspondingly higher [36,37]. The effect of Nd content on alloy hardness is more significant, meaning that as the Nd content increases, the hardness also increases.

In conclusion, compared to the alloys with three different Nd contents, electrical conductivity and hardness exhibited opposite trends, i.e., as electrical conductivity decreased, hardness increased. Regarding Nd content, higher Nd content led to lower electrical conductivity but higher hardness. This phenomenon is related to factors such as cooling rate, solid solution strengthening, and grain refinement. Columnar grains have a relatively fixed orientation, while equiaxed grains have a more random orientation. A faster cooling rate is conducive to the formation of higher hardness [38].

4. Discussion

This study focused on the synergistic effects of cooling rate and solute Nd content on the microstructures and physical properties of the alloy. The obtained results are of great theoretical and practical significance. Changes in the cooling rate significantly affected the grain morphology, size, and the morphology of the eutectic $\text{Al}_{11}\text{Nd}_3$ in the alloy. As the cooling rate decreased, the grains transformed from columnar crystals to equiaxed crystals, showing different distribution characteristics in different regions. Region A was mainly composed of columnar crystals, regions B and C had a mixture of columnar and equiaxed crystals, and region D was mainly equiaxed crystals. Moreover, a low cooling rate played a role in grain refinement. This was because the cooling rate affects the heat flow distribution and solute redistribution during the solidification process. The growth of columnar crystals stems from the temperature gradient formed by the chill of the mold wall, while the low cooling rate provides conditions for the nucleation and growth of equiaxed crystals [30,39]. At the same time, the grain size gradually decreased and the dendrite arm spacing gradually increased; this was related to the nucleation rate, growth rate, and solute diffusion [40].

The impact of the cooling rate on the morphology of eutectic $\text{Al}_{11}\text{Nd}_3$ was also quite evident. As the cooling rate dropped, the eutectic transformed from a skeletal shape to a lamellar one, and then further into a needle-like shape. This was related to the solidification growth kinetics and solute distribution. An increase in the Nd content caused the needle-like eutectic to gradually grow larger. When the Nd content was low, the eutectic morphology was not obvious. As the content increased, the eutectic became coarser and more distinct; this was due to the fact that the Nd content modified the growth morphology of the eutectic.

During the dissolution of solute Nd in Al, the lattice constants in the slow-cooling regions D and C were larger than those in the fast-cooling regions A and B. Firstly, in terms of atomic diffusion and phase formation, the cooling rates in regions D and C were relatively slow, which provided sufficient time for the diffusion of Nd atoms in the Al lattice. Nd atoms could fully interact with Al atoms and aggregate at suitable positions, thus having the opportunity to form an intermetallic compound phase. The formation of this phase will trigger the reconstruction of the lattice structure, causing the lattice to expand and increase the lattice constant. In regions A and B, however, due to the relatively high cooling speed, atomic diffusion was severely inhibited. Nd atoms did not have enough time to fully react with Al atoms to form the intermetallic compound phase, and the degree of lattice reconstruction was limited, so the lattice constants were relatively small. The lattice constant was the largest in region C mainly because, under an appropriate cooling rate, the Nd solute atoms can aggregate and form a more ordered arrangement in the Al lattice [41]. Since the atomic radius of Nd (182 pm) was larger than that of Al (143 pm) when Nd atoms aggregated and arranged in a specific manner, they exerted a continuous stretching effect on the surrounding Al lattice. As time went by, the lattice distortion caused by this stretching effect accumulated continuously, gradually increasing the lattice constant. In contrast, in the rapidly cooled regions A and B, the atoms did not have enough time for such orderly aggregation and arrangement. The stretching effect of Nd atoms on the Al lattice was limited, and the increase in the lattice constant was less significant than that in regions D and C. A large amount of supersaturated solid solution is formed in region C.

The variation in the solubility of the Al-Nd alloy depended on the synergistic effect of the Nd content and the cooling rate. The solubility reached its maximum when the Nd content was 11 wt.%. This was because, at this content, an equilibrium was achieved in the interaction between Nd atoms and Al atoms, ensuring that enough Nd atoms could dissolve while not forming excessive second phases. In terms of the cooling rate, the

solubility in Zone C was the highest. This was because during the cooling process in Zone C, atomic diffusion was more favorable for the dissolution of Nd atoms in the Al lattice compared to other slow-cooling regions.

Regarding physical properties, the hardness and electrical conductivity of the alloy exhibited an inverse variation trend. As the cooling rate went up, rapid cooling gave rise to more lattice defects and additional grain boundaries [42], which impeded electron conduction and gradually lowered the electrical conductivity. On the other hand, grain refinement and solid solution strengthening led to a gradual increase in hardness [36,37]. Notably, when the solute Nd content was 11 wt.%, its solubility reached the maximum, and the solid solution strengthening effect on hardness was highly prominent, causing the Al-11 wt.% Nd alloy to attain its peak hardness value. Nevertheless, the cooling rate also had a vital impact on hardness, and these two factors mutually influenced the hardness performance of the alloy.

Simultaneously, the content of solute Nd exerted a significant influence on both hardness and electrical conductivity. At low solute levels, the hardness was at its lowest while the electrical conductivity is at its highest. With a growing Nd content, solid solution strengthening elevated the hardness, and the increasing number of solute atoms led to more lattice scattering centers, thus decreasing the electrical conductivity. Moreover, as the Nd content rose, the eutectic morphology became more pronounced, the grain size shrank, and the dendrite arm spacing widened. These microstructural alterations were closely tied to the role of solutes during alloy solidification, further uncovering the intrinsic relationship between the alloy's microstructural and physical properties.

5. Conclusions

1. Both the cooling rate and the solute Nd content can modify the microstructure of the alloy. When the cooling rate decreased, the grain structure transformed from columnar crystals to equiaxed crystals. This led to grain refinement and an increase in the dendrite arm spacing. The grain distribution varied in different regions. As the Nd content rose, the needle-like eutectic gradually enlarged, and the eutectic morphology became more prominent. In the slow-cooling regions (D and C), compared with the fast-cooling regions (A and B), Nd atoms diffused more thoroughly, resulting in larger lattice constants. Specifically, due to its special cooling rhythm and atomic arrangement, Zone C had the largest lattice constant among the slow-cooling regions.
2. The solubility of Nd in the Al-Nd alloy depended on the combined effect of the Nd content and the cooling rate. When the Nd content was 11 wt.%, the interaction between Nd and Al atoms reached an equilibrium, leading to the maximum solubility. Regarding the cooling rate, under the slow cooling condition in Zone C, atomic diffusion was more conducive to the dissolution of Nd atoms, making its solubility the highest among all cooling regions.
3. There is an inverse relationship between the alloy hardness and electrical conductivity. As the cooling rate accelerates, more lattice defects and grain boundaries are generated, which hinder electron conduction and cause the electrical conductivity to decline. At the same time, solid solution strengthening increases hardness. For the solute Nd content, at low levels, the alloy had low hardness and high electrical conductivity. As the content increased, solid solution strengthening boosted the hardness, while more solute atoms created more lattice scattering centers, reducing the electrical conductivity.

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