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Progress in Multi-Performance Enhancement Technology of Heat-Resistant Aluminum Alloy Conductor

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Abstract. Al-Zr heat-resistant aluminum alloy conductor are widely used in large-capacity overhead conductors due to its excellent thermal stability, but there is a mutual constraint relationship between electric conductivity, heat resistance, and strength. This article reviews the research progress on the synergistic improvement of mechanical-electrical-thermal properties of heat-resistant aluminum alloy conductor from the perspective of component design optimization. The micro-alloying control technology based on traditional experiment and the new ideas for component design based on advanced material calculation methods.

Keywords: Heat-resistant Aluminum Alloy; Al-Zr alloy; Electric conductivity; Component design.

1. Introduction

Overhead transmission conductors are significant carriers for power transmission. In recent years, the intensification of power load and large-scale grid connection of new energy have raised higher requirements for the transmission efficiency and capacity of conductors. Heat-resistant aluminum alloy conductors have advantages of high heat-resistance temperature, large capacity margin, low sag, better safety and reliability. They can fully exploit the existing line paths and tower resources, conserving space and land resources. Merely by replacing the transmission conductor, the transmission capacity can be augmented by more than 50%. The safety of electric transmission during peak hours can be guaranteed. The stability and controllability of the output of new energy sources can be ensured.

The electrical conductivity and heat resistance are the key indicators of heat-resistant aluminum alloy conductor. Heat resistance determines the transmission capacity, while the electrical conductivity determines the transmission efficiency. In 1949, R. Herrington [1] discovered that an appropriate amount of zirconium could enhance the heat resistance of pure aluminum. After over 60 years of research and development, an heat-resistant aluminum alloy system based aluminum-zirconium alloy on has been established. Nevertheless, aluminum alloy materials exhibit a mutual constraint relationship among mechanical, electrical and thermal properties. How to achieve multi-performance coordinative improvement has always been a research focus[2-4]. The improvement of the electrical conductivity of aluminum alloy is related to the periodic arrangement of atoms in the matrix. The heat resistance and strength are mainly due to the precipitation of high thermal-stability phases and strengthening phases. However, precipitation phases often disrupt the orderliness of crystal structure, resulting in a decrease in electrical conductivity [5]. Currently, the research on multi-performance enhancement of heat-resistant aluminum alloy conductor mainly centers on two aspects: component design and manufacturing technology. Among them, component design is the key to determining the type of precipitation phase and the basis for the research and development of aluminum alloy conductor. From the perspective of alloy component design， this

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paper provides a review of the methods for multi-performance enhancement of heat-resistant aluminum alloy conductor, providing reference for the independent research and application promotion of high-performance heat-resistant aluminum alloy wires.

2. Composition Optimization Approach of Heat-Resistant Aluminum Alloy Based on Orthogonal Experiment

Al-Zr alloy is the matrix material of heat-resistant aluminum alloy. As the main alloying element, zirconium can effectively improve the heat resistance and anti-recrystallization capacity of the aluminum alloy by forming Al_3Zr phase. The Al_3Zr phase is $L1_2$ structure, which is coherent with the aluminum matrix and has a low lattice misfit [6]. Simultaneously, Al_3Zr phase demonstrates excellent precipitation thermal stability (remaining kinetically stable at 475°C) [7]. However, the diffusion rate of Zr in α-Al matrix is low, and the precipitation process of Al_3Zr phase is slow. The nucleation time of Zr is relatively long and the volume fraction of precipitated phase is less than 1%, which limit the beneficial effects of Zr in aluminum [8].

Microalloying is an effective method to improve the performance of aluminum alloys. The single/composite addition of fast-diffusing rare earth elements (RE) and transition elements (TM) can firstly form Al_3M (M=RE or TM) phases, such as Sc, Ti, Y, Er and Yb. Al_3M phases can be the nucleation sites for zirconium and then form $Al_3(M_{1-x}Zr_x)$ phases to accelerate the kinetics of precipitation.

Gu et al. [9] observed the phase evolution of Al-Zr-Y alloy using three-dimensional atomic probe. In the early stage of aging, yttrium precipitates as Al_3Y phase and becomes the heterogeneous nucleation core for zirconium, accelerating the precipitation of Al_3Zr. The $Al_3(Zr, Y)$ phase with small size and high density with a $L1_2$ structure is formed. Zhao et al. [10] obtained fine and dispersed $Al_3(Er, Sc, Zr)$ phase with a nucleus-double-shell structure by using a dual-stage aging process combined with the tri-component composite addition of Zr, Er and Sc. Er has the fastest diffusion rate and promotes the desolvation and precipitation of Zr and Sc, resulting in a good match between conductivity, strength, and thermal stability. Liu et al. [11] designed a heat-resistant aluminum alloy conductor using Er and Y microalloying. The conductivity of Al-Er-Y wire was greater than 61%IACS, and the strength retention rate at 230℃ was greater than 90%. Li et al. [12] found that the composite addition of erbium and zirconium could improve the heat resistance of aluminum alloys. The conductivity of Al-0.04Er-0.05Zr alloy can up to 60%IACS. Al-0.04Er-0.05Zr alloy can meet the performance requirements of super-heat-resistant aluminum alloy.

3. Composition Optimization Approach of Heat-Resistant Aluminum Alloy Based on the First-Principles Calculation

The microstructures of materials determine the macroscopic properties. The research of the correlation between microstructure and macroscopic properties is an effective method to achieve performance optimization. For electrical aluminum and aluminum alloy conductors, the matching rules between microstructural evolution and performance changes are the core technical problems. Traditional experimental methods have certain blindness, long cycle and high cost. Materials calculation methods can achieve targeted design of aluminum alloys and accelerate the research cycle of high-performance materials [13-14]. The first-principles calculation based on the density functional theory (DFT) is a calculation method based on quantum mechanics theory and fundamental physical quantities (such as Planck's constant, electron mass, vacuum light speed, etc.), which can accurately predict the structure, thermodynamic properties and electronic structure of materials [15-16]. The first-principles calculation, as a commonly used atomic-level calculation method, can supplement the observation by optical microscope. The structure, properties and distribution of different precipitation phases can be simulated, which helps to reveal the mechanism

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of impurity distribution. Based on the characterization results by atomic probe microscopy, Liu et al. [18] used the first-principles calculation method to establish the crystal model of Al_3(Sc, Zr) precipitation phase and then constructed an interface model of matrix and the Al_3(Sc, Zr) precipitation phase with core-shell structure. By calculating the formation energy of common alloying elements like Zn, Cu and Mg at different positions in the model, the segregation of each element in the alloy was analyzed and the experimental characterization results were comprehensive explained.

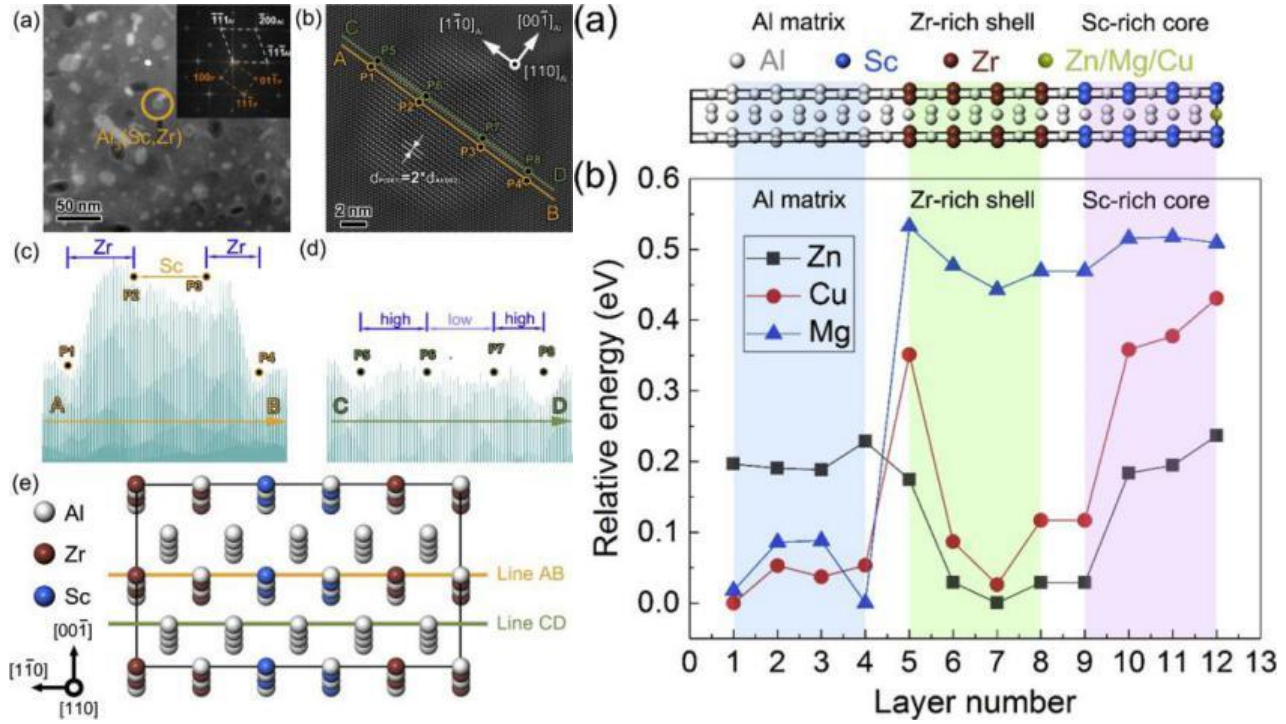

Fig. 1 (a) HAADF-STEM image and Al_3(Sc, Zr) precipitation phase model of Al-Zn-Mg-Cu-Zr-Sc alloy; (b) two-interface supercell model and DFT calculated layer-by-layer profiles of the relative energy of solute atoms substitution for Al atoms in the double-interface model. [18]

Wang et al. [19] used the first-principles calculations to evaluate the common $L1_2$ nano precipitates in Al-Zr-Er alloy. The thermodynamic information such as interface formation energy between different phases and the Al matrix were calculated. The Zr/Er ratio to form a stable core-shell structure was optimized and selected, which can guide the addition of alloying elements. Zhong et al. [20] used the DFT to calculate the formation enthalpy, binding energy, density of states and mechanical properties of different Al_3X (X = Zr, Ti, Ce, Er) compounds in heat-resistant aluminum alloys. The calculation results show that among the Al_3X (X = Zr, Ti, Ce, Er) compounds, Al_3Zr is the most easily formed and has the best thermodynamic stability; Al_3Ce is the most difficult to form, and Al_3Er has the worst thermodynamic stability.

Wang et al. [21] used the first-principles calculations to reveal the orientation relationship between the Al/Al_3(Zr, Y) interface and explain the appearance of shell layer of the Al_3(Zr, Y) composite (Figure 2). The calculations results showed that in the early stage of nucleation, Zr atoms began to concentrate towards the surface. With the increase of the content of substituting atoms at the interface, Zr atoms began to be replaced by Y atoms under the influence of the adhesion energy. Ultimately, the Al_3(Zr, Y) composite with shell layer was formed. The Y/Zr atomic ratio of the composite obtained by calculation was basically consistent with the experimental value.

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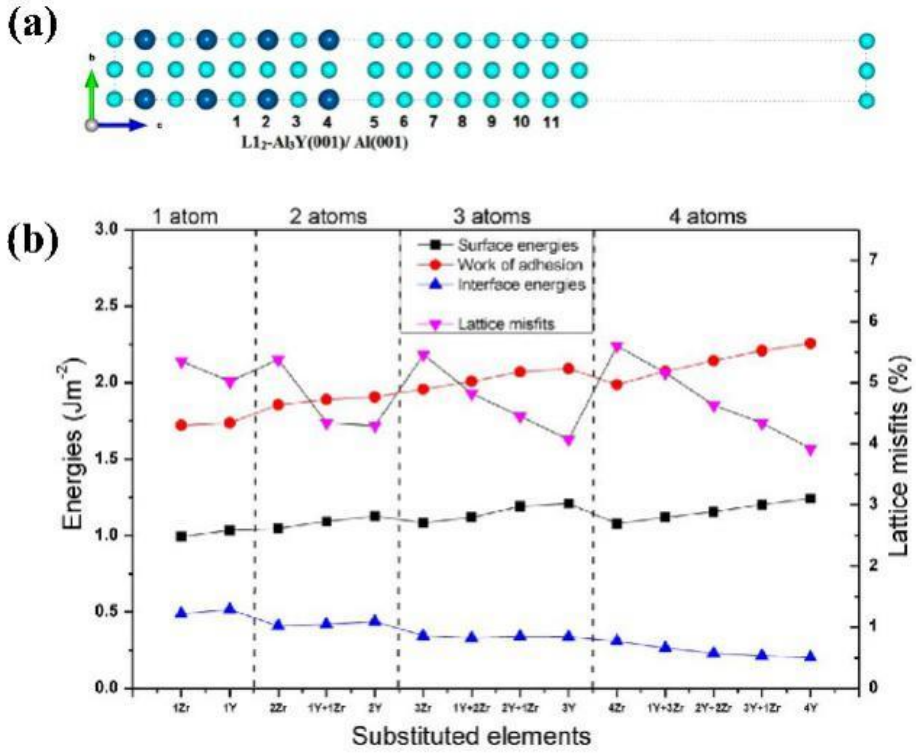

Fig.2 (a) Structure of Al/Al$_3$(Zr, Y) interface; (b) Surface energies, interface energies, lattice misfits, and work of adhesions as a function of substituted atoms[21]

4. Summary

High-resistant aluminum alloy conductors have a promising future in grid applications due to their excellent heat resistance performance. To meet the needs of multiple scenario applications in the future power system, high-resistant aluminum alloy conductors are developing towards high conductivity and high heat resistance grades. How to achieve the coordinated improvement of conductivity while ensuring the mechanical properties and heat resistance temperature is the key technical difficulty in the research and development of high-temperature resistant aluminum alloy conductor. Microalloying is the commonly used method to achieve the performance improvement of high-resistant aluminum alloys. Rare earth elements were commonly added singly or in combination with suitable preparation processes. Compared with traditional orthogonal experimental methods, advanced micro-nanoscale material calculation methods can explore the interaction mechanism between heat resistance and conductivity of aluminum alloy materials. The precise regulation of composition, process, structure and performance can be achieved, helping researchers reveal the correspondence between key performance indicators and characteristic microstructures. Furthermore, a performance regulation models for high-resistant aluminum alloy conductor can be constructed, achieving the optimal configuration of conductivity, heat resistance and other performance. The combination orthogonal experiments, high-precision characterization and advanced calculation methods can further explore the performance potential of current high-resistant aluminum alloy conductor, improve the stability of material microstructure and performance, and prepare high-performance aluminum alloy wires.

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