Analysis of the mechanical properties and electrical conductivity of aluminum wire by the dissolution temperature

Xiang Yu

Chongqing Academy of Metrology and Quality Inspection, Chongqing, 40112, China

Email: 20227497@qq.com

Key words: transmission line; conductivity; mechanical properties; solution temperature

Abstract. Aiming at the fact that relevant conductivity of corrosion resistant aluminum conductor already used in the transmission line currently is reduced when the corrosion resistance is increased, the approach of "conduction equilibrium of rare earth and corrosion resistant alloy" is proposed that cerium-rich rare earth is added to the aluminum wires already meeting the electric engineering aluminum standards and then corrosion resistant alloying elements are added before special process treatment so that equilibrium is realized while meeting the international standards for aluminum wires for electric engineering. Its mechanism is analyzed and studied preliminarily. Meanwhile, the conductivity and corrosion resistance of the draw-forming aluminum conductor are compared and the results show that this technology is an effective way to improve the corrosion resistance of aluminum conductor while maintaining good conductivity.

1 Introduction

There was relationship spectrum between alloying elements and resistance as early as 1930s and the conductivity of aluminum material was studied qualitatively and quantitatively with МИТИССЕН-ФИЛЕМНГ rule. It is concluded in the study that the resistance of aluminum material is determined by residual resistance due to matrix resistance and alloying elements. Besides, the influence relationship between the mass ratio of alloying elements and elements is elaborated quantitatively with mathematic model. However, the resistivity calculated with this rule is smaller due to other factors during rolling process of aluminum rod in practice. In recent decades, researchers at the forefront of the science have explored the influence of alloying elements on conductivity of aluminum alloy by combining simulation and practice and more and more people are aware of the importance of quantitative study on conductivity and strength. For example, Xu and Wang have explained separately the influence modes of elements in alloy and made the curve fitting to present the influence of elements with the content increase.

2 Mechanical experiment and establishment of mathematic model of conductivity

2.1 Experiment step design

The model crucible is heated to 710℃ and alloying elements Si, Mg, Fe and Cu are added in turn after the aluminum in the crucible is fully melted. It is heated to 730℃ for refining after the temperature is stable. When the metal inside the crucible is fully melted, the liquid metal is slag removed and stirred and argon refining is conducted. Keep it still and hold the temperature for certain time, cast the metal into the metal mold to get the ingot of 126 mm×300 mm. The cast ingot is hot extruded with 400℃ to aluminum rod of Φ12mm. Seven groups, 35 experimental samples in total are taken at different positions for each component. In order to improve the alloy performance, heat treatment of 200℃×1.5h is conducted. Performance and composition test of the prepared experiment sample are conducted and the test results are shown in Tab. 1.

Tab.1 Aluminum resistance data after hot extrusion

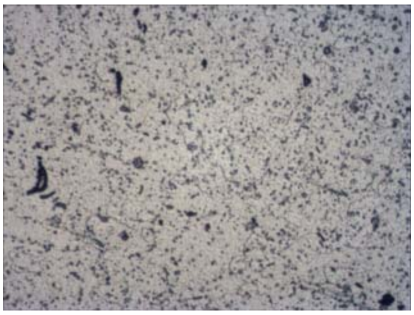
	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
	ρ	ρ	ρ	ρ	ρ
1	0.2569	0.2631	0.2754	0.2779	0.2767
2	0.2566	0.2621	0.2746	0.2756	0.2769
3	0.2561	0.2620	0.2741	0.2766	0.2776
4	0.2563	0.2611	0.2749	0.2755	0.2777
5	0.2564	0.2572	0.2758	0.2742	0.2775
6	0.2567	0.2631	0.2735	0.2758	0.2777
7	0.2561	0.2621	0.2739	0.2758	0.2769
δ	21.5	20.4	16.5	19.7	17.5
W%	0.89	0.99	10.9	1.29	1.49

Note: ρ is resistance ($\times 10^3 \Omega/m$), σ is tensile strength (MPa), W% is the weight percentage of alloying elements and δ is average elongation rate.

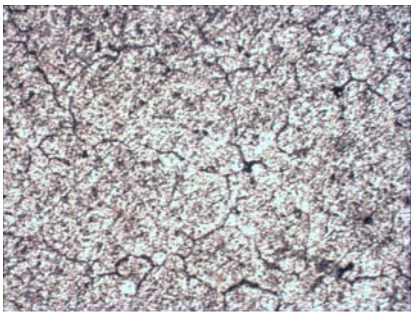
2.2 Influence of alloying element amount on conductivity

It is believed by МИТИССЕН-ФИЛЕМНГ rule that addition of alloying elements except matrix metal can increase the alloy resistance. Therefore, the influence of alloying element amount on the alloy conductivity is studied by different element weight percentages in the alloy. As shown in the test results in Tab. 1, the resistance value increases with the increase of weight percentage of alloying elements, which verifies the correctness of МИТИССЕН-ФИЛЕМНГ rule.

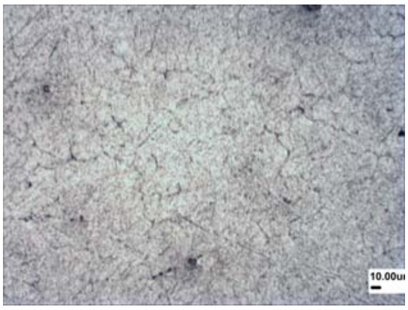
The metallographs with different compositions are shown as follows:



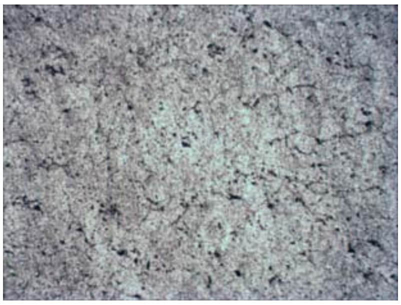
(1)



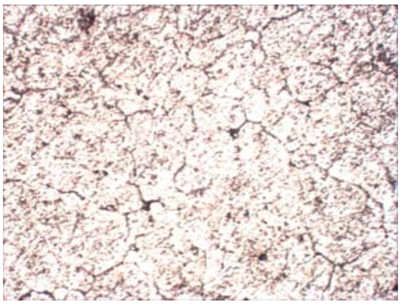
(2)



(3)



(4)



(5)

Fig. 1 Conductive aluminum sample metallographs

The larger the Mg and Si weight proportion, the denser the black particles of small sharp corner shape as the second phase Mg2Si. Since the Mg2Si solution in Al is very small, it mainly exists in semi-coherent or non-coherent form with the parent phase. Therefore, the lattice distortion becomes smaller as compared with solution state and is more concentrated and it is easy to be taken as pinning particle during deformation which results in more defects [1].

Residual Si in Al after aging exists in bulk shape and Si affects largely the conductivity at this moment. Intergranular corrosion is caused once the residual Si exceeds 0.06% [2]. The added element Fe will combine with residual Si to form AlFeSi phase in rod shape or needle shape so as to reduce the surplus Si content, promote effectively the Mg2Si enrichment and fuse the sharp corners of strengthening phase. Apart from increasing the tensile strength of the matrix, it can reduce the crack source and decrease the macro resistance caused by micro lattice distortion [5].

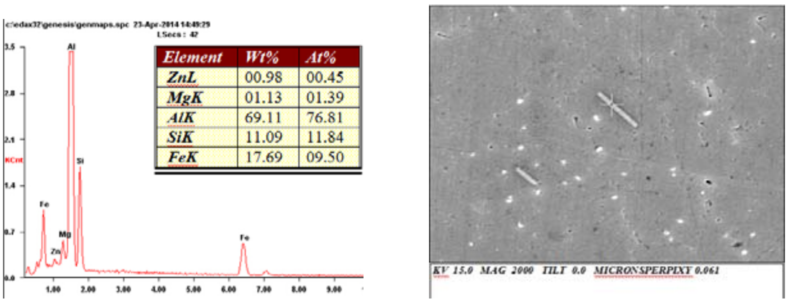


Fig. 2 Al-Fe-Si phase scanning electron microscope and corresponding energy spectrum

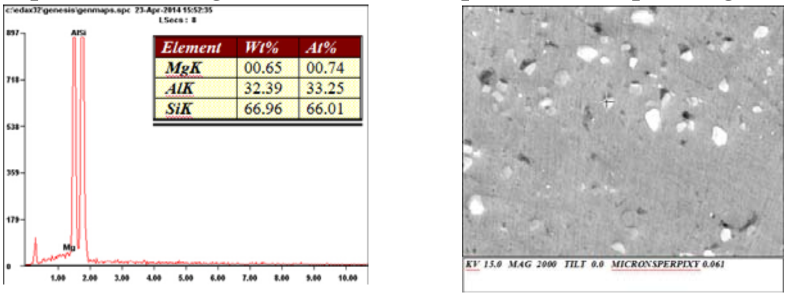


Fig. 3 Surplus Si phase phase scanning electron microscope and corresponding energy spectrum

3 Experiment result analysis and application test

Optimal screening is conducted in terms of conductivity and corrosion resistance from three aspects: type selection and addition amount of intermediate alloys of different aluminum-based corrosion resistant elements; type selection and addition amount of different aluminum-based rare earth intermediate alloys; mixture content proportion and addition sequence of two kinds of aluminum-based intermediate alloys. It is finally determined that: to add in the electric engineering class of aluminum ingot:

Aluminum-based cerium-rich rare earth: 0.12～0.23％ wt

Aluminum-based niobium + MB11 0.18～0.27％ wt

Two kinds of intermediate alloys are mixed with SAN-04 (slag bubble type) aluminum purifying and homogenizing agent. They are added in way of ball sinking for overall homogenization to form corrosion resistant aluminum-based alloy rod for test. Tab. 1 shows the experiment results of comparison of conductivity and corrosion resistance of corrosion resistance aluminum-based alloy rod and electric engineering class of aluminum ingot rod.

Tab. 2 Comparison of conductivity and corrosion resistance of electric engineering class of aluminum ingot rod and corrosion resistance aluminum-based alloy rod

Electric engineering class of aluminum ingot rod		Corrosion resistant aluminum-based alloy rod	
Average value of five groups of Φ9.51 samples		Average value of five groups of Φ9.51 samples	
Resistivity Ω • mm^2/m	Corrosion resistance salt spray weight loss approach g/m^2 • hr	Resistivity Ω • mm^2/m	Corrosion resistance salt spray weight loss approach g/m^2 • hr
0.02798	0.479	0.02794	0.187
Average value of five groups of Φ6.43 samples		Average value of five groups of Φ6.43 samples	
Resistivity Ω • mm^2/m	Corrosion resistance salt spray weight loss approach g/m2 • hr	Resistivity Ω • mm2/m	Corrosion resistance salt spray weight loss approach g/m^2 • hr
0.02804	0.481	0.02817	0.179

Salt spray test conditions: NaCl: CuCl2, 50±5g/L: 0.26±0.2g/L; pH=3.1～3.3; test temperature: 50±1℃ and the test period is 96 hours.

Φ 650 aluminum-based alloy rod is cold drawn to aluminum wire and it is tested that the electric properties of aluminum wire meet the national GB 3955-83 standards. Tab. 2 and Tab. 3 show the results of salt spray corrosion test and immersion corrosion test of mass produced aluminum-based wire. The salt spray test conditions are shown in Tab. 1.

Tab. 2 Salt spray accelerated corrosion test

Experimental sample No.		Size mm		Corrosion weight loss rate $g/m^2 \cdot hr$	Average weight loss rate $g/m^2 \cdot hr$
		Diameter	Length		
Corrosion resistant aluminum based alloy wire	1	2.807	160.1	0.186	0.184
	2	2.706	150.4	0.169	
	3	2.701	150.7	0.163	
	4	2.703	150.9	0.150	
Electric engineering class of aluminum wire	1	2.704	150.7	0.456	0.498
	2	2.707	150.3	0.461	
	3	2.703	150.1	0.447	
	4	2.706	150.5	0.449	

Tab. 3 Immersion corrosion test

Experimental sample No.		Sample diameter (mm)	Corrosion weight loss rate $g/m^2 \cdot hr$	Average weight loss rate g/m2·hr
Corrosion resistant aluminum-based alloy wire	1	2.707	0.423	0.366
	2	2.701	0.330	
	3	2.703	0.335	
Electric engineering class of aluminum wire	1	2.707	0.541	0.571
	2	2.704	0.520	
	3	2.702	0.580	

Immersion corrosion test conditions: 4.5～5.5％ NaCl solution, adjusted to pH=7.0 with acetic acid, 25℃ constant temperature without stirring. It is considered preliminarily based on system experiment results, current theoretical study and analysis observation:

4 Improvement approaches

4.1 Addition of rare earth

Among three kinds of aluminum-based rare earth intermediate alloys, i.e. aluminum-based lanthanum-rich intermediate alloy, aluminum-based cerium-rich rare earth intermediate alloy, aluminum-based lanthanum and cerium hybrid rare earth intermediate alloy, when same content is added, the aluminum-based cerium-rich rare earth intermediate alloy performs best in terms of conductivity improvement, which indicates that cerium plays the main role in rare earth. And the lanthanum-rich series performs worst in improving conductivity when same content is added. The fact that aluminum-based cerium-rich rare earth intermediate alloy can improve the conductivity is probably because: the replacement of silicon in cerium and aluminum is solved in the impurity phase and the main factor affecting the aluminum conductivity is the content of silicon in the aluminum. This kind of replacement solution mass transfer reduces the silicon content in the aluminum solution so as to improve the conductivity of aluminum conductor, which is consistent with the literature report. The energy spectrum analysis suggests that the silicon content in pure aluminum particle phase is between 2.31 % and 2.53 % while the silicon content in aluminum particle phase with rare earth added is between 3.27 % and 6.72 %, which also indicates that the addition of rare earth is able to reduce the silicon content in aluminum solution.

4.2 Addition of alloying elements

The key of “electric equilibrium technology of rare earth and corrosion resistant conductivity” is to improve the conductivity after the rare earth is added and the increase amplitude decides the amount of adding corrosion resistant alloying elements. Since the improvement of conductivity is limited, the amount of adding corrosion resistant alloying elements shall be as much as possible so that the influence of “conductivity decrease due to addition of corrosion resistant alloying elements” is minimized. When the corrosion resistant alloy is used to the minimum, the corrosion resistant alloying element which can improve largely the corrosion resistance shall be selected and the type of corrosion resistant alloying element with high conductivity shall be used as much as possible. The experiment results show that aluminum-based niobium + MB11 intermediate alloy can meet the requirements above. In particular, the addition of MB11 produces obvious effect. It is generally considered that this corrosion resistant element should affect largely the conductivity. However, it does not show large influence during the experiment. This is probably because this alloying element registers similar mass transfer performance to rare earth, and it is enriched in aluminum particle phase while the aluminum solution is small in content. Meanwhile, the addition method and sequence also affect largely its role, which has yet to be further studied and discussed.

5 Conclusions

The addition of any alloying element s can results in the increase of matrix resistance. Main elements added to the aluminum alloy are Mg and Si with large influence, which produce large residual resistance during theoretical value calculation according to M-Φ rule. However, with the increase of weight percentage, the theoretical value fluctuates in small range and it is largely different from actual resistance value. The analysis shows that apart from electron scattering and lattice distortion caused by element itself of the residual resistance, the defects are also factor leading to resistance increase. On each unit volume cross section of atomic layer, the defects can be regarded as positive and negative vacancy. Therefore, vacancy can be utilized to form concentration and its influence parameters to describe the residual resistance produced by the vacancy. After calculation and formula derivation, the corrected M-Φ rule is more accurate in terms of theoretical value calculation and the maximum error rate is less than 1.8%, much more accurate than original M-Φ rule, so it can be used as the budget for aluminum alloy resistivity under hot extrusion.

Reference

[1] Dabbagh A, Abdullah B J, Ramasindarum C, et al. Tissue-Mimicking Gel Phantoms for Thermal Therapy Studies[J]. Ultrasonic Imaging, 2014, 36(4):291-316.

[2] Dybowski B, Szymszal J, Poloczek Ł, et al. Influence of the Chemical Composition on Electrical Conductivity and Mechanical Properties of the Hypoeutectic Al-Si-Mg Alloys[J]. Archives of Metallurgy & Materials, 2016, 61(1):353.

[3] Li X M, Starink M J. Analysis of Precipitation and Dissolution in Overaged 7xxx Aluminium Alloys using DSC[C]// Materials Science Forum. 2000:1071-1076.

[4] Liu, Oliveira A S, Maria A S. Electrodeposition of polypyrrole films on aluminum from tartrate aqueous solution[J]. Journal of the Brazilian Chemical Society, 2007, 18(1):143-152.

[5] Won Y M, KYU HWAN O H. Effect of preheating on the mechanical properties of tough pitch copper made from copper scraps[J]. Journal of Materials Science, 1997, 32(8):2045-2054.