Acta Technica 62, No. 3B/2017, 545–554

The analysis of resistance uniformity influencing factors of nickel chromium alloy[1]

Xuemin Yuan[2,3,5], Zhonglei Zhao[4]

Abstract. Nickel chromium electrothermal alloy is the most common electrothermal alloy of which resistivity is one of the most important indexes. The nickel chromium electrothermal alloy wire resistance is influenced by many factors. In this paper, the chemical composition, impurities and defects concentration were studied, resulting in drawing the conclusion that silicon was the main reason for high resistance of nickel chromium electrothermal alloy wire, the resistance of nickel chromium electrothermal alloy wire is increased with the increase of silicon content, there is a linear relationship between the resistance and the content of silicon. Element content and size of the crystalline grain also has impact on electrothermal alloys wire resistance. Therefore, it is necessary to lay down strictly operations of alloy wire material preparation, including melting, material weighing, forging, rolling and drawing process. In melting process, there was no floating sand in the furnace using cleaning material, and preventing melt oxidation in order to avoid inclusion. The melting temperature, material feeding time and melting length etc. were controlled in order to reduce element evaporation. The forging, rolling and drawing process should be strictly enforced accordance to the process requirements.

Key words. Resistivity, resistance, uniformity, nickel chromium electrothermal alloy, influencing factor.

[1]The authors acknowledge the Advanced Research Fund in Jinchuan of China (Jinchuan2015002).

[2]Information Search Center, Institute of science and technology information of Gansu, Lanzhou, Gansu, 730000, China

[3]Key Laboratory of Science and Technology Evaluation and Monitoring of Gansu Province, Lanzhou, Gansu, 730000, China

[4]Drawing Wire Workshop, Nickel Alloy Co., Ltd. of Jinchuan Group, Lanzhou, Gansu, 730101, China

[5]Corresponding author

1. Introduction

Electrothermal alloy is generally divided into Ni-Cr-(Fe) and Fe-Cr-Al series [1]. Cr20Ni80 and Cr20Ni35 are the most common alloys in Ni-Cr-(Fe) series and the maximum service temperature of Ni-Cr-(Fe) series electrothermal alloy is 1100 °C, while 0Cr21Al6Nb, 0Cr25Al5 are the most common alloys in Fe-Cr-Al series and the maximum service temperature of Fe-Cr-Al series electrothermal alloy is 1400 °C [2]. Some furnaces, commonly used in industry, such as muffle furnaces, tube furnaces, pit furnaces etc., are used in the production of various heating elements. Generally, electrothermal alloy can be processed into wires, strips, bars, wire rods etc., for its advantages of large resistivity, stable resistance value, high melting point, low temperature coefficient of resistance, high temperature oxidation resistance and good processability.

Chromium plays an important role in the oxidation resistance of nickel chromium electrothermal alloy [3], because chromium can form a dense Cr_2O_3 film on the surface of electric heating element [4]. Electrothermal alloy also contains a little of silicon, which can be oxidized to Si_2O_3 at high temperature. Si_2O_3 can enter the chromium oxide film to improve the film density, oxidation resistance, and the plasticity of nickel-base alloy [5], [6]. The influencing factors of metal resistivity (or resistance) include temperature, chemical composition, crystal structure (grain size), impurity and defect concentration and mobility [7]. Kubisztal [8] studied the effects of temperature on resistivity of nickel-base alloy. The resistivity increases and the plasticity decreases at high temperature due to the physical and chemical reaction between different mediums and nickel chromium electrothermal alloy. Peng [9] studied the effect of grain size on the resistivity of Cr20Ni80 electrothermal alloy. It was considered that the change of grain size leads to the increase of grain boundary. The increase of grain boundary leads to the increase of dislocation density and vacancy, and the increase of resistivity. Dudova [10] studied the deformation mechanisms in Cr20Ni80 alloy at elevated temperatures, the deformation-behavior characteristics is explained by the transition from high-temperature dislocation climb, which is controlled by lattice self-diffusion, to low-temperature dislocation climb, which is controlled by pipe diffusion. Zhang [11] introduced the non-metallic high-temperature materials, and the advantages and disadvantages of electric elements.

In this paper, the measurement of the resistance of the nickel chromium electrothermal alloy wire was carried out at room temperature, and the fluctuation of the temperature during the measurement was low. Therefore, it was not necessary to consider the effect of temperature on the resistance. The same alloy grade and processing technology produced the same crystal structure. This paper, mainly studied on the preparation of the Ni20Cr35 nickel chromium electrothermal alloy wire, and the influence of chemical composition, impurities and defects concentration on the resistivity of nickel chromium electrothermal alloy wire were discussed as well.

2. Experimental procedure

In this experiment, the nickel chromium electrothermal alloy was melted in a 1.0 T medium frequency induction furnace, and smelted fourteen batches which were labeled as 1#, 2#, ...14 #. The components of nickel chromium electrothermal alloy were analyzed by a new type Full Spectrum Direct Read Spectrometer, version DW-TY-9000. The chemical composition of particular batches of nickel chromium electrothermal alloy is given in Table 1.

Table 1. Chemical composition of nickel chromium electrothermal alloy

Batch number	C	Mn	Si	P	S	Cr	Ni
1#	0.040	0.58	2.19	0.017	0.0086	19.36	38.42
2#	0.037	0.59	1.96	0.012	0.0030	19.37	38.36
3#	0.038	0.60	2.42	0.012	0.0016	19.16	38.27
4#	0.041	0.62	1.98	0.017	0.0037	19.15	38.65
5#	0.043	0.57	1.68	0.012	0.0034	19.32	38.42
6#	0.040	0.54	2.17	0.012	0.0034	19.25	38.73
7#	0.040	0.58	2.08	0.013	0.0025	18.74	37.74
8#	0.037	0.54	2.00	0.014	0.0033	19.30	38.42
9#	0.037	0.53	2.16	0.014	0.0032	19.30	38.60
10#	0.038	0.54	2.03	0.014	0.0035	19.40	38.40
11#	0.042	0.58	2.19	0.015	0.0038	19.25	38.90
12#	0.042	0.57	2.18	0.010	0.0025	19.16	38.42
13#	0.040	0.53	2.07	0.012	0.0039	19.41	38.64
14#	0.039	0.55	1.95	0.013	0.0035	19.32	38.42

Twenty-nine ingots can be melted per furnace, the weight of one ingot is about 36 kilograms. After forging, rolling, annealing, drawing with multi-passes and annealing, nickel chromium alloy wire with a diameter of 1.0 mm was maded. The rate of final product was different in the process of forging, rolling and drawing, therefor the final sample number was different in different batches. Fourteen batches of nickel chromium electrothermal alloy wire, two hundred and fifty samples were chosen to measure their resistances. The length of the sample was one meter. Resistance test was carried out using four probe tester, model number: SZT-2C. The maximum value, the minimum value and the average value are given in Table 2.

The preparation of metallographic sample: we took 5 mm nickel chromium electrothermal annealed alloy wire in length, and it was inlaid with mosaic powder, the diameter of the wire being 1.0 mm. The samples were grinded with metallographic sandpaper and polished with Cr_2O_3 polishing solution, and ultrasonically cleaned with acetone and deionized water. The microstructure corrosion inhibitor was a mixed acid of HNO_3 and HCl. The metallographic photographs were obtained by 11xd-pc microscope and the grain size was measured by its analysis software. The microstructure was analyzed using scanning electron microscopy and energy spectrum.

Table 2. Chemical composition of nickel chromium electrothermal alloy

Batch number	Specification	Aver. resistance	Max. resistance	Min. resistance	Remarks
Standard	Diameter (mm)	less than 1.418			
1#	1	1.395	1.409	1.381	26 samples
2#	1	1.391	1.402	1.377	20 samples
3#	1	1.416	1.435	1.403	23 samples
4#	1	1.392	1.417	1.374	26 samples
5#	1	1.381	1.404	1.375	16 samples
6#	1	1.393	1.408	1.378	23 samples
7#	1	1.379	1.391	1.373	12 samples
8#	1	1.392	1.403	1.376	27 samples
9#	1	1.403	1.414	1.391	19 samples
10#	1	1.395	1.406	1.391	6 samples
11#	1	1.392	1.397	1.382	14 samples
12#	1	1.413	1.417	1.405	12 samples
13#	1	1.398	1.413	1.39	6 samples
14#	1	1.388	1.398	1.382	19 samples

2.1. Influence of chemical composition on nickel chromium alloy resistance uniformity

Silicon in the alloy reduced the conductivity and temperature coefficient of resistance and improved the resistivity. Manganese in steel increased the resistivity, reduced the conductivity, and decreased temperature coefficient of resistance. Nickel strongly reduced the conductivity, increased the resistivity. Chromium decreased the conductivity and temperature coefficient of resistance of steel, and improved the resistivity [12, 13].

According to Tables 1, 2 and Figs. 1, 2, the content of chromium mostly was between 19.15 % to 19.41 %. Nickel was about 38.5 % except for the 7# batch. When the Cr content was between 19.15–19.41%, the resistance fluctuations were from 1.381–1.416 Ω/m. The fluctuation of the resistivity was caused by nickel and chromium content fluctuation.

Combined with table 1, 2 and Fig. 3, the statistical results showed that the range of the Mn content of nickel chromium electric heating alloy was very narrow, the fluctuation was not more than 0.1 %, and the element content was controlled well. So the effect of manganese on the resistance could be ignored.

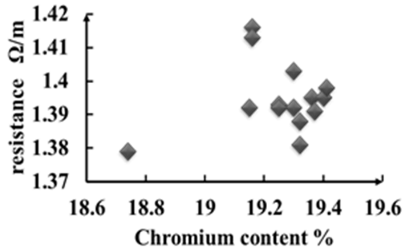

Fig. 1. The relationship between resistance per meter and chromium content

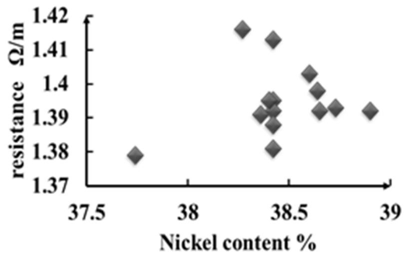

Fig. 2. The relationship between resistance per meter and nickel content

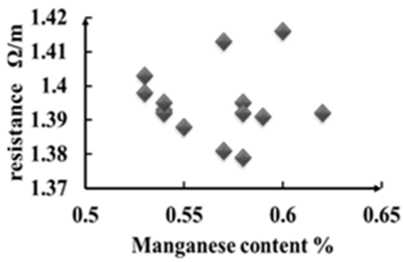

Fig. 3. The relationship between resistance per meter and manganese content

Figure 4 presents the relationship between the resistance per meter and silicon content. It can be observed that the silicon content fluctuates greatly in all fourteen batches. The content of silicon fluctuates was between 1.6–2.5 %, the resistance of nickel chromium electrothermal alloy wire was increased with the increase of Si content, and the relationship between the resistance and the content of silicon was linear.

Comparing Table 1, Table 2, Fig. 1 and other figures, it is obvious that the 7# batch nickel chromium electrothermal alloy wire resistance was minimum, the average value was 1.379 Ω/m and its Ni and Cr content was lower than in in other batches, as shown in Table 1. Comparing batches 1#, 5# and 9#, their manganese, chromium and nickel contents were nearly the same. Through the above data analysis, we can draw the conclusion that the higher the silicon content, the higher the resistance. The greater slope of the curve, the greater contribution of the element to

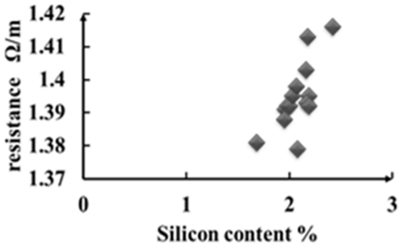

Fig. 4. The relationship between resistance per meter and silicon content

the resistivity, as shown in Fig. 5. There was a certain relationship between nickel chromium electrothermal alloy resistance and manganese, nickel, chromium and silicon content, in which silicon played a dominant role. Al, Mg and other elements in the alloy did not have to be considered.

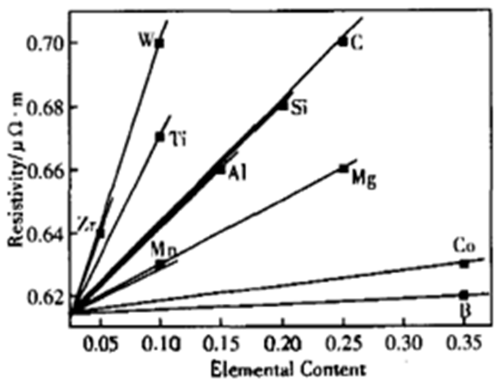

Fig. 5. The relationship between Ni-M alloy resistivity and element content [12]

3. Influence of impurities and defects on nickel chromium alloy resistance uniformity

When the electron wave passes through an ideal perfect crystal at absolute zero, it will be transmitted without scattering and without hindrance, and that's recorded in the book of quantum mechanics. Actually, there are defects and impurities in the metal. When the temperature is not absolute zero, due to ion movement caused by temperature, impurity atoms, dislocations and point defects in crystals, the electron wave scattering occurs in these places, and the resistance of the materials increases.

According to Matthiessen rule, the resistivity of the metal can be expressed by the formula

$$\rho = \sum_i \rho_i = \rho(\mathrm{T}) + \rho_{\mathrm{remnant}} \,. \tag{1}$$

In the formula, ρ is defined as resistivity, $\rho(T)$ is defined as basic resistance at temperature related, ρ_{remnant} is a kind of residual resistance, which is caused by chemical defects and physical defects, and has nothing to do with temperature. From the microscopic point of view, it is the interaction among electron and impurity atoms and crystal lattice. Viewed from the macroscopic point, it is the impurity defects, surface quality defect and grain changes, in this study, impurity defect refer to inclusion defect. Experience tells us that the grain size of polycrystalline reduction implied the grain boundary increasing and grain boundary defect increasing. So it can draw the conclusion that the bigger the grain size, the less the grain boundary area, the smaller the resistance of the electrons passing through the grain boundary, the smaller the resistivity, and the larger the conductivity. Contrarily, the resistivity increases with the decrease of grain size.

Figs. 6 and 7 show the microstructures of nickel-chromium electrothermal alloy and its energy spectrum analysis. From Figs. 6 and 7, it can be seen that no larger metal inclusions were found on the nickel chromium electrothermal alloy microstructure, and no larger metal inclusions were found in all the batches. On-site detection statistics showed that the surface quality of the batch products was better, the effects of inclusions and surface quality defects on resistivity could not be considered. This is because metal inclusions were not found in the nickel chromium electrothermal alloy wires.

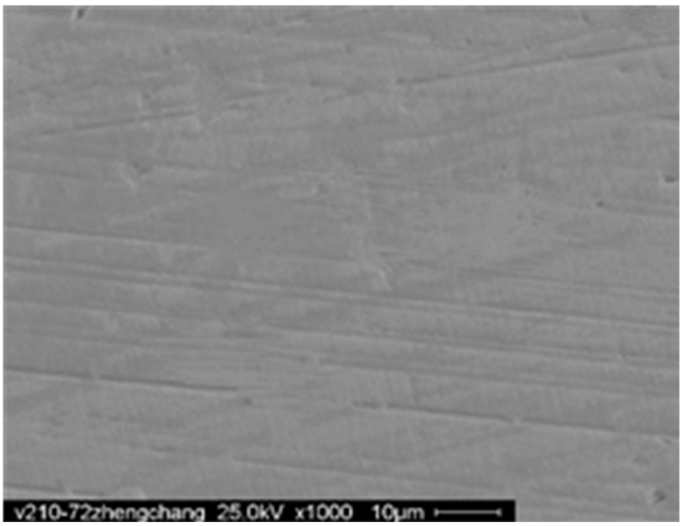

Fig. 6. Microstructure of nickel chromium electrothermal alloy wire

For the same alloy, the smaller the grain size, the more the grain boundary, the greater the resistivity will be. The metallographic structure of the nickel chromium electrothermal alloy wire with abnormal resistance is shown in Fig. 8. Figure 8a is the cross section through metallographic structure of the nickel chromium electrothermal alloy wire with abnormal resistance, Fig. 8b is the longitudinal section through metallographic structure of the nickel chromium electrothermal alloy wire

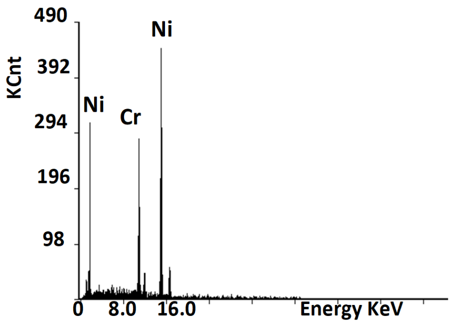

Fig. 7. Energy spectrum analysis of nickel chromium electrothermal alloy wire

with abnormal resistance. The grain size analysis was carried out by metallographic microscope and grain size analysis software, and the grain size of the cross section is 8.2 grade. The metallographic structure of the nickel chromium electrothermal alloy wire with normal resistance is shown in Fig. 9. Figure 9a is the cross section through metallographic structure of the nickel chromium electrothermal alloy wire with normal resistance, Fig. 9b is the longitudinal section through metallographic structure of the nickel chromium electrothermal alloy wire with normal resistance. The grain size analysis was also carried out by metallographic microscope and grain size analysis software. And the grain size of the cross section is about 8.1 grade. The grain size of the the nickel chromium electrothermal alloy wire with abnormal resistance and normal resistance were almost the same.

The resistances of the two batches of nickel chromium electric electrothermal alloy were different, the abnormal one was 1.416 Ω/m, the normal one being 1.381Ω/m. But the grain sizes from the cross section and longitudinal section exhibited almost no difference. So, the grain size was not the main factor affecting the resistance in this experiment.

4. Conclusion

Contrasting the chemical composition of nickel chromium electrothermal alloy wire, experiments showed that the higher silicon content was, the higher resistance of nickel chromium electrothermal alloy wire would be, under the circumstance of the same grain size and the same manganese, chromium and nickel content. The analysis showed that the high content of silicon was the main factor that led to the high resistivity, and the main reason for the uniformity of resistivity was the fluctuation of silicon content, and the relationship between the resistance and the content of silicon was linear. At the same time, the content of other alloy elements in the nickel chromium electrothermal alloy would also cause its resistance fluctuation. It was necessary to strictly control the composition of the alloy in smelting, especially the control of silicon content. Therefore, it was necessary to lay down strictly oper-

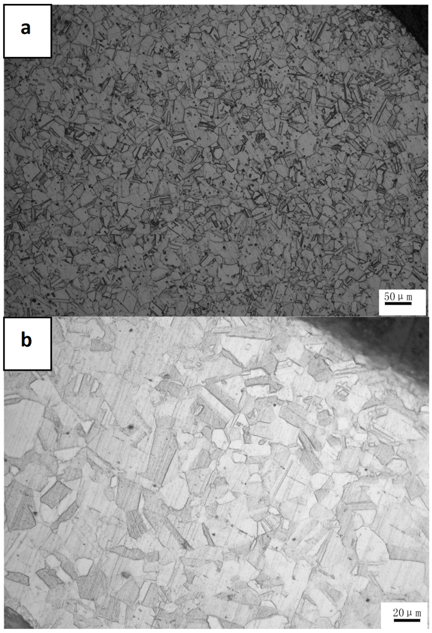

Fig. 8. Metallographic structure of chromium electrothermal alloy with abnormal resistivity: a–cross section, b–longitudinal section

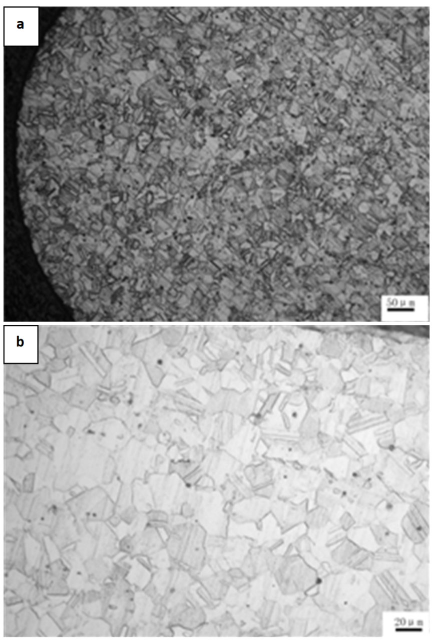

Fig. 9. Metallographic structure of chromium electrothermal alloy with normal resistivity: a–cross section, b–longitudinal section

ation of alloy wire material preparation, including material weighing, measurement precision, temperature measurement, material feeding time, melting length, etc.

Under the same chemical composition, the difference of grain size and impurities would cause the resistance uniformity of the nickel chromium electrothermal alloy wire, which means that the forging, rolling and drawing process should be strictly enforced in accordance with the process requirements. In melting process, there was no floating sand in the furnace using cleaning material, and melt oxidation was prevented in order to avoid inclusion.

References

[1] X. Zou, H. Nan, L. Han, S. DONG, C. Miao: *Research progress on electrothermal alloy*. Foundry technology (2009), No. 4, 554–557.

[2] H. Hattendorf, J. Webelsiep, H. J. Balke: *Iron-chrome aluminium-alloy*. Patents US 20040131493 A1 (2004).

[3] C. M. Wylie, R. M. Shelton, G. J. P. Fleming, A. J. Davenport: *Corrosion of nickel-based dental casting alloys*. Dental Materials *23* (2007), No. 6, 714–723.

[4] S. Mrowec, Z. Grzesik, B. Rajchel, A. Gil, J. Dabek: *The influence of aliovalent impurities on the oxidation kinetics of nickel at high temperatures*. Journal of Physics and Chemistry of Solids *66* (2005), No. 1, 115–120.

[5] J. Namkung, M. C. Kim, C. G. Park: *Effect of Si addition on the magnetic properties of melt-quenched Ni–Fe alloy strip*. Materials Science and Engineering: A *449–451* (2007), 430–434.

[6] T. Z. Liu, N. Liu, J. Shen, X. J. Wang, T. D. Xia: *Advances in research on influential factors of longevity for Cr20Ni80 electric-resistance alloy*. Nonferrous Metals *62* (2010) No. 4, 34–37.

[7] Y. Fan, X. Zhou, J. Cao, Y. Cao, J. Chen: *Usability of Cr20Ni80 alloy and influence factors*. Hot Working Technology *3* (2013), No. 20, 42–46.

[8] J. Kubisztal, A. Budniok, A. Lasia: *Study of the hydrogen evolution reaction on nickel-based composite coatings containing molybdenum powder*. International Journal of Hydrogen Energy *32* (2007), No. 9, 1211–1218.

[9] Y. Peng, K. Liu, Q. Peng: *Effects of different deformation on microstructure and mechanical properties of Cr20Ni80 electrothermal alloy*. Heat Treatment Technology and Equipment (2012), No. 4, paper 5.

[10] N. R. Dudova, R. O. Kaibyshev, V. A. Valitov: *Deformation mechanisms in Cr20Ni80 alloy at elevated temperatures*. The Physics of Metals and Metallography *107*, (2009), No. 4, 409–418.

[11] Y. Y. Zhang, Y. G. Li, K. Zhang, Y. Tian: *Research and development of high temperature electrothermal materials*. Hot Working Technology (2011), No. 18, 17–22.

[12] J. Zhang, X. Zhang, X. Yuan, X. Zheng, Z. Li: *Preparation for foil material of new nickel matrix alloy*. Rare Metals Letters *25* (2006), No. 4, paper 21.

[13] J. Namkung, M. C. Kim, C. G. Park: *Effect of Si addition on the magnetic properties of melt-quenched Ni–Fe alloy strip*. Materials Science and Engineering: A *449–451* (2007), 430–434.

Received April 30, 2017