Proceedings of Iran International Aluminum Conference (IIAC2012)
May 15-16, 2012, Arak, I.R. Iran

Thermite Welding of Aluminum Conductor by Addition of Copper

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Abstract: Aluminum conductors welding is an important issue in electricity transportation industry. Thermite welding is a good method to weld such parts. In some conditions, electrical arc welding or friction stir welding could not be used to weld these conductors due to environmental conditions, lack of welding tools, etc. In these cases, thermite welding could be used as an appropriate method. In this work, two aluminum conductors (with 9.3 mm diameter and 12.5 cm length) were welded by the use of thermite welding. These conductors were made of commercially pure aluminum (Al>99%) to enhance the weld strength, different contents of copper (0.73- 2.4 wt%) were added to the thermite powder and mechanical properties, electrical resistance and microstructural changes were studied by the use of hardness testing, resistance measurements and optical metallography, respectively. The results show that increasing the percentage of copper causes the reduction of electrical conductivity and increases the strength and hardness of the welded joint. Furthermore, grain size decreases due to Cu presence in the weld.

Keywords: Thermite welding, aluminum, copper, mechanical strength, electrical conductivity

Introduction

Termite welding (TW) or exothermic welding belongs to a group of welding processes which do not require an electrical source and it is performed by an exothermic chemical reaction. Joining is done by heat of a reaction between a reducing metal such as Al and a metallic oxide. As a result, alumina oxide and a molten metal are achieved. By the use of a filler metal, a molten alloy could be resulted. If a filler metal is used in the thermite powder, the obtained molten metal could contain some contents of the filler metal. This process is used only in special situations, because other processes are more effective. However, in some cases the thermite welding is the best method for a specific need. Thermite welding is used for butt welding of railway rails, joining of very thick parts of cast iron or steal and joining of very thick bars. This method is one of the most commonly used methods in rail welding. The reactions of this process are as follows [1,5-7,8]:

$$Fe_2O_3\,(s) + 2Al\,(s) \rightarrow 2Fe\,(l) + Al_2O_3\,(s) + 181.5\ kcal \quad (1)$$
$$3Fe_3O_4\,(s) + 8Al\,(s) \rightarrow 9Fe\,(l) + 4Al_2O_3\,(s) + 719.3\ kcal \quad (2)$$

This type of welding is especially useful for joining dissimilar metals, e.g. Cu and steel to create electric joints. Another important application of this method is aluminum and copper conductors welding. Suban *et al.* performed this method for joining of steel surface and copper conductor by the following chemical reaction [2]:

$$3CuO\,(s) + 2Al\,(s) \rightarrow 3Cu\,(l) + Al_2O_3\,(s) + Heat \quad (3)$$

Rejdak used this method for welding of aluminum and other metals by the use of the following basic reactions [3]:

$$3SnO_2\,(s) + 4Al\,(s) \rightarrow 2Al_2O_3\,(s) + 3Sn\,(l) + heat \quad (4)$$
$$3SnO\,(s) + 2Al\,(s) \rightarrow Al_2O_3\,(s) + 3Sn\,(l) + heat \quad (5)$$

Thermite welding process of aluminum conductors used in electricity transportation industry. It has great importance in recent decades due to the arc welding problems. Joining of electricity transmission conductors (Cu or Al) is one of the thermite welding developed applications. Thermite welding is a unique method due to environmental conditions, speed, accuracy and the obtained properties. In some conditions thermite welding is the only applicable methods because it is not possible with other methods [4,6-8]. In this work, two aluminum conductors (with 9.3 diameter and 12.5 cm length) were welded by the use of thermite welding. The required heat was obtained from the following chemical reaction:

$$3CaSO_4\,(s) + 8Al\,(s) \rightarrow 3CaS\,(s) + 4Al_2O_3\,(s) + Heat \quad (6)$$

Experimental Procedure

In this work, thermite powder mixture contained calcium sulfate, aluminum powder (44µm average particle size), bulk aluminum and copper and cryolite. Calcium sulfate and aluminum are used as exothermic materials of reaction (eq. 6) and bulk aluminum and copper is used as the filler metals, also, cryolite is used as flux. Thermite powder is fed into a preheated graphite mould and with using an ignition, exothermic reaction begins. Then obtained heat causes the bulk aluminum to melt. The heat of the reaction causes the end of the two conductors to be melted. After solidification of molten metal, the two conductors are joined together. The effect of Cu addition on the electrical conductivity, mechanical properties and microstructure of welded zone was investigated. In these tests, there is no need for the powder combustion and for starting the reaction an igniter such as firecracker was used. Powder mixtures were prepared for three different tests with different percentages of copper that are given in Table 1. Aluminum conductors used in these tests were

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Table 1. Powder composition of thermite mixture (wt %)

	Na_3AlF_6 %	Al % (powder)	Al % (bulk)	$CaSO_4$ %	Cu % (bulk)
Test A	14.87	22.93	18.06	43.38	0.73
Test B	14.75	22.74	17.91	43.03	1.5
Test C	14.62	22.54	17.75	42.65	2.42

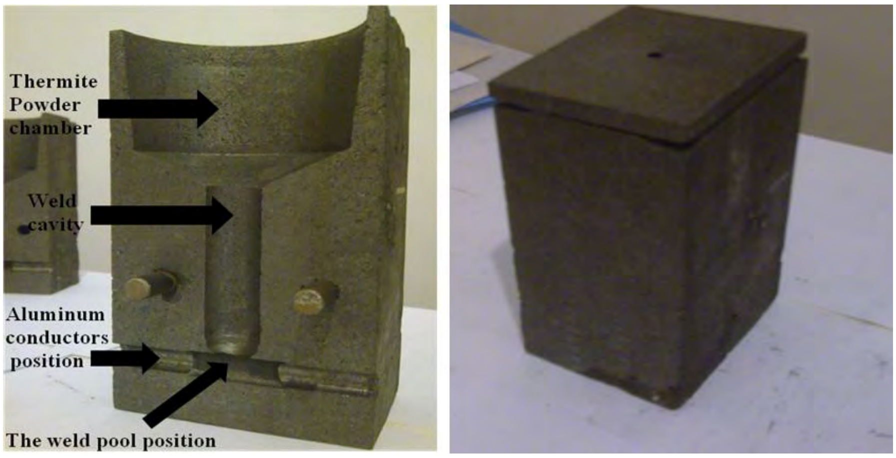

Figure 1. Graphite mould used for thermite welding of aluminum conductor.

made from pure commercially aluminum (99.7%). Graphite mould was designed by using CATIA software and then machined. Graphite mould is shown in Figure 1. Important features of the graphite that is used as mould material are long life, low adhesion, easy cleaning and high temperature applications. The high thermal conductivity of the graphite is the main disadvantage of the graphite mould. The amount of aluminum powder is slightly more than the amount of stoichiometric content because aluminum is an active metal and could be oxidized quickly. In order to prevent the reaction of copper and calcium sulfate, bulk copper is used instead of copper powder. Calcium sulfate reaction with metals powder is significantly easier than bulk of them, and could result high loss of the filler metal.

To determine weight percent of materials (or stoichiometric coefficients of reaction) was used software HSC3.0 thermodynamically software was used. The software could calculate the stoichiometric coefficients of reaction, the heat produced during the reaction and the resulted theoretical adiabatic temperature. The theoretical adiabatic temperature is about 2700°C. An example of the calculations with HSC3.0 software is shown in Figure 2. After preparation of aluminum conductors with diameter of 9.3 mm and length 125mm, the end parts of the conductors is cleaned with sandpaper because aluminum

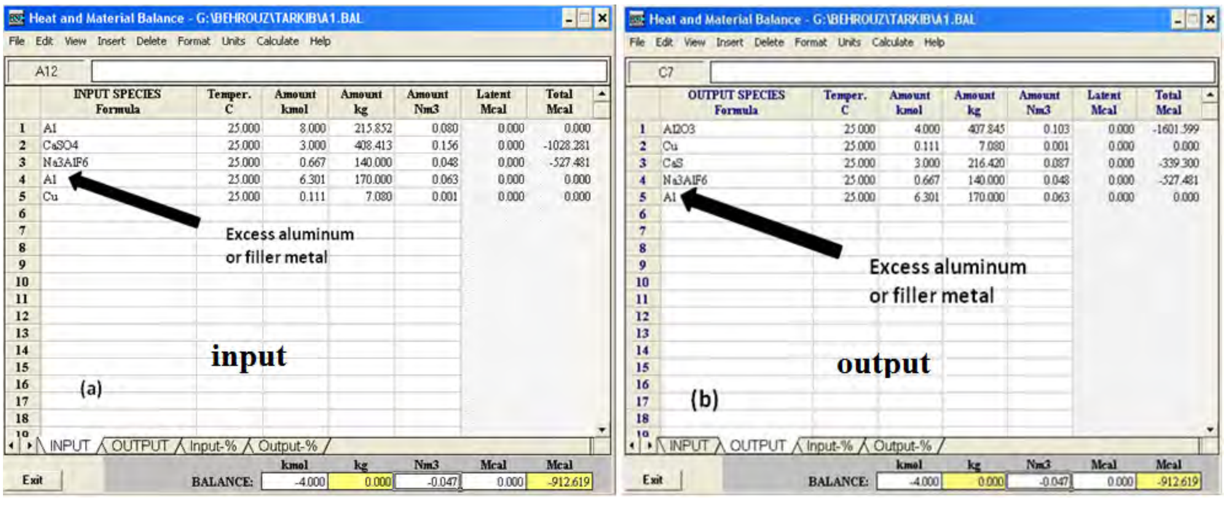

Figure 2. The weight percent calculation of (a) input materials and (b) output materials with respect to stoichiometric coefficients and the theoretical adiabatic temperature (about 2700°C)

oxide prevents appropriate joining. Aluminum conductors are placed in embedded position in the mould and then preheating begins. When the thermite powder is fed into the mould, powder compaction should be optimized. Too high or too low powder compacts is not suitable for the welding. High compaction of thermite powder in the graphite mould makes the test time to be longer and this is not desirable because in longer times loss of heat could be occurred. Also, low compaction of powder causes the exothermic reaction rate increases because much oxygen is available. This is not desirable too because the melt could be oxidized as a result of high temperature and high oxygen content of atmosphere. So the powder compaction should be optimized.
The distance between two conductors was 3mm. The mould was fastened by a clamp to prevent separation of the mould parts. Graphite mould before and during the test is shown in Figure 3.

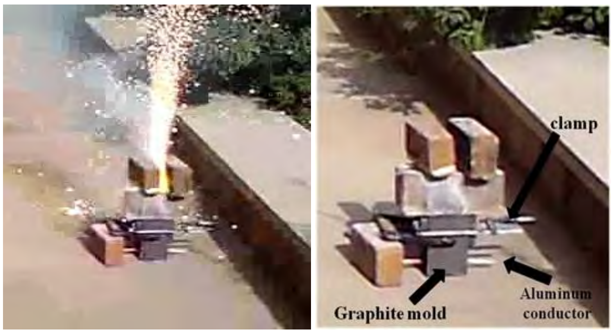

Figure 3. The graphite mould sealed before and during the test

After ignition, thermite reaction was done too fast. Reaction time was about 10-20 seconds. After welding operations, specimens were checked in terms of appearance and dimensions. The excess parts of welded zone were machined and prepared sample is shown in Figure 4. All tests were performed more than 3 times to achieve repeatable results.

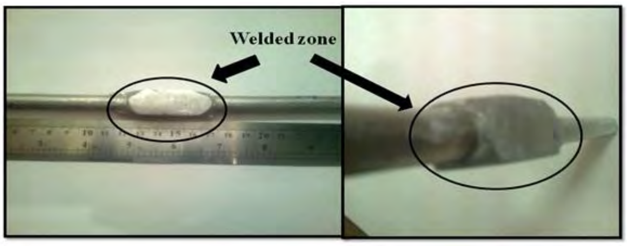

Figure 4. A sample of welded aluminum conductors

Due to the application requirements of aluminum conductors, it is necessary that electrical conduction be acceptable in the weld zone. Therefore, the electrical resistance of welding area was measured by using an ohm meter.

In order to evaluate the microstructure of welding zone, cross section of specimens was studied metallographically. For this purpose, specimens were paper grinded and then polished by alumina powder, and then etched by a reagent contained 35ml HF acid and 65ml industrial ethanol alcohol. Then, etched surface of specimens were studied by using optical microscope and an image analyzer software.
Brinell hardness of welded zone section was measured by using HPO 250 system. Applied load is 31.35 kg and diameter of shot used for the aluminum was 2.5 mm.

Results and Discussions

The following exothermic reaction could be proposed for the process:

$$(Al\ (s) \text{ and } Cu\ (s)) + 3CaSO_4\ (s) + 8Al\ (s) \rightarrow 3CaS\ (s) + 4Al_2O_3\ (s) + (Al\ (l) \text{ and } Cu\ (l)) \quad (7)$$

Optical images analyzed by the image analyzer software are shown in Figure 5. It could be observed that in all specimens a uniform microstructure is formed. Some gas and shrinkage pores could be detected in the weld area. High solidification and cooling rates of weld zone could be a reason for shrinkage porosity. These high rates are related to high thermal conductivity mould material (graphite) and small amounts of molten metal in weld zone. By the use of proper contents of flux (cryolite), the temperature of process and the fluidity of slag could be increased. As a result, better separation could be achieved between the slag and the melt. Thus more molten metal is obtained and could help the feeding of the weld zone. It causes the weld zone to be clean and free of shrinkage pores.
Figure 5 (a) shows the weld zone microstructure for specimen with 0.73% copper. Less porosity could be observed in this specimen in compare to 1.5% and 2.4% copper containing specimens (Figure 5 (b) and (c), respectively). According to Figure 5, by increasing the copper content, coarse Al_2Cu precipitates (analysed by EDS spectroscopy, Figure 5 (d)) increased in the grain boundaries. Al_2Cu or θ phase is an intermetallic phase in Al-Cu phase diagram. Also grain size decreases with increasing the percentage of copper. Copper causes the nucleation sites to be increased, because copper could be segregated during solidification. Increasing the nucleation sites lead to reduction of grain size. Also, high copper contents specimens could be etched more easily. It could be a direct result of grain boundaries high energy and could be related to Al_2Cu precipitation.
Figure 6 shows the effect of copper content of thermite powder on the Brinell hardness of weld zone. As it could be seen, hardness is increased with the increase of copper content due to increased Al_2Cu precipitates. Al_2Cu is a hard and brittle phase and formation of this phase could enhance the weld zone hardness.
Figure 7 shows the effect of percentage of copper on electrical resistance (R) of conductors. As it is observed, the electrical resistance increases by increasing the percentage of copper and subsequently electrical

conductivity decreases. Although the electrical conductivity, because of Al_2O_3 precipitation. Also, dissolved Cu in Al distorts the crystal lattice of aluminum, hence impeding the drift velocity and then the mobility of electrons will decrease. There is a simple relation between mobility of electrical conductivity.

$$\sigma = n.q.\mu \tag{8}$$

Where n is the numeral density of electrons, μ is their mobility, σ is the electrical conductivity of material and *q* is the elementary charge capacity [9-10].

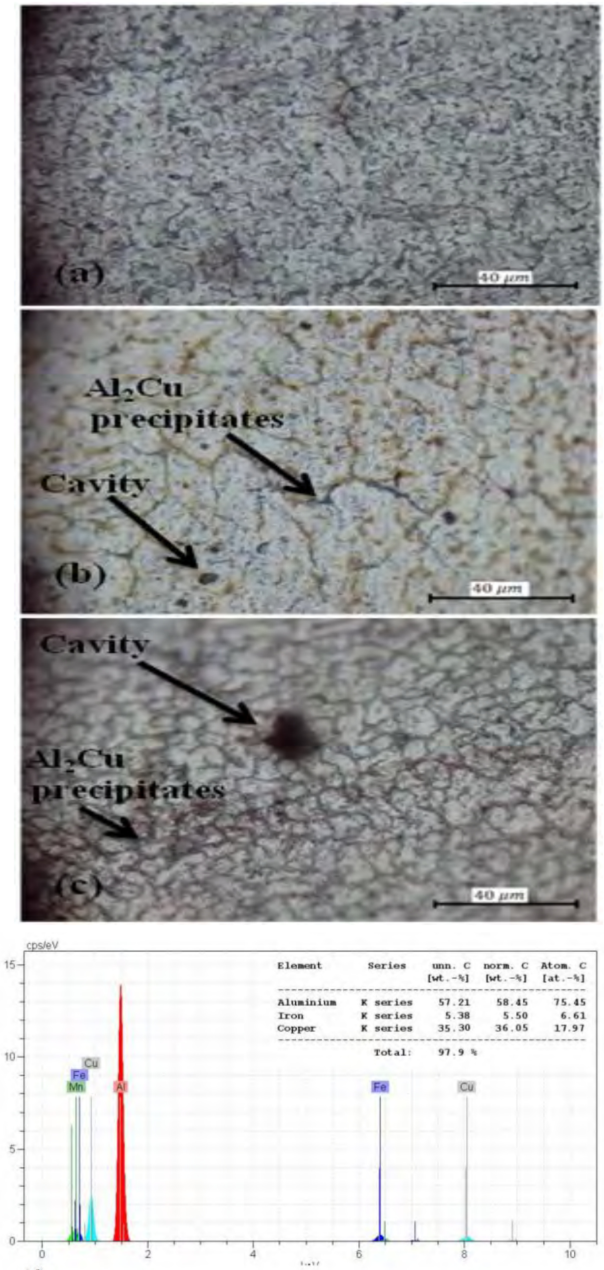

Figure 5. Cross section of specimens with (a) 0.73% (b) 1.5% (c) 2.4% of copper in thermite powder mixture and (d) EDS spectroscopy of precipitates.

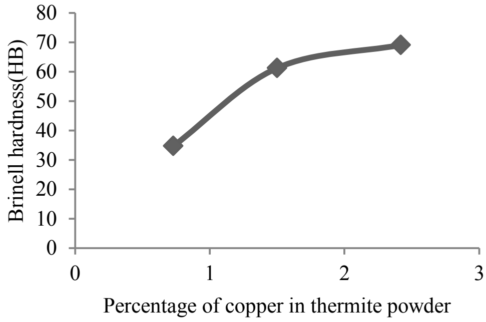

Figure 6. Hardness changes compared to the percentage of copper in the thermite powder mixture

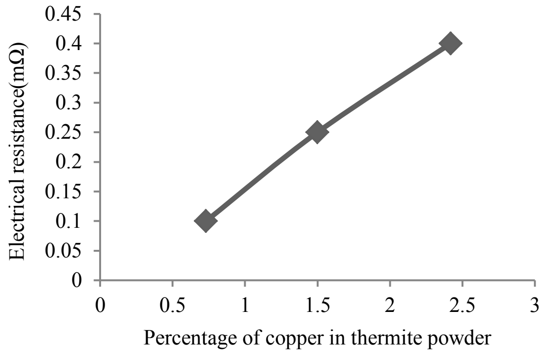

Figure 7. Changes in electrical resistance of welded specimens versus the copper content of thermite powder.

Conclusion

The following results could be concluded from this study:

1. Increasing the percentage of copper in the thermite powder from 0.73 to 2.4 causes the electrical resistance enhancement in the welded specimens from 0.09 to 0.41 mΩ.
2. Increasing the percentage of copper in the thermite powder will increase hardness of welded metal from 32 to 72 BHN.
3. More etch solution attack could be observed in high Cu- content specimens.
4. In optical images, Al_2Cu precipitates increased by increasing the percentage of copper in grain boundaries.
5. The nucleation sites were increased by increasing the percentage of copper in the thermite powder mixture and subsequently finer grain size is obtained in the weld metal.

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