Light Metals 2013 *Edited by: Barry Sadler*
TMS (The Minerals, Metals & Materials Society), 2013

OPTIMIZATION OF THE ANODE-STUB CONTACT: EFFECT OF CASTING TEMPERATURE, CONTACT STRESS AND TEMPERATURE AND SURFACE ROUGHNESS

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Keywords: Aluminium, Anode, Contact resistance

Abstract

In electrolysis of aluminum, the contact between the anode and the anode stub is normally facilitated by cast iron. Important parameters are the effect on the anode stub contact resistance from:

- Casting temperature of the iron,
- Temperature of the stub-anode coupling
- Uniaxial stress between carbon and cast iron
- Surface roughness

In the current work, standard grey iron was cast at three temperatures, 1430, 1340 and 1250°C, maintaining actual rodding cooling rate, to simulate the tendency of white iron forming during casting. The specimens were subjected to contact resistance measurements with anode carbon at 1 A/cm^2 current density, varying the uniaxial stress and temperature. Both stress and temperature increase reduced the contact resistance, while low casting temperature did not affect the resistance significantly. The influence from the surface roughness on the contact resistance was not significant.

Introduction

Electrical power accounts for the largest part of the aluminum production cost, therefore there is a drive for enhanced energy efficiency in the production plants. Much work is done to reduce the energy loss in the coupling between the steel conductors and the carbon electrodes in reduction cells. Currently cast iron is used to provide good electrical, mechanical and thermal contact between the steel stubs and the graphite anode. The steel stubs are positioned into specially designed stub holes in the carbon anode, and molten cast iron is poured into the gap between the steel stub and the stub hole. The resulting electrical contact depends on the obtained mechanical contact between the involved surfaces. The basis for analysis of electrical contact between rough surfaces has been laid out by Holm [1] and Greenwood and Williamsson [2][3]. At first, rough surfaces in contact have an effective area of contact smaller than the nominal area. A constriction of the flux lines and a reduced effective area contribute to a localized voltage drop rationalized as an interface resistance. In situ and laboratory experiments on anodic cast iron connectors were carried out in the seventies by Peterson, with apparently contradictory conclusions. Contact resistance seemed to represent a fair portion of the anodic drop when it was measured in situ [4], while it was reported to drop to negligible values when it was measured in the laboratory [5]. In 1984, Brooks and Bullough [6] analyzed the impact of connector thickness on cast iron to carbon electrical contact resistance, and found that both temperature and contact pressure were key variables. Later Sorlie and Gran [7] studied the contact of carbon and steel/cast iron cylinders, instrumented with voltage probes and thermocouples, in a hydraulic press fitted with a furnace, allowing a wide range of pressures and temperatures to be obtained. They found that pressure and temperature greatly influenced the contact resistance.

In addition to the above considerations, the casting process and the cast material introduce some challenges that need to be addressed in order to minimize the energy loss in the finished stub-anode coupling. These challenges include i) correct positioning of the stub in or close to the centre of the hole to ensure adequate filling of iron all the way around the stub, ii) control of the pouring rate of the cast iron, iii) control of the cast iron pouring temperature, and iv) control of the cast iron cooling rate.

Cast irons are iron-carbon-silicon alloys that always contain minor constituents (<0.1 %) and often alloying (>0.1 %) elements. The carbon content is normally in the range 3 to 4 % and the silicon content in the range 1 to 3 percent. Grey cast irons are the most used of the general purpose engineering irons. Their name derives from the characteristic grey color of the fracture surface. During solidification graphite and austenite precipitate, the graphite forming interconnected flakes. If the iron is low in carbon and silicon content and subjected to rapid cooling, white cast iron may be formed. This type of cast iron solidifies into austenite and carbides. The carbides are hard and brittle and have reflective fracture surfaces which give white cast irons their name. When the iron cools below around 800°C, austenite becomes thermodynamically unstable and transforms into ferrite and/or pearlite. The amount of ferrite and pearlite formed depends on chemical composition and cooling rate. The process of making electrical and mechanical connection between the anode and the stubs with cast iron involves very high cooling rate, frequently also thin sections, if the stub is not correctly positioned in the stub hole. If the control over the pouring temperature is inadequate, the temperature can become too low which results in the time before the iron starts solidifying becoming too short to avoid forming of white cast iron.

Dependent on the stub hole geometry, the uniaxial stress between the cast iron and the anode can vary. If it becomes too low, the electrical contact may suffer. The surface roughness might also influence in the real contact area.

A factor influencing the surface roughness is the cutting of the stub hole. The iron will solidify on the anode surface, thus reflecting it. Cast iron shrinks during solidification and subsequent cooling, and has a linear thermal contraction value of about twice the value of carbon materials [8][9], and normally has above 1% volume reduction from molten iron at T_m to solid iron at room temperature [10]. Thus, the iron and anode surfaces will move, and become slightly offset from each other and this will have effect on the real contact resistance.

The purpose of the current paper is to present and discuss results from inaccurate casting temperature, varying stress between cast iron and anode, and differences in the roughness of the surfaces created.

Materials

The iron used was a standard grey iron, and in agreement with common practice in aluminum industry rodding shops, it was not inoculated. The chemical composition is shown in Table I. After melting, the iron was allowed to superheat to 1480°C before pouring at either 1430, 1340 or 1250 °C into molds at room temperature.

Table I: Chemical composition of the cast iron.

Iron composition	C (%)	Si (%)	P (%)	Mn (%)	CE
Grey iron	3.34	2.47	0.04	0.43	4.2

The molds were cut from an anode, and six 50 by 50 mm cylindrical holes cut into it for casting of iron test specimens, as shown in Figure 1. The cooling curves are shown in Figure 2, recorded from casting at 1430 °C. Generally, the cooling rate is a bit higher than observed in the rodding work shop, but with less than a factor of two.

Experimental procedure

Microstructure
Samples from the different casting temperatures were characterized with respect to the content of white iron (cementite) closed to the surface against the carbon mold. White iron has lower electrical conductivity, and should be avoided.

Contact resistivity
The contact resistance was measured simultaneously on two interfaces:
a) Between the cast iron and machined anode carbon surfaces, and
b) Over a reference interface between levelled surfaces of grey cast iron and anode carbon.

A general outline of the test setup with wiring is shown in Figure 3, the assembly was encased in two half-tubes with cut out for wiring. The cast iron specimens had the top surface levelled, while the bottom surface was as formed in contact with the carbon mold. The sample was assembled in the test rig with the cast surface against machined anode carbon with surface texture and roughness resembling a production anode.
The assembly was tested in inert atmosphere at 400, 650 and 900°C.
For each temperature, resistance measurements were carried out at 1 A/cm^2 current density, and the current direction was reversed between measurements to avoid building up of polarisation. The uniaxial pressure was cycled between 0 and 5 MPa throughout the resistance measurements.

The aim was originally to apply the more realistic current density of 10 A/cm^2, however this produced so much heat in the assembly that temperature control was rendered impossible.

Effect of carbon surface roughness on contact resistivity
The effect of the surface roughness of carbon on the contact resistance was tested on two specimens cut from an anode. The specimens were leveled using the same type of equipment used to cut the stub hole in anodes. Two surfaces were cut, shown in Figure 4, a *rough* cut with a 12 mm diameter spherical bit, feeding rate 600 mm/min and speed 250 rpm, and a *smooth* cut with a 6 square bit, feeding 600 mm/min and speed 500 rpm. The diameter of the specimens were 50 mm. The contact resistance between the carbon surfaces and the cast iron specimen in Figure 3, surface against mold, were measured in order to measure the effect on the surface roughness on the contact resistivity.

Figure 1. Anode carbon mold with cast iron test specimens.

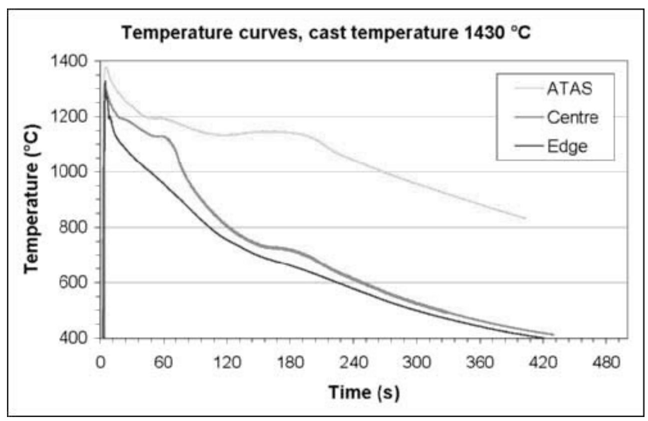
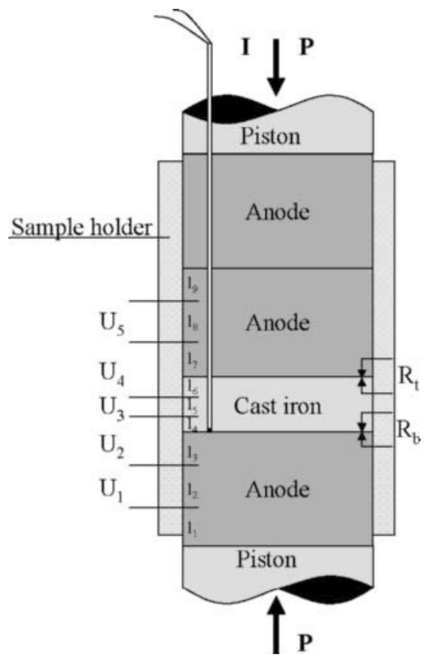


Figure 2. Cooling curves for iron cast at 1430 °C, edge and center, together with a separate ATAS cooling test . (The ATAS test is especially designed to monitor and interpret cooling curve data. It is performed in a standardized crucible fitted with a thermocouple).



$$R_t = \frac{(U_4 - U_3\frac{l_6}{l_5} - U_5\frac{l_7}{l_8})\cdot A_t}{I} \qquad R_b = \frac{(U_2 - U_1\frac{l_3}{l_2} - U_3\frac{l_4}{l_5})\cdot A_b}{I}$$

- U1 - U5 = Measured voltages (V)
- l1 - l9 = Gap between the measuring points (mm)
- I = Current (A)
- A_b and A_t = contact area for bottom ant top sample surface, respectively (mm^2)
- Upper surface of cast iron is machined
- Lower surface of cast iron is as formed in the casting.

Figure 3. General outline of the wiring for contact resistance measurement, with equations for calculating the resitance. Top right shows a grey iron specimen, showing holes for electrodes (left), surface against mould (middle) for measuring of R_b, and leveled surface (right), for measuring of R_t.

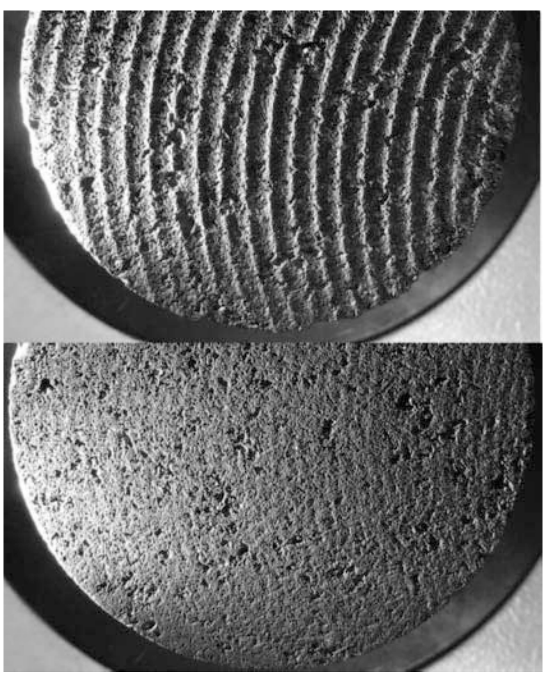


Figure 4 The two surfaces. Rough (top) was cut with a 12 mm diameter spherical bit, feeding rate 600 mm/min and speed: 250 rpm.
Smooth (bottom) was cut with a 6 mm square bit, feeding 600 mm/min and speed 500 rpm.
The diameter of the specimens were 50 mm

Microstructure at the surface against carbon

Grey iron starts solidifying at about 1180 °C. Lowering of the pouring temperature will reduce the metal's ability to transfer heat to the mold before solidification sets in, resulting in more rapid cooling if the iron with increased risk of formation of white iron. Iron poured at 1430° C and 1340 °C (Figure 5 a and b) showed pearlitic structure (0.02-0.03mm) close to cast bottom, containing graphite flakes of type D in a matrix of ferrite and pearlite. Carbide plates found 0.38mm from bottom.

Iron poured at 1430 °C (Figure 5a) showed finely divided graphite lamellas of type D in a matrix of ferrite and pearlite. The structure is pearlitic close to the surface facing the mold.

Poured at 1340 °C (Figure 5b) the specimen consisted of finely divided lamellas of type D/E in a matrix of ferrite and pearlite. Some areas with carbide plates close to the surface facing the mold

However when poured at 1250 °C (Figure 5c) white iron appeared. The structure close to the mold surface consisted of massive carbide (cemetite) plates in a pearlite matrix, with globular graphite. The interior of the specimen consisted of dfinely divided graphite of type D in a matrix of ferrite and pealite, as for the other temperatures.

The distribution of graphite throughout the matrix (not shown), and thus the distribution of grey and white iron, revealed graphite flakes in a matrix of ferrite and pearlite, with only sporadic carbide areas, , indicating grey iron throughout the samples. Except from a layer of white iron close to the surface agasinst carbon, the specimen poured at 1250°C also consisted of grey iron in the interior, but with slightly more prominent areas of carbide (cementite).

White iron has somewhat higher electrical resistance at room temperature (0.8•10-6 ohm•m) than grey iron (0.1•10-6 ohm•m), but the layer is very thin (1 mm), and is not expected to affect the overall electrical resistance much.

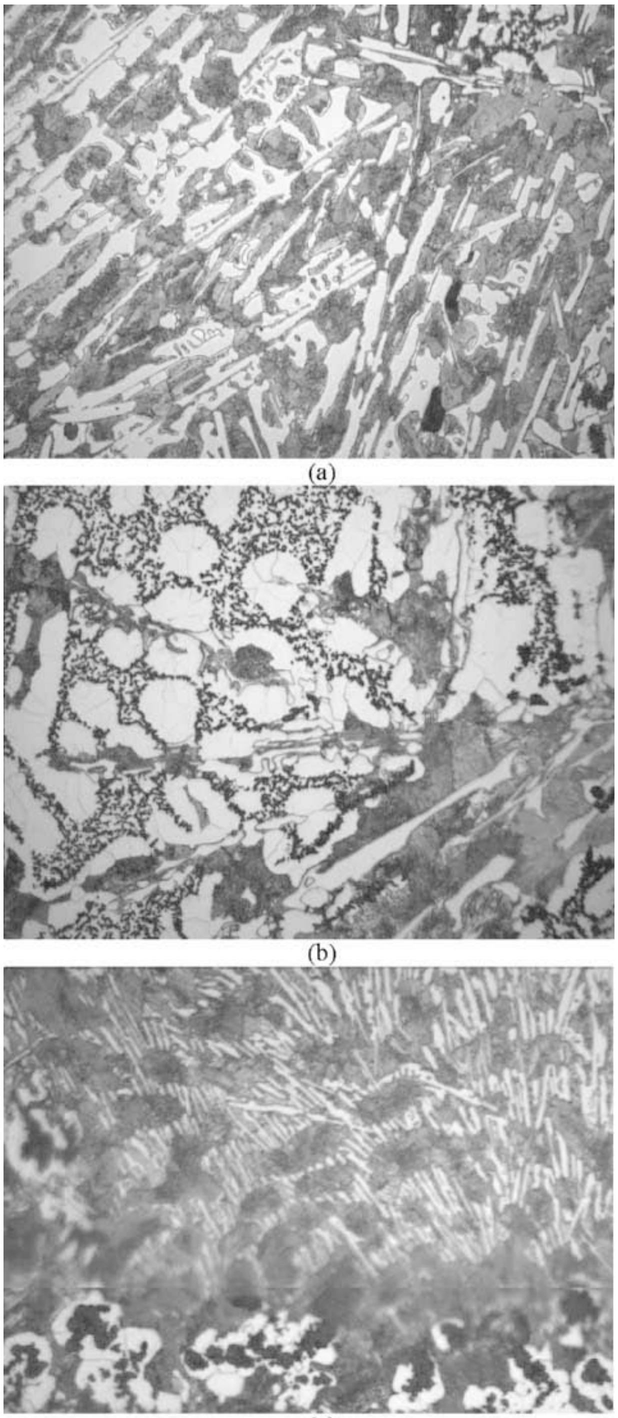


Figure 5. Microstructure of the irons poured at (a) 1430 °C, (b) 1340°C and (c) 1250°C. All pictures taken from the region at the surface facing carbon.

Contact resistivity

Figure 6 indicates that there is no decisive effect on the resistivity from the pouring temperature. The higher content of the less conductive white iron in the specimen poured at 1250 °C does not have a significant influence on the overall contact resistivity between carbon and iron. The contact resistance is highly dependent on the uniaxial stress, shown at 500 °C in Figure 6. Due to surface roughness, the true contact area is only a small fraction of the nominal. When (uniaxial) force is applied, the stress at the contact points increases to the extent that local deforming and crushing occur, thus increasing the true contact area, leading to reduced contact resistivity as observed. Increasing the stress from about zero (the weight of the assembly) to 5 MPa, reduced the contact resistance to 10-20 % of the value without stress.

The effect of the two introduced surface roughnesses of the carbon is shown in Figure 7. The difference between rough surface (dotted line) and smooth surface (solid line) is small but significant. At low temperature and stress the rough surface showed slightly higher resistivity, most likely due to a slightly smaller true contact area. However at stresses higher than 0.5 MPa the rough surface displayed the lowest resistivity. This could be because this surface had lower effective contact surface and thus higher true stress, this indicating a relatively high contribution from the uniaxial stress in the total.

The measurements indicated that variations in the contact stress and –temperature are far more important factors than the surface roughness. The effect of the measuring temperature was the same in all tests, showing a fairly high resistance is low temperatures, tended to decrease rapidly up to about 250 °C, from where it follows a steady lowering slope up to operational temperature. As the Figur 7 indicates, the contact resistivity at 600 °C was reduced to about 15% of the initial value at RT, while the reduction due to increased stress also here was reduced to 10-20 % of initial values at zero stress.

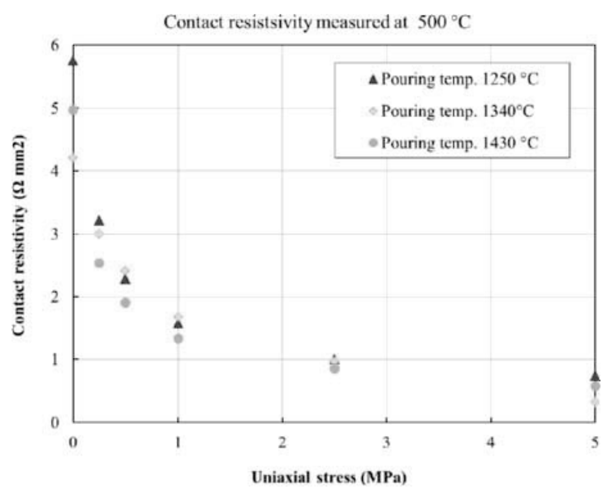


Figure 6. Contact resistivity variation with pouring temp.

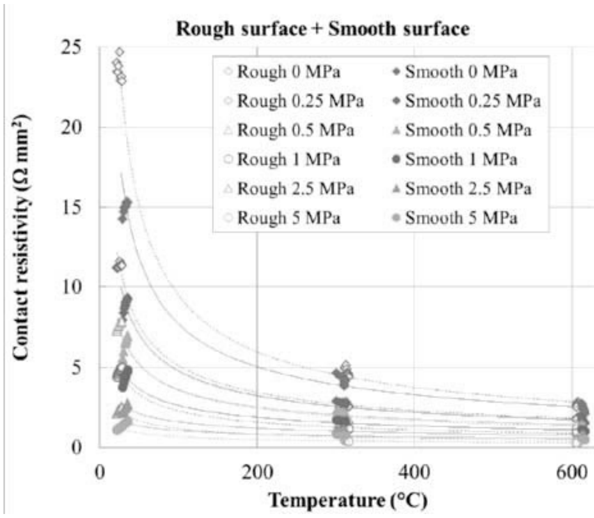


Figure 7. Effect on carbon surface roughness on contact resistivity.

Conclusion

The cast iron alloy - anode contact resistivity were investigated with respect to iron pouring temperature, contact temperature and uniaxial stress, as well as the anode carbon surface roughness. Based on examination of the irons the following main conclusions can be drawn:

- The as cast microstructure in grey iron poured at 1250 °C, 1340 °C and 1430 °C consists of graphite flakes in a matrix of mainly ferrite with a small amount of pearlite. The graphite is mainly of type D. Close to the surface facing against the carbon mold, the specimen poured at 1250 °C showed a section of massive carbide plates (cementite, white iron), while when poured at higher temperature only minor amount of carbide was precent.

- The pouring temperature did not show any clear influence on the contact resistivity, the content of white iron present in grey iron cast at 1250 °C did not increase the resistivity in any detectable amount.

- The main impact on the contact resistivity comes from the uniaxial stress and measuring temperature. In the investigation, the resistivity is reduced to 10-20 % of its initial value by each of the two factors, by increasing the temperature from RT to 600 °C for a given stress, and by increasing the stress from about zero (weight of the assembly) to 5 MPa at a given temperature.

- The effect from the surface roughness on the contact resistance was small, but significant. At low stresses the rough surface showed higher resistivity than the smooth; at 0.5 MPa and higher the rough surface had lowest resistivity, indicating a strong contribution from the net uniaxial stress, which was believed to be higher with the rough surface.

Acknowledgement

The authors express their thanks to Hydro Aluminium for financial support and for allowing the publication of these data. The present work was carried out within the project "Process Innovations for High Current Density", which was financed by Hydro Aluminium and the Research Council of Norway.

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