Contact Resistance versus Pressure of Electrical Connections Used in Aluminium Smelter Potlines

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Abstract

The contact resistance of electrical connections used in aluminium smelter potlines are a source of wasted energy consumption. This excess energy consumption depends on initial contact surface cleanliness, contact pressure, contact area, and long term corrosion. The variability of contact resistance between the anode rod and anode beam (known as ‘clamp drop’), and between the collector bar and flex connectors can cause uneven current distribution across the reduction cell which negatively impacts process performance. This research studies the correlation of contact resistance to contact pressure with different surface cleanliness and with nickel plating. The materials studied include aluminium and steel connections which are predominantly used in modern smelter anode and bus connections. The nickel plating is studied as a surface treatment to lower contact resistance of normally fast oxidizing surfaces such as aluminium, and to reduce long term corrosion between the contacting surfaces.

Keywords: Electrical contact resistance; energy consumption; clamp voltage drop; anode rod; anode beam.

1. Introduction

Approximately 160 mV [1] to more typically 300 mV of total voltage drop, depending on line amperage, or 4 - 7 % of total smelting power is consumed in the electrical resistance of the bus bar materials and interfaces, measured as external voltage drop from the collector bar/flex connection to the anode beam/rod stem interface. The contact resistance between the anode beam and rod stem is part of this total, however it demonstrates high variability due to poor rod surface condition, uneven clamping pressure and unpredictable contact area. The resulting voltage drop, also known as clamp drop as measured during smelter operation, may add over 35 mV to the total cell voltage drop [2].

This paper details laboratory research on contact pressure versus contact resistance for a range of aluminum and steel materials with varying surface conditions and the use of Hatch’s nickel plating application for rod stems [3]. The results presented herein demonstrate the potential reduction in electrical contact resistance that may be obtained by either improving surface condition, increasing contact pressure or by nickel plating of these interfaces.

2. Electrical Contact Conditions

The electrical contact resistance between two surfaces, shown in Figure 1, is well known to be primarily a function of:

- Contact pressure: the higher the contact pressure ~ the lower the contact resistance.
- Contact area: the larger the contact area ~ the lower the contact resistance.
- Surface condition: the cleaner the contact surface ~ the lower the contact resistance.

These factors are generally independent of the contact materials, although the hardness and strength of the materials will limit the achievable contact pressure before they deform.

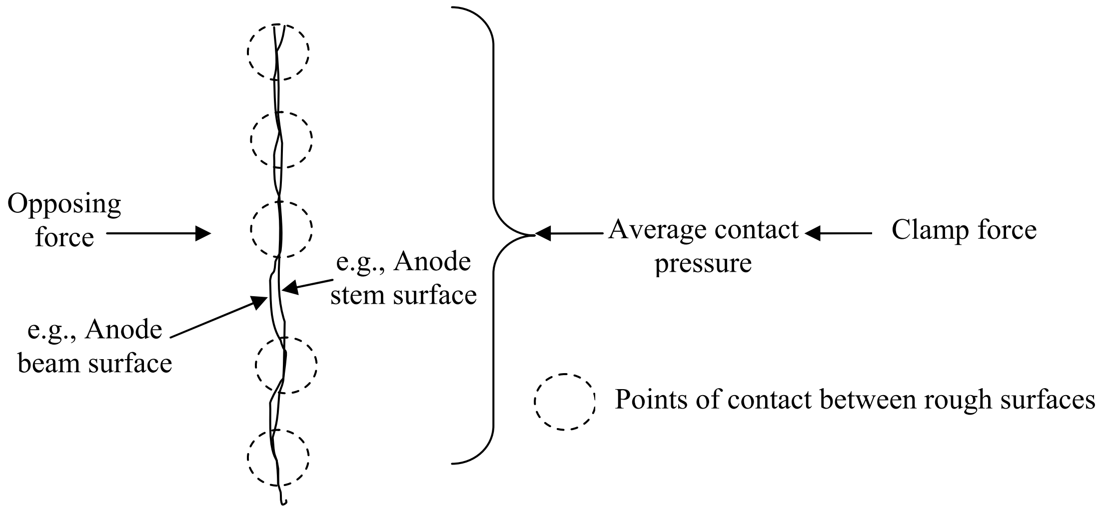

Figure 1. Closeup of electrical contact area between two surfaces.

The inverse conditions also apply to increase resistance. Any increased electrical resistance is a source of wasted power that does not contribute to the production of aluminum.

2.1. Rod stem and anode beam conditions

Rod stems are typically formed by direct chill continuous casting, without machining to a flat surface. During operation the stems are subject to local deformation from the anode beam clamps and the beam raiser machine clamps, oxidation, pitting from electric arcs, physical abrasion during beam raising, and uneven wear from repetitive rod brushing.

Anode beam contact surfaces are machined during manufacture, however during use the contact surface may be exposed to oxidation, physical abrasion against the rod stem, and pitting from electric arcs. Rod stems are clamped to the anode beam either across the entire anode beam/rod stem area, or on top of 'buttons' welded to the anode beam. Clamping the stem on the flat anode beam surface provides a large contact area, but results in low and uneven contact pressure. The use of contact 'buttons' typically used with copper rods and manually applied stem clamps can provide a higher contact pressure but only over a small contact area.

2.2. Anode beam clamp pressure and stem/beam contact pressure

The typical modern screw actuated stem clamp exerts two horizontal lines of contact pressure on the surface of the rod stem which are adequate to support the weight of the anode assembly and bath cover. This clamping force also provides the contact pressure of the rod stem to the anode beam to provide an acceptable electrical connection.

The ANSYS symmetric model shown in Figure 2 illustrates the transfer of clamp force from the clamp/stem interface to the stem/beam interface. The model used a typical clamp force of ~ 89 kN, resulting in a clamp contact pressure on the rod stem up to a maximum of 343.6 MPa over the very small area of the line of contact, while assuming contact over the full width of the stem.

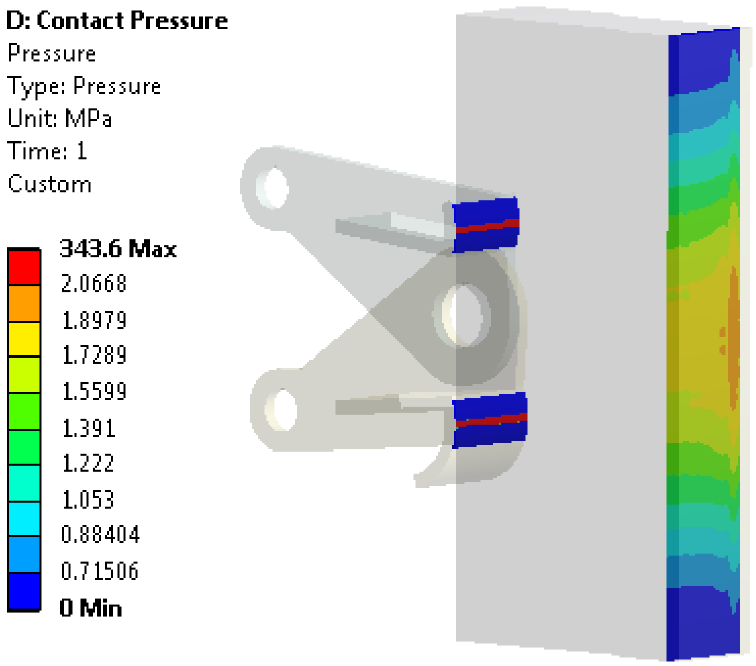

Figure 2. ANSYS contact pressure model of clamp/stem and stem/beam interfaces.

The clamp force imposes contact pressure between the clamp and rod stem contact surfaces, which transfers to the rod stem and the anode beam interface with typical distribution patterns of contact pressure as shown. This pressure distribution illustrates deflections of the clamp and rod stem, which in practice may also vary locally subject to the surface condition of the rod stem and beam. The maximum contact pressure at the anode stem and anode beam is in the order of 2 MPa for a small area. This pressure decreases to zero over the unaffected upper and lower regions of the contact area. The average contact pressure for the above model is 1.24 MPa, over a 160 x 450 mm contact area between the rod stem and anode beam.

2.3. Collector bar bolted connection

The bolted connection between the cathode collector bar and the flex connector is also a source of power consumption due to contact resistance. Some smelters may use welded connections which are superior for electrical resistance but may have reduced contact area. Steel collector bars with bolted connections may be subject to oxidation of the contact surfaces and material creep over their lifetime that may reduce contact pressure and increase contact resistance. Bolted connections may exceed 8 MPa under the bolt shoulder depending on bolt size, strength and torque.

3. Contact Pressure versus Contact Resistance Testing

The aluminum testing program compared aluminum surfaces typical between an anode stem and anode beam. The steel testing program compared clean steel/clean steel, nickel plated steel/clean steel and nickel plated steel/nickel plated steel connections. All tests were conducted at ambient temperature, average 25 °C.

3.1. Materials and surface conditions

The surface materials tested included:

1. Five surface finishes for aluminum were considered, as shown in Figure 3:

a. <u>Dirty</u> – thick oxide layer formed over multiyear use.
b. <u>Approximately 75 % clean</u> – partially cleaned with powered stainless steel wire brush to a cleanliness considered to be representative of the results of a good rod brushing system commonly used in smelter operations. This surface was tested > 24 hours following cleaning to allow for normal air oxidation of the surface.
c. <u>100 % clean</u> – cleaned with powered stainless steel wire brush with all visible oxides removed from the surface and pits. This surface was tested > 24 hours following cleaning to allow for normal air oxidation of the surface.
d. <u>Nickel plated aluminum</u> – commercial grade acid clean, zincate and nickel plating process to ~ 0.0254 mm (~ 25 µm) thickness, as estimated by plating deposition rates.
e. <u>Nickel plated aluminum</u> – commercial grade acid clean, zincate and nickel plating process to ~ 0.076 mm (~ 76 µm) thickness, as estimated by plating deposition rates.

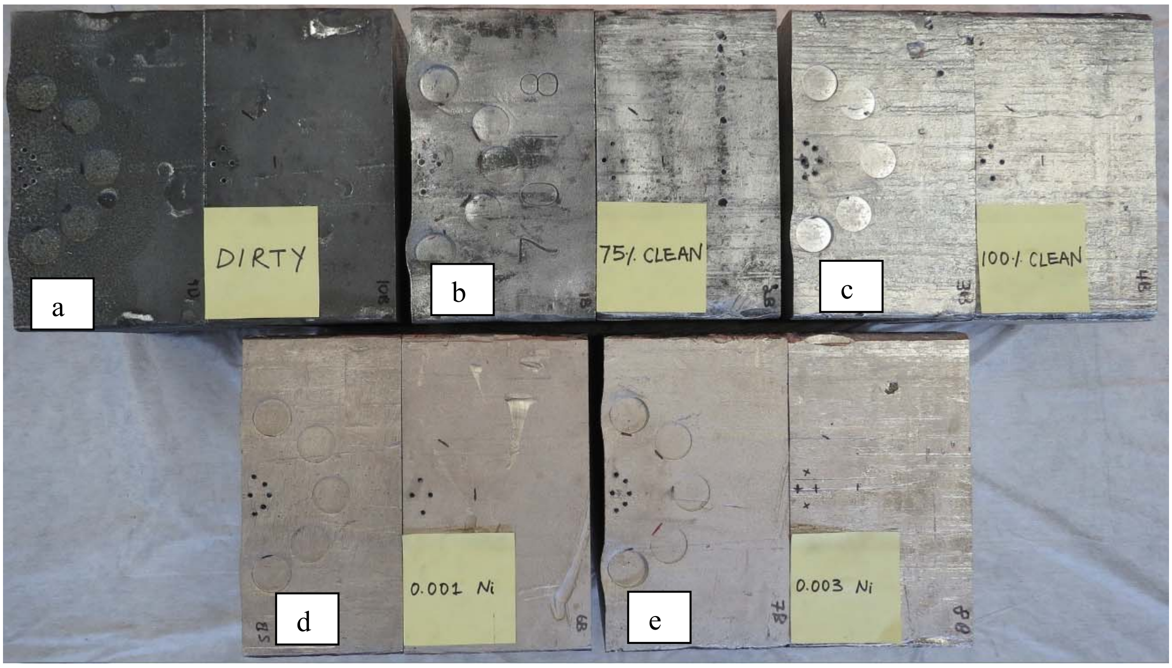

Figure 3. Five surface conditions of aluminum stems.

The hardness of nickel plated aluminum is difficult to determine by indentation methods due to the composite and thin nature of the nickel plating clad onto a deep aluminum base. However as an indication of surface hardness by use of a HRC file test, the 0.0254 mm thick nickel plating indicated 45 - 50 HRC, and the 0.076 mm thick nickel plating indicated 50 - 55 HRC. This surface hardness is only an indication of potentially good resistance to light abrasion, since the plating is too thin to add significant strength to resist denting or gouging of the aluminum stem. The nickel plating demonstrated a good bonding to the aluminum base without flaking during the high pressure testing which deformed the aluminum as shown in Figure 3.

2. Clean aluminum block – ground clean and flat and allowed to air oxidize > 24 hours, see Figure 4. Contact area of the aluminum block is 50.8 x 50.8 mm. This block simulated the contact surface of an anode beam in new condition.

Figure 4. Surface appearance of aluminum block.

1. Nickel plated mild carbon steel, alloy 1020, see Figure 5.
2. Mild carbon steel – milled finish, clean, no rust, alloy 1020, see Figure 5.

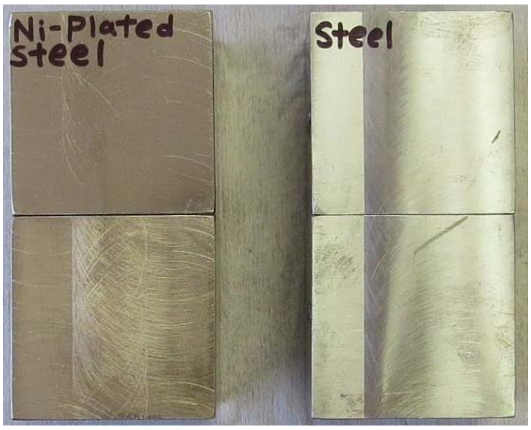

Figure 5. Surface appearance of steel and nickel plated steel samples.

3.2. Test apparatus

The test apparatus shown in Figure 6 included:
- MPK 254 micro-ohmmeter (5 A)
- 20-ton hydraulic press
- Honeywell model LCW load cell and reader, and tool steel load cell holder.

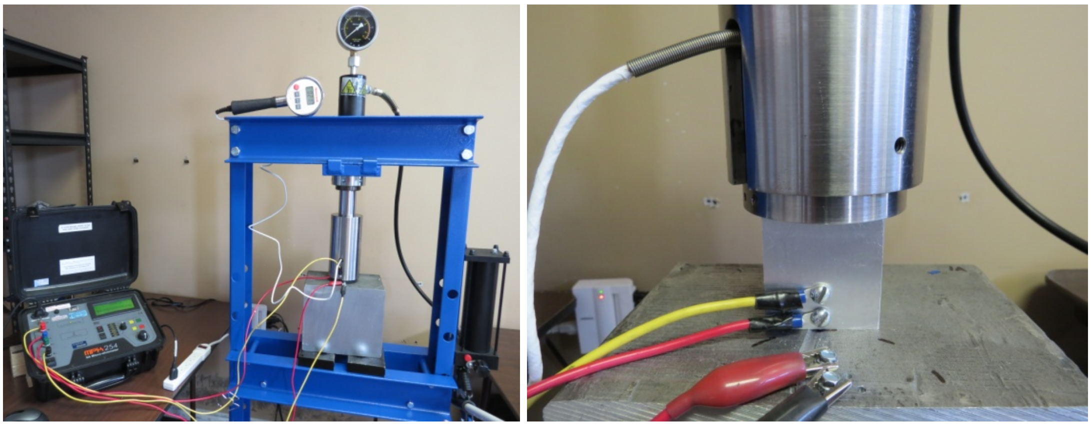

Figure 6. Contact pressure versus contact resistance test apparatus.

4. Aluminum Samples/Aluminum Results

The contact resistance versus contact pressure as shown in Figure 7 illustrates the high contact resistance of the 'Dirty' aluminum stem surface. The nickel plated surfaces showed no significant difference in contact resistance between the 25.4 µm and 76.2 µm thicknesses, so only the 25.4 µm results are shown.

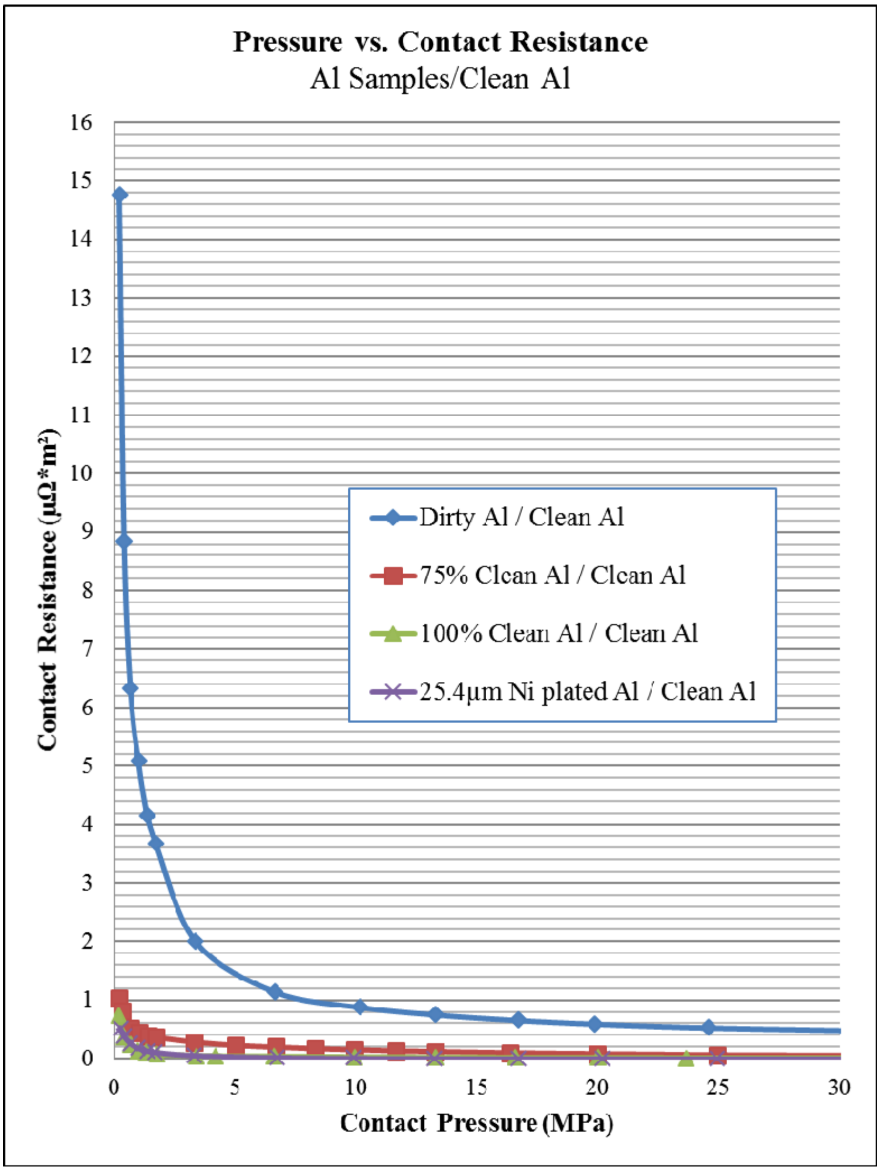

Figure 7. Contact resistance versus contact pressure of aluminum samples versus clean aluminum.

Since the 'Dirty' condition is not normal for operation, a close up of the lower pressure regions are provided in Figure 8.

The test results show that the nickel plated aluminum has approximately the same behavior as the 100 % clean aluminum. The normal cleanliness of a rod stem from typical rod brushing is only 75 % clean (see Figure 3), which demonstrates significantly higher contact resistance than the nickel plated aluminum. This comparative resistance does change with simulated corrosion as discussed below.

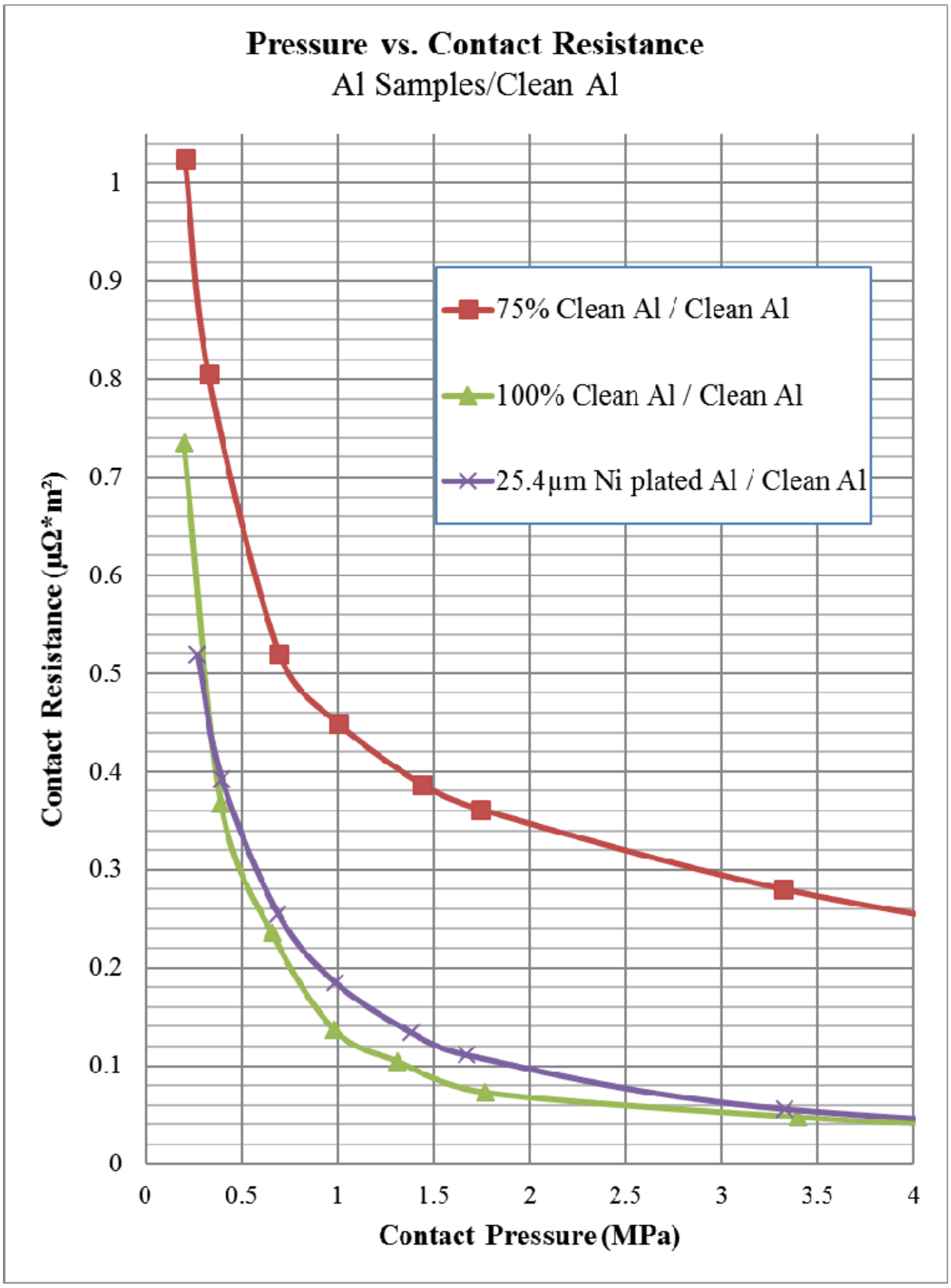

Figure 8. Contact resistance versus contact pressure of aluminum samples versus clean aluminum – normal operating region.

4.1. Estimated voltage drop savings

The normal method used by smelters to determine contact resistance of the beam to rod stem connection is by means of the voltage drop (clamp drop) across these two components. This method is convenient and good for comparison measurements if done consistently at the same location and by normalizing the measured voltage drop with variations in the stem currents. However, since the geometry of the connection cannot be considered an infinite length conductor, there will be variations of current density along the surface of the stem, resulting in variations in the measured voltage drop depending on contact location. For instance, variations on the outer surface versus the side of the stem, and whether high or low relative to the anode beam. A wider spread of the voltage meter connections, such as from the top of the beam to the stem just above the pot hood, would provide a more consistent measurement for comparison between stems, even though it would include additional material resistance.

The estimated voltage drop across the beam/stem connection can be calculated from the contact resistance data in Figure 8, using an assumed contact pressure and degree of stem cleanliness.

In comparing the contact resistance at 1.24 MPa (Figure 2 model) between the 75 % clean stem at ~ 0.41 μΩm², and the nickel plated aluminum at ~ 0.15 μΩm², this provides a contact resistance savings of ~ 0.26 μΩm². Based on an assumed 10 000 A/stem, and stem/beam contact area of .160 m X .450 m, this would provide an estimated voltage drop savings of 36 mV.

$$V_{savings} = IR_{savings} \tag{1}$$

Where: $V_{savings}$ Voltage savings (mV) across the stem/beam interface, i.e. clamp drop,
$R_{savings}$ Contact resistance savings (μΩm²) / contact area (m²).

$$R_{savings} = \frac{0.26\ \mu\Omega\text{m}^2}{0.160\ \text{m} \times 0.45\ \text{m}} = 3.61\ \mu\Omega$$
$$V_{savings} = 10\ \text{kA} \times 3.61\ \mu\Omega = 36\ \text{mV}$$

This estimate of 36 mV compares high to clamp drop measurements typically ranging from 10-15 mV, which difference may be due to the above mentioned variations in current density which impacts the 'clamp drop' voltage measurements. To compare the contact resistance of unplated to nickel plated stems, they should be compared in a field test with adequate number of each type of stems and a consistent measurement methodology.

The contact pressure will also significantly impact the contact resistance.

5. Corrosion Resistance

In order to compare the corrosion resistance of nickel plated aluminum to 100 % clean aluminum, one sample of each type was boiled in a saturated NaCl brine solution (~ 25 % NaCl by weight) for 90 minutes. The nickel plating was 25.4 µm thick on the nickel plated sample. Both samples exhibited surface corrosion resulting in a visibly flat finish.

The 100 % clean aluminum sample corroded to a much higher resistance than the 75 % clean sample, while the nickel plated sample corroded less, as illustrated in Figure 9. At ~ 1.24 MPa, the average contact pressure from the stem clamp example above, the contact resistance of the 100 % clean aluminum increased from ~ 0.11 μΩm² to ~ 0.67 μΩm², while that of the 25.4 µm thick nickel plated aluminum increased from ~ 0.15 μΩm² to ~ 0.31 μΩm².

This test indicates that the nickel plated aluminium may maintain low contact resistance for much longer than even the 100 % clean aluminium. Nickel plating may even eliminate the need of rod brushing. However, in-pot tests are required to observe the long term corrosion and abrasion resistance of the nickel plating in a potroom environment.

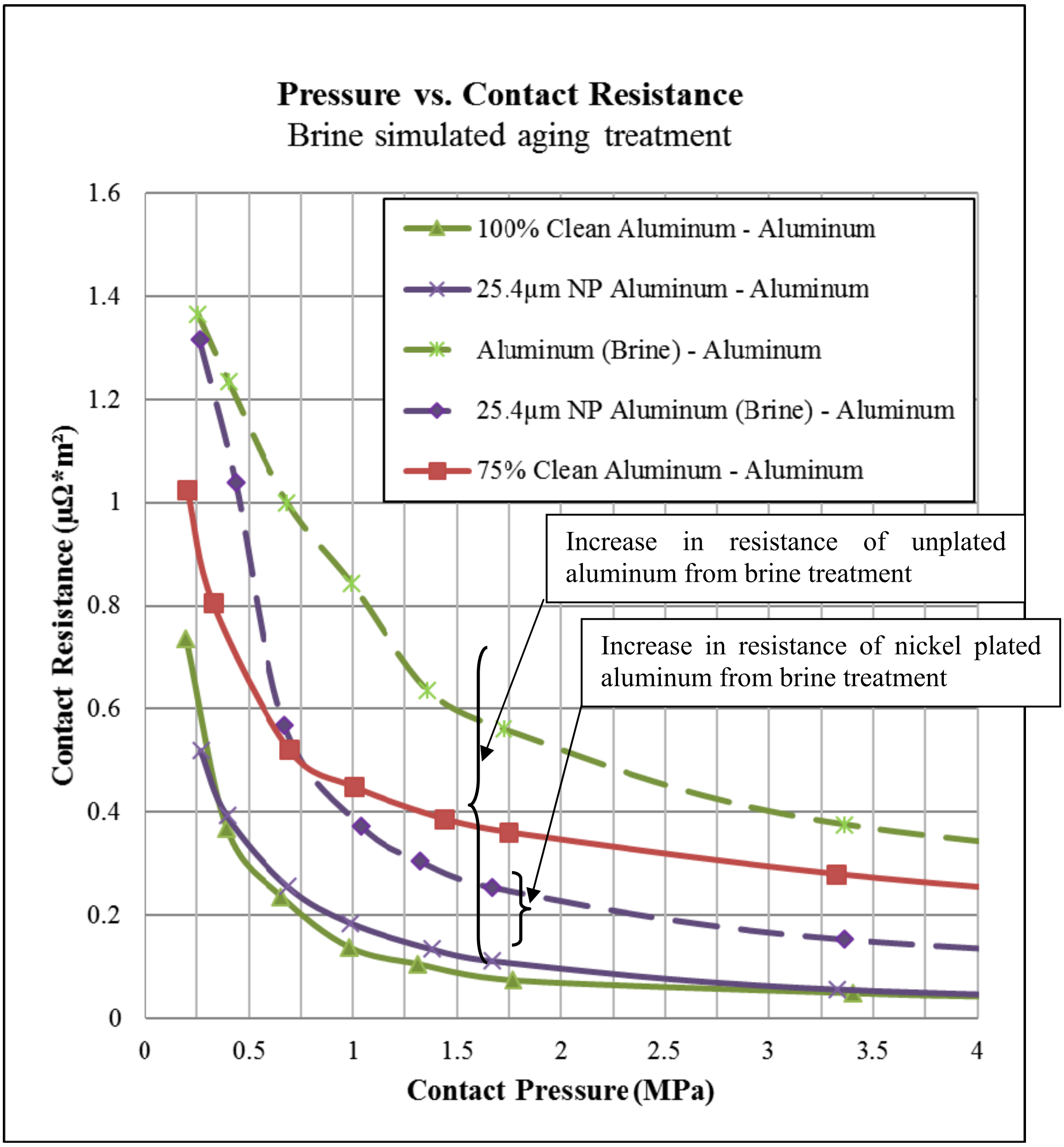

Figure 9. Corrosion testing of unplated and nickel plated aluminum.

6. Steel/Steel Test Results

The testing of the steel/steel connections was performed between steel blocks of the same dimension. The results are shown in Figure 10. The results demonstrate that the clean steel/clean steel surface does not benefit from nickel plating. The contact resistance increases with nickel plated to one of the two surfaces, and increases similarly again when both surfaces have nickel plating.

Unless there is a deterioration of the steel to steel surface which nickel plating may reduce, there is otherwise no voltage savings benefit from plating the steel/steel contact surfaces.

7. Conclusions/Discussion

The experimental results show:

- The relationship of contact resistance to contact pressure.

- The relationship of the cleanliness of the surface for aluminum/aluminum connections.
- The use of nickel plating on aluminum showed similar behavior to that of 100 % cleaned aluminum; significantly lower contact resistance than that of 75 % clean aluminum.
- The nickel plated aluminum demonstrated significantly less increase in contact resistance versus 100% clean aluminum, after simulated aging by boiling in NaCl brine.
- The use of nickel plating on clean steel was shown to only introduce additional resistance.

The results of the nickel plating on the aluminum stem indicate a potentially significant reduction in contact resistance, and therefore potential power savings. Field tests are suggested to determine if the nickel plating is durable enough to minimize contamination risk of the aluminum in the pots. Field tests may also indicate if the process of brush cleaning of the rod stems can be avoided with nickel plating to further save operational costs.

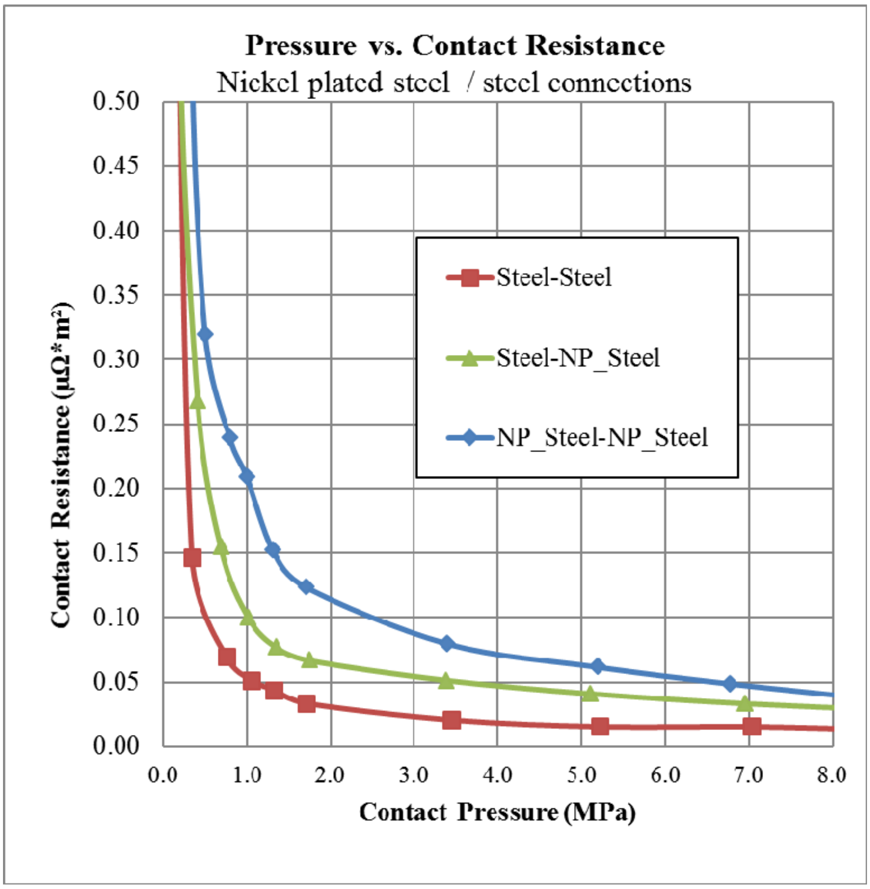

Figure 10. Contact resistance versus contact pressure of steel versus nickel plated steel.

8. References

1. W. Haupin, Interpreting the components of cell voltage, *Essential Readings in Light Metals*, Vol. 2, 2013, 153-159, from Light Metals 1998.
2. D. Molenaar, T. Kilpatrick, Anode rod to beam contact, *Light Metals* 2014, 511-516.
3. W. Berends, Low resistance electrode assemblies for production of metals *Patent CA2838113A1*, CIPO, 2014.