

ELECTRICAL RESISTANCE OF ALUMINUM-STEEL ELECTRIC TRANSITION JOINTS vs TIME AND TEMPERATURE

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Abstract

Electrical transition joints (ETJ) are used for welding aluminum to steel in reduction cells. ETJs can experience temperatures up to 600°C which can cause strength loss and resistance increase. This results from formation of brittle, high resistance Fe-Al intermetallics at the bond. Over the time required for mechanical failure to occur, the resistance can increase dramatically. The increase can be altered by inserting a titanium or chromium interlayer. Compared to Bi-clad, the temperature at which resistance begins to increase is raised significantly with a titanium interlayer. As-manufactured, resistance of a standard bi-clad specimen is 40.0 m-ohm, chromium interlayer ETJ is 55.8, and titanium interlayer ETJ is 44.4. After 188 hours at 500°C, the bi-clad had fallen apart, the chromium interlayer ETJ resistance had increased to 11,250 and the titanium interlayer ETJ exhibited no change.

Introduction

Electrolytic reduction cells for manufacture of aluminum and magnesium typically require a high current density electrical connection between copper or aluminum buss systems and steel anode and cathode components. Bolted connections exhibit high electrical resistance, which further deteriorates over time due to oxide buildup, corrosion, and arcing. The various permutations of copper, aluminum, and steel are all non-weldable by traditional fusion welding processes. Solid state welding processes, such as explosion welding, cold roll bonding, and friction welding, provide a means for making a strong, ductile metallurgical bond between these various metal combinations. However, none of these technologies are applicable for traditional equipment fabrication methods. The concept of an electrical transition joint (ETJ) was introduced as a practical solution for this problem. ETJ's are small, bi-metal assemblies that are manufactured using one of the solid state welding processes. ETJ's are often referred to as Clads in the aluminum smelting industry. The ETJ concept and technical issues related to manufacture and mechanical performance are presented in a 2001 TMS paper [1]. That paper discusses the effects of simulated operating conditions upon the mechanical properties of three different ETJ products. This paper addresses the electrical resistance of the same three products and the effects of simulated operating conditions upon the resistance.

Products Evaluated

Three different ETJ products were evaluated. Two explosion welded products and one rollbonded product were tested.

1. Direct Aluminum-Steel explosion weld, no interlayer. Product commonly called Bi Clad ETJ. Manufactured by DMC Nobelclad Div. by explosion welding. The product tested consisted of 13mm thick aluminum (alloy 1050) explosion welded direct to 38mm thick low carbon steel (alloy C1008).
2. Titanium interlayer between aluminum and steel. Trade Name ETJ 2000. Manufactured by DMC Nobelclad using explosion welding. The product tested consisted of 13mm thick aluminum (alloy 1050) explosion welded to 38mm thick low carbon steel (alloy C1008) with an interlayer of 1.5mm thick unalloyed titanium (Grade 1). In the unique ETJ2000 manufacturing process, both the aluminum-titanium weld and the titanium-steel weld are simultaneously produced by a single detonation.
3. Chromium interlayer between aluminum and steel. Manufactured by an American company using rollbonding technology (samples provided to the authors from a production lot by a major aluminum producer.) The product tested consists of 13mm thick aluminum (alloy 1100) rollbonded to 38 mm thick carbon steel (alloy 1020) with an interlayer of chromium, approximately 0.002 mm thick.

Electrical Resistance of ETJ's

In service, the electricity path is through the thickness of the ETJ. The electrical resistance through the thickness of an ETJ is the total of the following components in series:

$$\begin{aligned} & \text{Resistance of the Aluminum Layer, } R_{Al} \\ & + \text{Resistance of the Interlayer, when applicable, } R_{Int} \\ & + \text{Resistance of the Bondzone, } R_{Bz} \\ & + \text{Resistance of the Steel Layer, } R_{St} \end{aligned}$$

The resistance of the bondzone was determined by measuring the resistance of each of the other three components individually and then subtracting this value from the measured resistance of the bonded specimens.

The electrical resistance of the components and the ETJ's joints was measured using 10 mm diameter cylindrical specimens. The design for an ETJ specimen is shown in Figure 1. Resistance was measured using a Sefelec Micro-Ohmmeter MGR10. Figure 2 shows a specimen during testing.

Table I presents resistance measurement for standard 10mm diameter x 35 mm long specimens of each of the primary component metals.

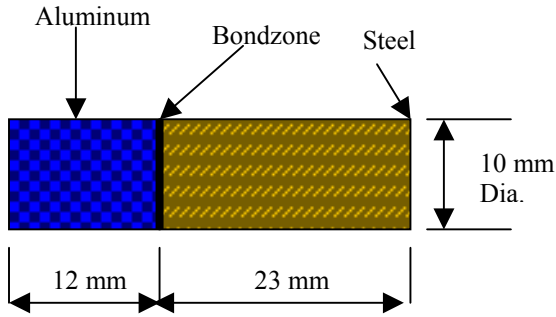


Figure 1: ETJ resistance test specimen design.

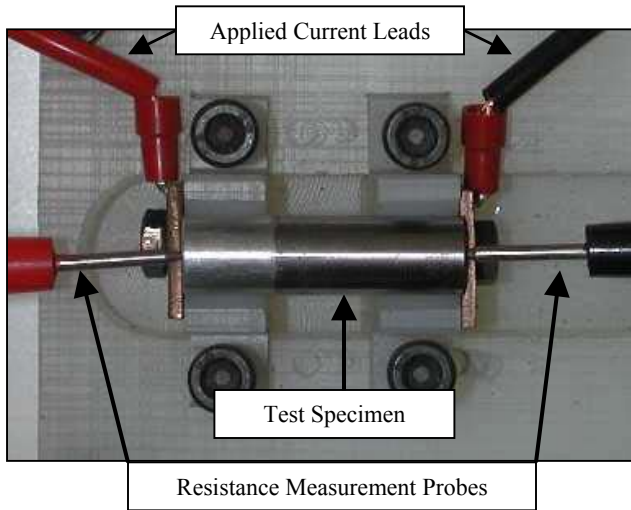


Figure 2: Resistance test arrangement.

Table I Component Metal Resistance

Material	Resistance (micro Ohm)	
	As-Manufactured	After 200-hr @ 500°C
Aluminum 1100/1050	12	12
Steel, Alloy C1008	55	55
Steel, Alloy C1020	79	79

The resistance of the interlayer metals was calculated from reference book data [2].

The titanium interlayer of the ETJ2000 specimen is commercially pure, ASTM B265 Gr 1. Textbook data for this alloy reports 42 microOhm-cm at 20°C. For the 1.5 mm thick titanium interlayer, the resistance at 10mm diameter is calculated to be 8.1 microOhm.

The interlayer of the Rollbond specimen is chromium. Textbook data for unalloyed chromium reports 13 microOhm-cm at 0°C. For the 0.002mm thick interlayer, the resistance at 10mm diameter is calculated to be 0.003 microOhm.

Specimens from each of the three part types were machined as shown in Figure 1 and tested as shown in Figure 2. Table II

presents the calculated resistance of ETJ test specimens (10mm OD x 35mm long) (microOhm), based upon resistance numbers presented above, compared with the experimentally measured resistance of the standard ETJ specimens. The data in Table II show that the measured resistance of the ETJ R_{ETJ} is equal to the sum of its component metals. This indicates that the Bondzone Resistance, R_{Bz} , is essentially negligible for all three of the part types when tested in the as-manufactured condition.

Table II: Measured vs Calculated Resistance

Calculated Resistance (microOhm)			
Component	Bi Clad ETJ	Ti Interlayer (ETJ2000)	Cr Interlayer ETJ
Aluminum, R_{Al}	4.0	4.0	4.0
Titanium, R_{Int}	0	8.1	0
Chromium, R_{Int}	0	0	0.003
Steel, R_{St}	36.0	32.4	51.8
$\Sigma R_{Al} + R_{Int} + R_{St}$	40.0	44.4	55.8
Measured Resistance (microOhm)			
ETJ Specimen, R_{ETJ}	40.0	44.4	55.8

Effects of Simulated Operating Conditions Upon ETJ Resistance

The earlier study [1] addressed the effects of long-term time at temperature upon ETJ mechanical properties. It showed that the mechanical strength of ETJ's decreased with increased

exposure times at elevated temperatures and that the performance was dependent upon product design type. The through thickness strength of the three products declined by 85% after the following time-temperature cycles:

- Bi Clad ETJ: 3 years at 320°C
- Cr Interlayer ETJ: 3 years at 420°C
- Ti Interlayer ETJ: 3 years at 490°C

The decrease in bond strength was shown to be related to gradual growth of intermetallics at the interface, primarily Fe_2Al_3 . The current work was performed to evaluate the effects of these conditions upon bondzone electrical resistance. In the earlier work, heat treatments were performed for periods up to 300 days. The data and technical analysis indicated that the results could be reliably extrapolated for longer periods. In this work, the maximum testing time was 41 days. The extrapolation logic presented earlier was assumed to be applicable; therefore, very long time, low temperature conditions were not simulated.

Two sets of heat treatment cycles were performed. In one, specimens were heated for 24 hour periods at temperatures ranging from 300°C to 630°C, followed by resistance measurements. In the other, specimens were held for periods up to 1000 hours at each of two temperatures, 375°C and 500°C.

The test results are presented in Figures 3 and 4. The test values are presented in Tables III and IV.

The data in Table I showed that the resistance of the component metals is essentially stable over this exposure period. Therefore, any resistance increase can be attributed to the bondzone, R_{Bz} .

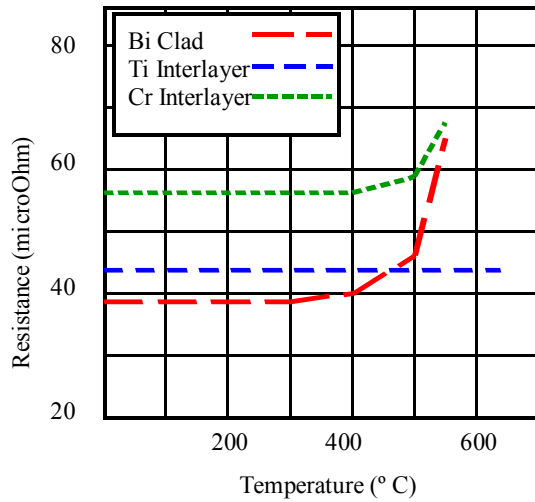


Figure 3: Resistance after exposure at temperature for 24 hours.

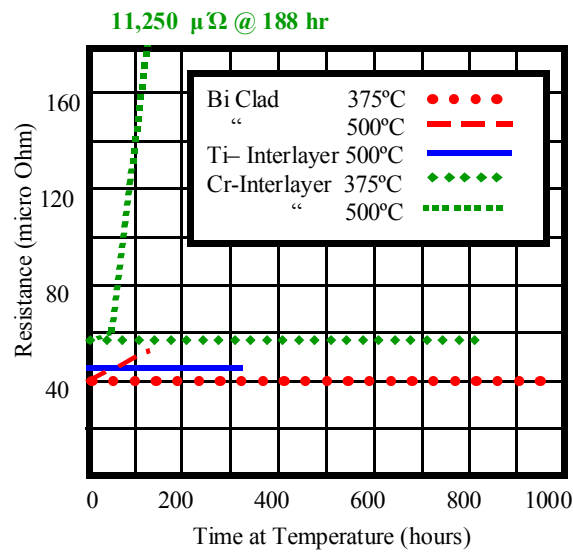


Figure 4: Resistance after exposure at 375°C and 500°C for up to 1000 hours.

Table III: Resistance measurements after 24 hour heat treatment program. Each value is the average of four or more data points.

Temp. (°C)	Resistance (micro Ohm)		
	BiClad	Ti Interlayer	Cr Interlayer
As Mfg.	40.0	44.4	55.8
300	39.0		
350	38.5	44.0	56.0
375	39.1		56.8
500	42.2	44.2	57.2
550	65.8	44.0	68.7
630		43.6	

Photomicrographs showing the Cr-Interlayer and Ti-Interlayer specimens as-manufactured and after 165 hour exposure at 490°C are presented in Figures 5 and 6. Figure 5(b) shows that an

Table IV: Resistance measurements after various times at 375°C and 500°C. Each value is the average of four or more data points.

Temp (°C)	Time (Hr)	Resistance (micro Ohm)		
		BiClad	Ti Interlayer	Cr Interlayer
375	24	39.2		56.8
375	48	39.7		
375	120	39.7		
375	195	40.4		
375	224			55.8
375	345			55.4
375	395	41.3		55.4
375	515	41.8		
375	630			55.4
375	745			55.9
375	800	42.3		55.4
375	915	42.6		
375	985	42.6		
500	24	42.2	44.2	
500	48	44.0	44.0	
500	62		44.1	60.9
500	72	44.1		
500	96	48.0		
500	125	47.8	44.4	177.4
500	188	Fell Apart	44.2	11,250
500	275	Fell Apart	44.2	Fell Apart
500	317		44.2	

intermetallic layer, approximately 20 microns thick, has formed at the bondzone. As shown in [1], this layer is composed of aluminum and iron, probably the Fe_2Al_3 intermetallic composition. There is no significant concentration of chromium remaining. It appears that the chrome layer has been completely eliminated by diffusion into the aluminum and/or steel. Once the chrome layer is gone, the aluminum-steel couple would be expected to revert to performance similar to BiClad.

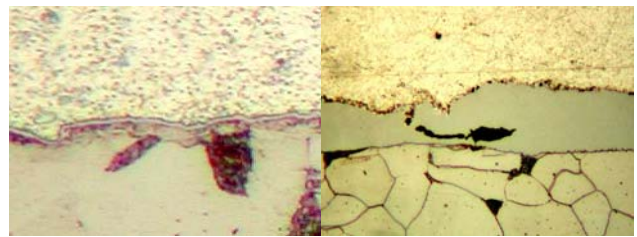


Figure 5. Chrome Interlayer Specimens, (a) as manufactured, (b) after 165 hours at 490 °C. 500 X

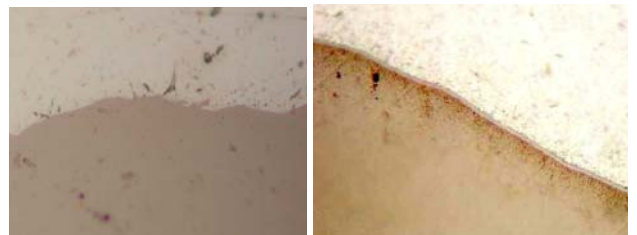


Figure 6. Titanium Interlayer Specimens: (a) as manufactured, (b) after 165 hours at 490°C. 500X

Discussion of Results

Two points are of significant interest: the differences in initial product electrical resistance and the increases in resistance under simulated operating conditions.

Initial Resistance: In the as-manufactured condition, the bondzone resistance of all three part types is essentially negligible. The higher resistance of the chrome interlayer parts appears to be driven by the steel alloy type it uses. The electrical resistance of carbon steel varies with the carbon content. The carbon content of C1020 is 0.20%. In comparison the carbon content of the C1008 steel used in both explosion bonded part types is 0.08%. The reason for selection of C1020 is not clear to the authors, but it could be driven by rollbond manufacturing considerations. The C1008 was selected for the explosion clad ETJ manufacture because it is the lowest resistance steel alloy commercially available in the plate form. In the explosion bonding process, it is irrelevant whether the base steel is C1008 or C1020 [3,4,5].

Resistance Changes: The changes in ETJ resistance after the high temperature exposures are caused by changes at the bondzone. As shown in Table I, the resistance of the component metals is not significantly affected by the heat treatments. The changes in bondzone resistance presented in Figure 3 exhibit a somewhat similar pattern to effects upon mechanical properties as presented in Figure 4 of Reference 1. The strength remains relatively constant up to a threshold temperature and then falls off quickly. This is supported by the technical discussion in that paper, indicating that the failures result from diffusion and intermetallic layer growth, which vary with the inverse of the temperature and the log of time. Consequently, small increases in temperature can dramatically increase the rate of intermetallic growth. Conversely, the time required for failure increases dramatically when the temperature is reduced a relatively small amount. Both studies indicate that the changes in the properties being measured are the result of intermetallic formation at the bondzone. A more detailed evaluation of resistance changes vs. time and temperature would be expected to exhibit the same patterns as that of mechanical properties, as presented in Figure 5 of Reference 1.

Although resistance measurements were not made at temperatures between 375°C and 500°C, based upon the knowledge of the metallurgical interactions causing the changes, it is expected that the resistance changes at intermediate temperatures would be similar to the mechanical property

Significance of ETJ Resistance Upon Operating Costs

ETJ's are a small component of the circuitry of an aluminum smelter, and have a relatively very small impact upon plant efficiency (unless they fail in service). However, if the ETJ's are considered as isolated components, the cost impact of the ETJ resistance is significant. The following calculation attempts to estimate this cost impact. The calculation is a gross simplification of a complex issue. The numbers are significant only in their general and comparative order of magnitude.

The cost study is based upon the following assumptions:

1. The plant has 408 cells, with 18 anodes each, operating at 170 kA.
2. Total cell voltage is 4.60 volts.
3. Each anode has one ETJ, 150mm x 150m x 51 mm thick.
4. The cost of electricity is \$0.05 USD/kw-hr
5. Typical ETJ service life is 7 years
6. Operating temperature is stable and below that which causes increased R_{ETJ}
7. Inflation, cost of money, and similar issues are ignored

The ETJ resistance is calculated from the data in Table II.

Table V presents calculated resistance of the ETJ, its voltage drop in stable service, and the cost of the power resulting from IR heating of the ETJ's. The analysis does not include the potential cost impact of increased resistance resulting from ETJ overheating. Once a part begins to fail and resistance begins to rise, it should alter characteristics of its anode relatively quickly, creating performance problems. If left in service appreciably longer, it will fail, potentially causing significantly higher cost problems.

Clearly, if the operating temperatures are sufficiently low for the BiClad product to remain sound over the expected service life, it provides the lowest operating cost. The data presented earlier [1] indicates that the BiClad should perform well for over a decade where operating temperatures are below 300°C. When operating temperatures are expected to exceed this, one of the other two products should be considered. The titanium-interlayer product offers the lowest operating cost of the two as well as the best high temperature performance in regards to both electrical resistance effects and mechanical property reliability.

Table V: Estimated variance in cell operating cost as a function of ETJ type used.

	Bi Clad	Ti Interlayer	Rollbond
ETJ Resistance, Ω	2.30×10^{-7}	2.44×10^{-7}	3.26×10^{-7}
Voltage Drop across ETJ	0.0021 v	0.0023 v	0.0031 v
Kw-hr/yr from IR heating	169	185	248
Annual Cost of Power/ETJ (USD)	\$8.45	\$9.25	\$12.4
Comparative Cost vs BiClad over lifetime	\$0	+\$5.60	+\$27.65
Δ Plant Cost over Lifetime (USD)	\$0	\$41,126.	\$203,062.

Conclusions

The electrical resistance of as-manufactured ETJ's is dependent upon the resistance of the component metals. All three products evaluated exhibited essentially no bondzone resistance in the as-manufactured condition. In the as-manufactured condition the resistance of the BiClad ETJ was the lowest, and the Cr-Interlayer the highest.

Bondzone resistance was affected by simulated time/temperature cell operating conditions. None of the products evaluated exhibited significant bondzone resistance change after extended periods 375°C. At 500°C the resistance of the Bi clad product began to increase and demonstrated a 23% increase after 125 hours. After 275 hours it had fallen apart. At 500°C the Cr-interlayer product resistance increased 300% over 125 hours and over 10,000% over 188 hours. Again after 275 hours, it fell apart. The resistance of the Ti-Interlayer ETJ was unchanged at all 500°C exposures and after 24 hours at 630°C.

Of the products compared, BiClad ETJ offers lowest operating cost in installations where its resistance and mechanical strength are stable, 300°C maximum. For equipment operating at higher temperatures, the Ti-interlayer product offers the lowest operating cost.

References

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