Aluminum-Steel Electric Transition Joints,
Effects of Temperature and Time upon Mechanical Properties

John Banker, DMC Clad Metal Div.
Boulder, CO USA
Antoine Nobili, DMC Nobelclad Div.
Rivesaltes, FRANCE

Abstract

Aluminum-steel electric transition joints (ETJ) are used in aluminum and magnesium reduction cells for making welded connections between aluminum buss systems and steel anodes and cathodes. Depending upon the cell design and operating procedures, ETJs can operate at temperatures ranging between 200 C and 500 C, and sometimes hotter. Over time, these thermal conditions can have significant deleterious effect upon the ETJ bond strength, resulting in eventual failure.

A detailed study was performed measuring ETJ bond strength as a function of time, temperature, and design. Specimens were maintained at temperatures of 300 C to 640 C for up to 300 days, and then tensile tests were performed. Metallographic and spectrographic analyses were performed to analyze the mechanism of bond degradation. Diffusion and subsequent intermetallic formation were the mechanisms causing bond degradation. Theoretical diffusion equations provide a basis for extrapolation of test data to longer time periods.

The addition of a thin interlayer between the aluminum and steel can alter this behavior. Several interlayer materials were evaluated, including chromium and titanium. Titanium provides the most significant improvement in performance. Extrapolations indicate that titanium interlayer ETJ's can be expected to operate for over 10 years at 450 C without significant degradation.

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 practical 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 which are manufactured using one of the solid state welding processes. The ETJ couplings provide similar metal surfaces suitable for joining by conventional fusion welding processes, Figure 1.

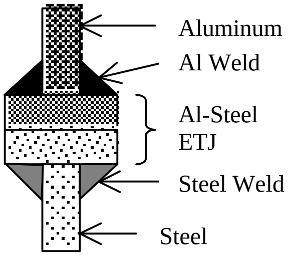


Figure 1: ETJ Concept.

Since it's introduction in the 1960's, the ETJ concept has become commonly accepted for making fusion welds between aluminum-steel, aluminum-copper, and copper-steel. Only aluminum-steel will be further addressed in this paper; however, it is important to note that the aluminum-copper products exhibit similar time-temperature performance concerns, but with lower temperature thresholds.

Making Aluminum-Steel Welds

The difficulties of welding aluminum to steel by conventional fusion processes results from the intermetallic phases that form between aluminum and iron at elevated temperatures. Figure 2 (Ref 1) presents the Al-Fe phase diagram which shows five well defined intermetallic phases. These intermetallics are typically hard and brittle. The solid state welding processes, commonly called cold welding processes, used for ETJ manufacture achieve bonding without exposing the metals to the time-temperature conditions which result in intermetallic compound formation. The methods by which these manufacturing processes achieve welding conditions are extensively presented in metallurgical handbooks. In the cold rollbonding process, aluminum and steel plates are passed through a rolling mill with sufficient pressure and reduction to break-up surface oxides on the mating surfaces and create bonding between the dissimilar metals (Ref 2). In the friction welding process, one component is rotated by a high

Draft of Paper for presentation at 2002 TMS 131st Annual Meeting
Seattle, WA, USA
February 17-21, 2002

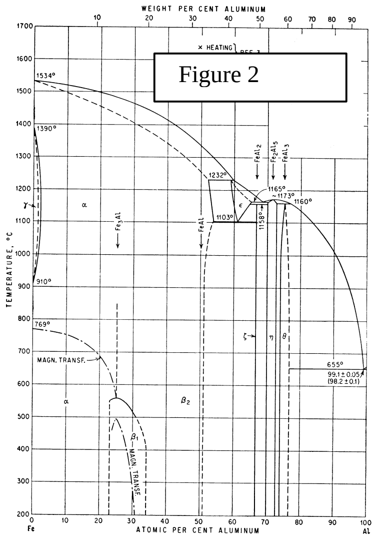


Figure 2

velocity fly-wheel and then forced under high pressure into the other component. The mating surfaces are heated by friction and then forged outward creating a similar bond (Ref 3,4). In the explosion welding process, the plates are accelerated together at an oblique angle by a high velocity explosive detonation. The pressure pattern at the collision point results in expulsion of the surface layers from the component metals, creating an atomic bond between the components (Ref 5,6,7).

The intermetallic phases which occur during aluminum-steel fusion welding can also form at temperatures well below the melting point of aluminum. The intermetallic formation rate is diffusion driven and is a function of time and temperature. This condition limits the time-temperature performance life of any ETJ product. As will be shown later, the time at temperature required to destroy the bond properties of a direct aluminum-steel couple is relatively short under some aluminum reduction cell operating conditions. This was first observed in several plants in the late 1960's. Product development efforts were undertaken to modify the diffusion characteristics of the Al-Fe couple by adding a thin interlayer of a third metal which exhibited improved diffusion resistance with both aluminum and iron. The three interlayer metals which gained acceptance in the subsequent years were chromium, titanium, and stainless steel. Stainless steel offered the least improvement of the three and is rarely used today. During that product development effort a long term study similar to the one presented herein was conducted by the senior author. That study included a number of other interlayer options beyond those discussed here. The results of that research effort were never published.

Depending upon the reduction cell design, the ETJ's can operate at temperatures ranging from 200 C to 500 C, with periodic thermal excursions even hotter. Over time, these thermal conditions can have significant effect upon the ETJ bond properties. The various product types have significantly different time-temperature-strength features. Selecting the proper product for the process conditions is critical for safe, cost effective cell operation.

Products Evaluated

1. Direct Aluminum-Steel Bond, 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) bonded direct to 38mm thick low carbon steel (alloy C1008).
2. Titanium interlayer between aluminum and steel. Tradename ETJ 2000. Manufactured by DMC Nobelclad using explosion welding. The product tested consisted of 13mm thick aluminum (alloy 1050) bonded 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 bond and the titanium steel bond 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 25mm thick carbon steel with an interlayer of chromium, approximately 0.002 mm thick.

Mechanical Property Testing: Mechanical properties of the joints were evaluated using tensile tests of the specimen design shown in Figure 3. The tensile test specimen is machined from the through thickness dimension of the ETJ. The gage length of this specimen extends beyond the bondzone into both the aluminum and steel. This allows failure to occur at the weakest point, whether it be in the bondzone or a component metal. The 10mm gage diameter assures adequate bond area for consistent, representative results.

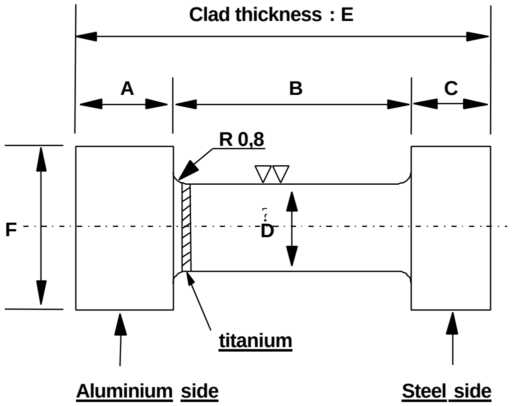


Figure 3: Tensile specimen design. Shown with 1.5 mm thick titanium interlayer

A & C = Grip thickness, 12 (+0,-1) mm
B = Gage length, typically 28 mm
D = Gage diameter, 10 (+/- 1)
E = Total ETJ thickness, typically 52 mm
F = Grip diameter, 20 (+1,-0)

Heat Treatments: Tensile testing was performed on specimens given heat treatments at specific times and temperatures. Two different heat treatment programs were conducted. First specimens of each product type were heat treated for 24 hours at each of the following temperatures: 300 C, 500 C, 525 C, 550 C, 600C and 640 C. The 24 hour test is typically specified by several aluminum producers.

In the second program, samples were also heated at 630 C, 600C, 580 C, 530 C, 490 C, 455 C and 375 C for periods up to 300 days, or until specimen failure, whichever was shorter. All heat treatments were performed in an electrically heated furnace.

Results- 24 hour Program:

Table 1 presents tensile strength and heat treat temperature of each product after each of the 24 hour heat treatments. The data are graphically presented in Figure 4.

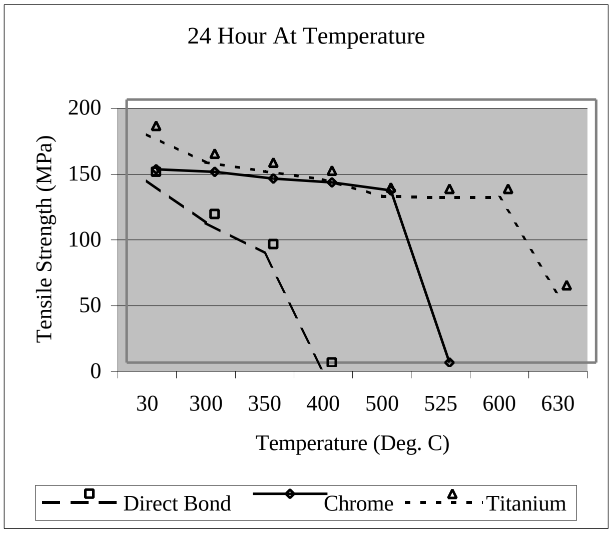


Figure 4: Room temperature ETJ tensile strength vs heat treatment temperature after 24 hour at temperature for the three bond types.

General observations from 24 hour tests:

Al-Steel Direct Bond: The strength began to drop off quickly above 300 C. Bond strength dropped to zero after the 400 C exposure. Specimens typically failed at the aluminum/steel bond.

Chromium Interlayer: The strength changed very little with temperature up to 500 C. Strength dropped to zero after the 525 C exposure. Strength variability was low. Fracture occurred at the bond between the aluminum and chrome.

Titanium Interlayer: Strength changed very little with temperature up to 600 C. Specimens exhibited 70% of initial values after exposure at 640 C, only 20 C below the melting point of aluminum.

<u>Results- Long Term Heat Treatment Program:</u>

In the longer term heat treatment program, a group of specimens of each type was loaded into the furnace together. Specimens of each type were removed at increasingly longer periods ranging from 1 day to 300 days. The specimens were then tested for bond tensile strength.

Tables 2 through 4 presents the times, temperatures, and tensile strengths for the long term program. Each tensile strength value shown is the average of at least three tests. The authors considered 20 MPa as the strength at which product strength had dropped to a level where failure in service was likely to occur. This strength level represents a 85% to 90% loss of original bond strength. The "Time to Failure", the time at temperature required to reduce strength to the 20 MPa level, was interpolated from the test data. Figure 5 presents a plot of "Time to Failure" vs "Temperature" for the three specimen types. The graph plots 1/T (deg K) vs log t. The logic supporting this presentation is presented later.

Metallographic Evaluation:

The heat-treated specimens were metallographically examined to observe the visual changes in the bond. Figure 6 presents the chrome interlayer specimens in the as-manufactured condition and after various exposure times at 490 C. Figure 7 presents the titanium interlayer specimens after the same exposures. In the "as-manufactured" condition, Figures 6 (a) and 7 (a), both products exhibit a clean interface between the aluminum and the adjacent metal. The 2 micron thick chrome layer is clearly visible in Figure 6(a). The subsequent pictures 6(b), (c), (d), which

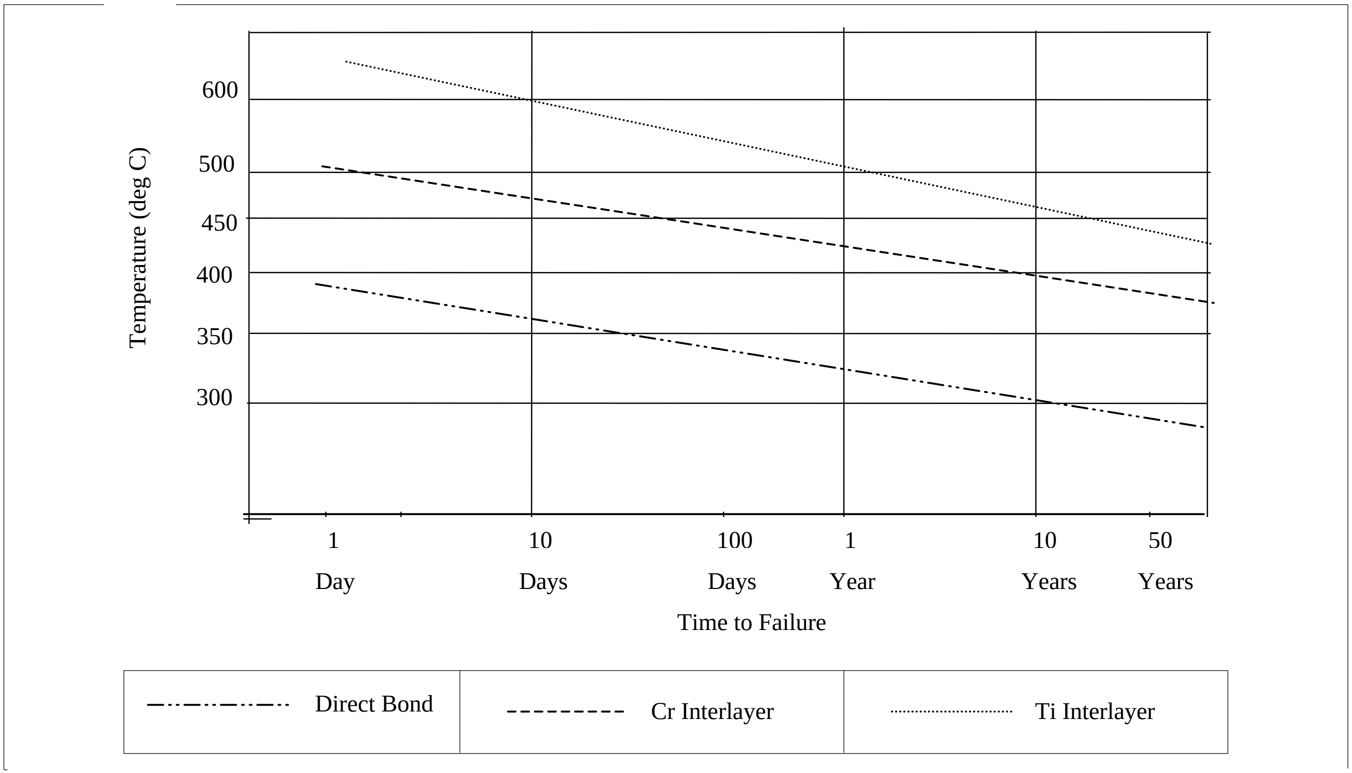
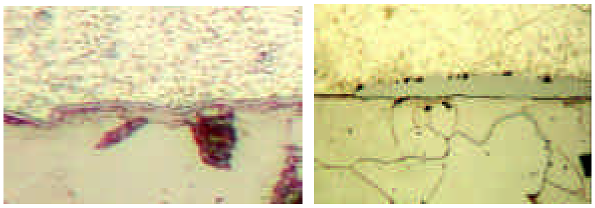


Figure 5: Time to Failure vs Temperature for the three part types. Plotted as 1/T(deg K) vs log t, reformatted for presentation.

are taken after sequentially increasing holding times, show an increasingly thick layer forming at the bondzone. After 165 hours at 490 C, the layer is approximately 20 microns thick.


6(a) As- Manufactured 6(b) 60 hours at 490 C

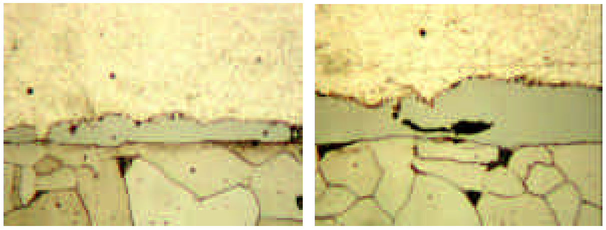

6(c) 108 hours at 490 C 6(d) 165 hours at 490 C

Figure 6: Chrome interlayer specimens after various exposure times at 490 C, 500x. Aluminum at top, steel at bottom.


7(a) As- Manufactured 7(b) 60 hours at 490 C

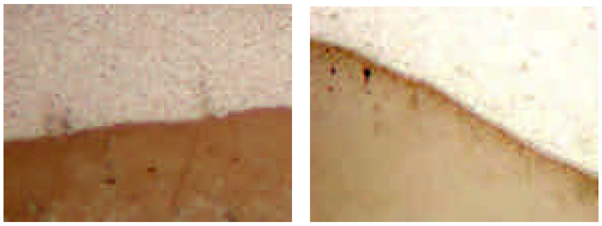
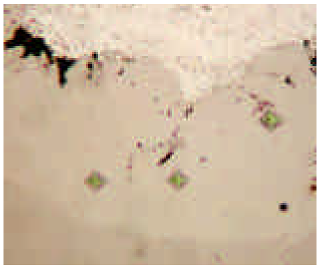

7(c) 108 hours at 490 C 7(d) 165 hours at 490 C

Figure 7: Titanium interlayer specimens after various times at 490 C, 500x. Only the aluminum-titanium bond is shown. Aluminum at top, titanium at bottom

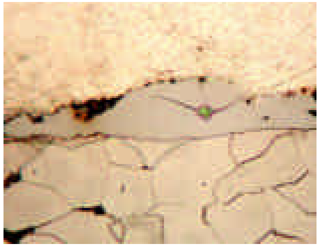
In the titanium interlayer specimens the intermetallic layer formation is significantly less. There is no visual evidence of a growth layer after 108 hours at 490 C, but a clearly defined layer, approximately 1.5 micron thick, after 165 hours, Figures 7(c) and 7(d) respectively.

Microhardness Examination: Microhardness measurements were made on the metallographic specimen shown in Figure 6 (d) and a titanium interlayer specimen which has been heated at 620 C for 48 hours to intentionally grow a thick intermetallic band. Measurements were taken in the aluminum and steel parent metals, the titanium interlayer, and the intermetallic layers which had formed at the aluminum interface during the thermal treatments. The chromium layer was too thin for hardness measurement. The hardness values for steel, titanium, and aluminum were typical for the respective metals in plate form. The intermetallic layer was exceptionally hard in the 750 Hv range. The impression point in Figure 9 exhibits fractures in the corners, indicating that this intermetallic layer is more brittle than that of the aluminum-titanium system in Figure 8.



	microhardness (Hv)
Steel	116;116
Titanium	115; 115 ;115
Aluminium	23; 25
Intermetallic compounds	720; 780

Figure 8: Micorhardness impressions in intermetallic layer formed at aluminum-titanium bondzone. Specimen heat treated 48 hours at 620 C prior to testing. (500X)

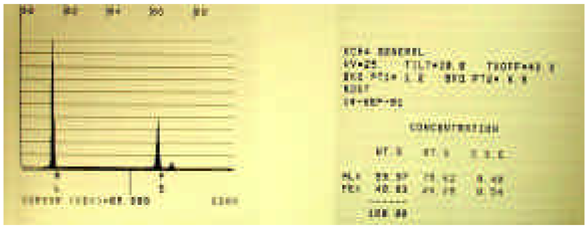


	microhardness (Hv)
steel	127; 127
Aluminium	23; 23
Intermetallic compounds	550; 760; 590

Figure 9: Microhardness impressions in intermetallic layer formed at aluminum-chromium bondzone. Specimen heat treated 165 hours at 490 C prior to testing. (500X)

Spectrographic Analysis: Spectrographic analysis was performed to determine the composition of the intermetallic layer of the specimens shown in Figures 8 and 9. The layer which had

10(a) Area of analysis (1500 x)



10(b) Spectrographic peaks showing growth layer composition

Figure 10: Spectrographic analysis of layer forming in chrome interlayer specimen after heat treatment for 165 hours at 490 C.

formed between the titanium and aluminum (Figure 8) exhibited a composition of 25% titanium and 75% aluminum, most likely $TiAl_3$. There was no evidence of iron in the intermetallic layer. The titanium interlayer remained present as a continuous barrier to iron-aluminum intermetallic formation.

The layer which had formed in the chrome interlayer sample was different. The newly formed layer was not uniform in thickness, varying significantly over short distances, Figure 10 (a). Spectroscopy showed minimal indication of the presence of chromium. The composition of the thicker layer that formed was 25% iron and 75% aluminum, Figure 10(b), probably the $FeAl_3$ intermetallic which is shown in Figure 2.

Discussion of Results

The photomicrographs and spectrographic analyses indicate that an intermetallic layer is gradually forming at the bond interface during elevated temperature exposure. The photomicrographs show that this layer grows thicker with increased time at temperature. The spectrographic scans confirm that diffusion is occurring between the component metals at the bond zones. The microhardness data confirm that the intermetallic layer is hard and brittle. We can conclude that the mechanism for bond strength deterioration with temperature-time exposure is diffusion and formation of intermetallic compounds at the bond. The rate of formation of these compounds and their relative mechanical properties determine the elevated temperature performance of each of the products.

Direct Al-St bond: The aluminum and iron are in direct metallurgical contact at the bond. The Al-Fe intermetallics ($FeAl_3$, Fe_2Al_5, and $FeAl_2$) begin to form at a relatively low temperature and are very brittle. After the 24 hours at 400 C, there is sufficient continuous intermetallic formation at the bond to reduce strength to near zero. Similar performance would be expected for direct aluminum-steel bonds made by other processes, such as friction welding.

Titanium Interlayer: The titanium interlayer provides a barrier which prevents formation of the Al-Fe intermetallics. At high temperatures the aluminum-titanium intermetallics (predominantly $TiAl_3$) form at the aluminum-titanium bondzone. However, these intermetallics begin to form at much higher temperatures than Al-Fe intermetallics. Also, in other work the Ti-Aluminides have been shown to exhibit greater mechanical integrity than most other intermetallic systems. Although there is potential for brittle titanium-iron intermetallics, these do not begin to form at the temperatures and times applicable to aluminum reduction ETJ's. The titanium layer is sufficiently thick that it is not breached by any of these reactions.

Chromium Interlayer: The chromium interlayer also provides a diffusion barrier which prevents formation of the Al-Fe intermetallics. Aluminum and chrome form a large number of intermetallic compounds; however, like the Al-Ti family, they begin to form at a higher temperatures than the Al-Fe system. The Fe-Cr system exhibits a Fe-Cr sigma phase which occurs above 425 C. It would be expected to be brittle if it were present, but the spectrographic data does not show it. It appears that the chrome layer is gradually absorbed into one or both of the adjacent metals by diffusion. Once it is consumed, it is no longer present as a diffusion barrier between the aluminum and steel. The Al-Fe intermetallics then begin to form quickly resulting in a transformation from a strong ductile bond to a weak brittle bond.

Data Analysis and Extrapolation

At normal reduction cell operating temperatures, 350 to 400 C, both the chrome and titanium interlayers prevented deleterious intermetallic formation over the 300 day duration of this test program. It was necessary to force both products to much higher temperatures to obtain failures within the time scope of the program. However, reliable performance over a much longer service life is mandatory for these products. For this data to be useful in predicting performance over longer time periods, we must have a reliable basis for extrapolation of the existing data.

After review of theoretical diffusion equations, the authors have concluded that a plot of (log t) vs (1/T) provides a logical presentation for longer service life extrapolations. The logic is as follows:

ETJ failure results from loss of bond strength due to brittle intermetallic formation over time at elevated temperature. The intermetallic growth requires diffusion. The diffusion rate is directly proportional to the Diffusivity, "D".

The relationship between the Diffusivity and Temperature is well established (Ref. 8) as

$$\log D = -(Q/2.3RT) + \log D_0$$

Where T is temperature in degrees Kelvin.

For a specific metal system, we can assume that Q, R, D_0 are constants that are unaffected by time or temperature.

Therefore: $\log D = -(C1/T) + C2$

The time, "t", to achieve a specific amount of diffusion and resulting intermetallic formation is inversely proportional to D. Therefore, D is proportional to a constant multiplied by 1/t or C3/t.

For simplicity of discussion, when establishing graph slope only (for a specific metal system) we can set C1, C2, and C3 all equal to 1.

Therefore: $\log(1/t) = -1/T + 1$ or $1/T = 1 - \log(1/t)$ or $1/T = \log t + 1$

This is the form $x = y + \text{constant}$, which is a linear equation.

Thus, a plot of $x = \log t$ (hours) and $y = 1/T$ (deg K) should be linear.

When the data of Tables 1 through 4 are presented in this manner, Figure 5, they fit a straight line fairly well.

Although this is very simplistic logic, it provides a basis for extrapolation of the test data of this program to longer time periods. An extrapolation of the data in Figure 5, predicts that the titanium interlayer product is good for over 10 years at 450 C and that the chromium interlayer product is good for about 10 years at 400 C, but only about 100 days at 450 C.

Conclusions:

Aluminum-Steel ETJ’s provide a reliable method for making fully welded metallurgical connections between aluminum and steel components. The solid state bond of the ETJ products can deteriorate over time at elevated operating temperatures. The deterioration is the result of diffusion and resultant formation of brittle intermetallic components.

For ETJ’s with operating conditions below 300 C, all of the products studied exhibit good mechanical performance and good resistance to thermal deterioration.

For operating conditions between 300 C and 400 C, both the titanium interlayer explosion bonded product and the chromium interlayer rollbond product offer predicted service for over 10 years. The direct bond Al-Steel product will fail in a few years at best.

When operating temperatures are above 400 C, the expected service life of the chromium interlayer product begins to drop off quickly. Expected service life at 450 C is about 100 days. The predicted service life of the titanium interlayer product at 450 C exceeds 10 years.

References

1. Hansen, Max, Constitution of Binary Alloys, New York, NY: McGraw-Hill Book Company, Inc. 1958, Page 91.

2. Author unlisted, “Roll Welding”, ASM Handbook, Vol 6 Welding, Brazing, and Soldering, ASM International, USA, 1993, Pages 312-314.

3. Elmer, J.W. and Kautz, D.D., “Fundamentals of Friction Welding”, ASM Handbook, Vol 6 Welding, Brazing, and Soldering, ASM International, USA, 1993, Pages 150-155.

4. Stotler, T., “Procedure Development and Practice Considerations for Inertia and Direct-Drive Friction Welding”, ASM Handbook, Vol 6 Welding, Brazing, and Soldering, ASM International, USA, 1993, Pages 888-891.

5. Patterson, A., “Fundamentals of Explosion Welding”, ASM Handbook, Vol 6 Welding, Brazing, and Soldering, ASM International, USA, 1993, Pages 160-164.

6. Banker, J.G, and Reineke, E.G. “Explosion Welding”, ASM Handbook, Vol 6 Welding, Brazing, and Soldering, ASM International, USA, 1993, Pages 303-305.

7. Smith, L.M., and Celant, M., Practical Handbook of Cladding Technology, Edmonton, Alberta, CA, CASTI Publishing, Inc. , 1998.

8. Reed-Hill, R., Physical Metallurgy Principles, Princeton, NJ, D.Van Nostrand Co. Inc., 1964, Page 280.

Table 1

ETJ Tensile Strength after exposure of test specimens to various temperatures for a 24 hour period.

ETJ	Temp. (deg C)	Avg. UTS (MPa)	# Tests	Std. Dev. (MPa)
Direct Bond	20	144	224	41
“	300	113	144	24
“	350	89	3	9
“	375	35	3	4
“	400	0	3	0
Titanium Interlayer	20	179	12	6
“	300	158	3	1
“	500	133	12	5
“	600	132	6	7
“	625	105	3	11
“	640	59	3	3
Chromium Interlayer	20	147	3	2
“	300	144	3	6
“	500	130	3	0
“	525	0	3	0

Table 2

Direct Bond tensile strength after various heat treatments.

Temp. (deg C)	Time (days)	Strength (Mpa)
As-Manufactured		144
300	1	131
375	2	61
375	10	27
375	30	12
375	90	7
375	300	0
400	1	0

Table 3

Chrome interlayer ETJ tensile strength after various long term heat treatments.

Temp. (deg C)	Time (days)	Strength (MPa)
As Manufactured		147
375	2	128
375	10	124
375	30	125
375	90	116
375	300	114
455	2	151
455	10	121
455	30	124
455	90	116
455	300	11
480	8	96
480	13	90
490	2	140
490	4.5	104
490	7	65
490	8.5	36
525	1	0

Table 4

Titanium interlayer ETJ tensile strength after various long term heat treatments.

Temp. (deg C)	Time (days)	Strength (MPa)
As Manufactured		179
375	2	160
375	10	160
375	30	157
375	90	145
375	300	134
455	2	154
455	10	156
455	30	149
455	90	142
455	300	111
530	1	142
530	2	129
530	10	141
530	21	128
530	102	30
530	120	17
580	1.25	136
580	2	133
580	10	73
580	17	44
600	1.1	66
600	3	39
600	9	9
630	1	34
630	1.5	30