Examination of Electrolytic Capacitors for Welding Applications

Jerry E. Gould[*], Toshihiko Furukawa[**], Sam Lewis[*], Tomokazu Hasebe[**], Hiroyuki Kato[**], and Wendell Johnson[***]
[*]EWI, [**]Nippon Chemi-Con, [***]Process Equipment Company

Abstract

This study examines the application of electrolytic capacitor arrays as potential replacements for film units in large-capacity systems. This work takes advantage of the recently developed open architecture CD system at EWI. Capacitors were arranged in a series/parallel array, in which six electrolytic units were placed to allow potential charge voltages of up to 3600 V. The array was also designed to provide a similar capacitance to commercially available film-type units (~1200 μF). The resulting E-cap system was roughly 20% the mass of the film cap counterpart. Welding tests were done using both the film and electrolytic capacitor variants. These trials were peformed with the same mechanical system, on commercially purchased three-projection weld nuts. Current range tests based on push-off strengths, as well as metallographic sections were used to compare performance. Performance results were found to be identical. Following these results, extended trials were done with prototype capacitor banks on a production system. Temperature measurements suggested some heating of the capacitors with extended use, so for future application some cooling capacity may be required.

Introduction

Capacitive discharge or CD welding is a variant of resistance welding[1,2]. The process differs from the conventional variants largely in the type of power supply used. Conventional systems provide some variant of alternating current to a transformer arrangement. The transformer arrangement produces low voltage, high current power that is suitable for resistance welding. With CD welding, the main energy is stored in a capacitor arrangement. In application, that energy is discharged through a transformer creating again low voltage – high current power for welding. CD welding does differ from conventional resistance welding in a number of ways[1]. First, primary current is drawn from the capacitors rather than the power line, dramatically reducing electrical infrastructure demands. Second, primary voltages can be quite high (>3000 V) compared to conventional resistance welding systems. This leads to differing transformer design requirements. Finally, secondary current pulse widths can be quite short (<10 ms) compared to conventional resistance welding processes.

Capacitive discharge welding, particularly for large-scale systems, is typically done using film-type capacitors. These capacitors store energy along alternating plates separated by a dielectric film. Charge is stored statically along the lengths of the plates. The basic configuration of the film capacitor is provided in Figure 1. The capacitance itself is controlled by the area and relative separation of the plates. The units are then packaged by wrapping the plates and dielectric film, and inserting them into a protective canister. The resulting package is shown schematically in Figure 2. These capacitors are advantageous as they are capable of handling high voltages (into the 10s of kV), can accommodate polarity reversals, and have lives in excess of 10-million cycles. However, these capacitors are both mass and volume inefficient. Current capacitors run mass and volume normalized capacitances of roughly 20 μF/kg and 0.027 μF/cm^3, respectively. The mass and size of the capacitor necessitates large stationary system designs. This leads to increased system costs and reduced (or non-existent) portability.

Electrolytic capacitors (E-caps) offer a potential alternative for large capacity CD welding systems. E-caps incorporate an electrolyte impregnated into a separator. The separator is then sandwiched between anodic and cathodic foils. A dielectric is also used to prevent direct contact of the foils with the electrolyte. Charge is then stored by separation of ions within the separator interacting with the foils themselves. The basic configuration of the electrolytic capacitor is provided in Figure 3. To create the actual capacitor, the foils and electrolyte are wound and integrated into an appropriate package. A schematic representation of this assembly is provided in Figure 4. The use of an electrolyte allows much higher densities of energy storage compared to conventional film capacitors. The design facilitates a factor of 10 reduction in film spacing, resulting in systems with much lower mass and volume (and associated costs). Sample E-caps show mass and volume normalized capacitances of roughly 2900 μF/kg and 4 $\mu F/cm^3$, respectively.

Use of E-caps for CD welding applications does have some challenges. Most notably, E-caps have limits to usable voltages before electrolyte break-down. Current maximum voltages for large capacity E-caps is on the order of 800 V. In addition, E-caps are relatively intolerant to voltage reversals. Applying reverse polarity voltages can damage the foils in the E-cap. Current E-caps are limited to a few volts of reverse polarity.

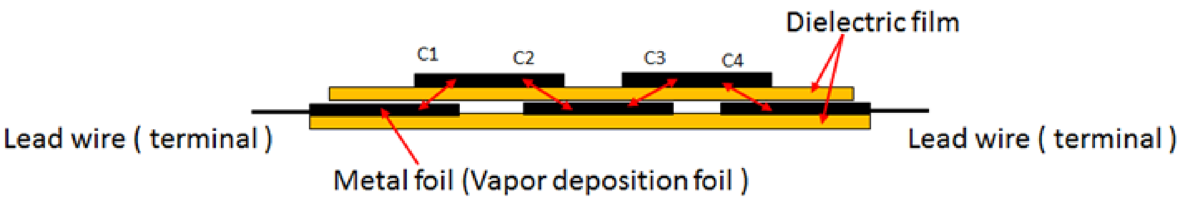


Figure 1. Conceptual Layout of a Film Type Capacitor (includes alternating charge plates separated by a dielectric film)

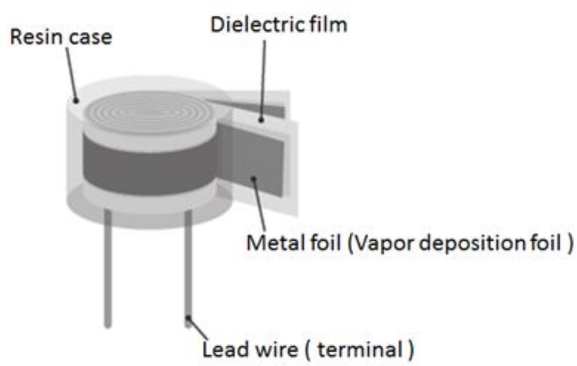
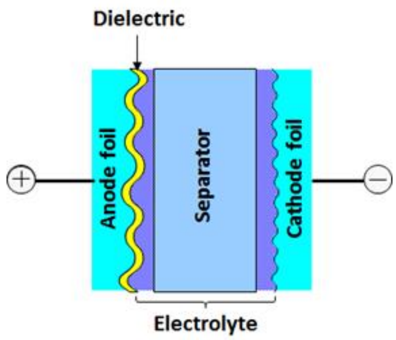


Figure 2. Packing of a Film-type Capacitor into a Cylindrical Configuration (package can be wound for either cylindrical or prismatic designs)

In this work, arrays of E-caps were used to achieve the necessary voltage tolerances for CD welding. E-caps were arrayed in series to provide necessary deliverable voltages, and in parallel to achieve desired capacitances. The developed system was then integrated into an open architecture CD welding machine available at EWI[(3)]. The system was then used to conduct weldability for a representative projection welding application. That work paralleled previous activity using a similar-sized film capacitor. Results were used to assess similarities and differences between E-cap and film cap based power systems, and define a potential new generation of lower cost/more portable CD welding machines.



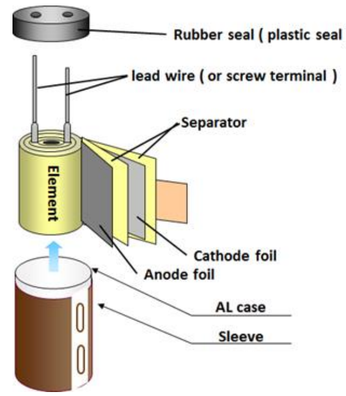


Figure 3. Schematic Representation of the Foil-Separator Layout in an Electrolytic Capacitor

Figure 4 – Packaging of an Electrolytic Capacitor (note continuous foils and separator)

Experimental

As suggested above, previous work(3) was done on an open architecture CD welding system available at EWI. That system has been described in detail elsewhere. The available system is capable of charge voltages up to 3000 V, and was equipped with the 1280-μF film type capacitor. The system included a polarity reversing capability that facilitated direct application of stacked core type welding transformers. The transformer employed series/parallel windings combined with an auto-transformer. This resulted in 128 tap settings with windings ratios ranging from 65:1 up to 1625:1. The transformer and power supply were integrated into a small pedestal-type welding frame. This frame was capable of welding forces up to about 5 kN, and had a total moving mass in the secondary of roughly 110 N.

Individual E-type capacitors rated at nominally 700 V and 3300 μF manufactured by Nippon Chemi-Con were employed in this study. These units were built into an array to provide allowable voltages in access of 3000 V, and a capacitance as close as possible to that used for comparison work(3). The array was designed by placing capacitors in series to achieve the necessary voltage (five) and adding sufficient additional ones in parallel to maintain desired capacitance. The resulting design is shown in Figure 5. This is a square array with two units in parallel and five in series. Of note, there was concern about voltage balancing during charging for series-type capacitor arrangements. As a result, 100,000-Ω resistors were placed between each of the five series capacitor sets to allow such voltage balancing. The resulting array was capable of charging to 3500 V, and had an overall capacitance of roughly 1320 μF. The array itself is shown in Figure 6.

Welding was done at two separate sets of windings ratios. This included turns-ratios of 103:1 and 213:1. The transformer acts to couple the power between the primary and secondary, so changing the turns-ratio has a direct influence on the resulting current waveform (3,4). The turns-ratios used here paralleled that from the previous study(3). The influence of turns-ratio on the resulting secondary current waveform is provided in Figure 7. The waveforms shown here are operating at different charge voltages to achieve the same peak currents. It can be seen that for a similar (15 kA) secondary current, doubling the turns-ratio of the transformer increases the rise times and total widths of the resulting pulse by roughly an equivalent amount.

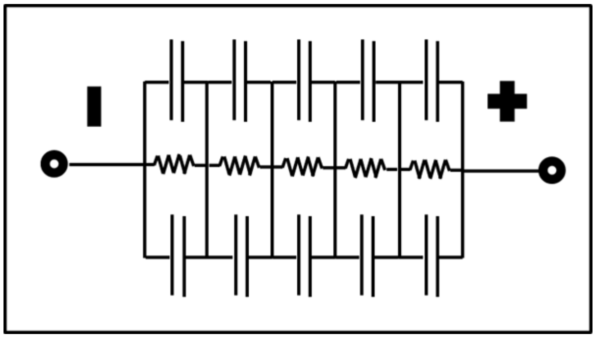


Figure 5. Design of the Capacitor Array used in this Study (included five sets of two capacitors in parallel each placed in series; note the balance resistors between each parallel capacitor set)

Figure 6. Actual Array of Capacitors Used in This Study (note the large aluminum shunts coordinating the capacitors in the series and parallel configuration, and the balancing resistors)

Process trials were performed on a commercially purchased weld nut. The details of that nut are provided in Figure 8. The nut is manufactured from low carbon steel, is nominally 19 mm in diameter, and contains three projections. These are embossed projections nominally 2.5 mm in diameter and 0.95-mm tall. In these trials, nuts were welded to a nominal 0.8-mm mild steel. Coupons for testing were sheared to a nominal 50×50mm size, with an access hole drilled for placement of the weld nut.

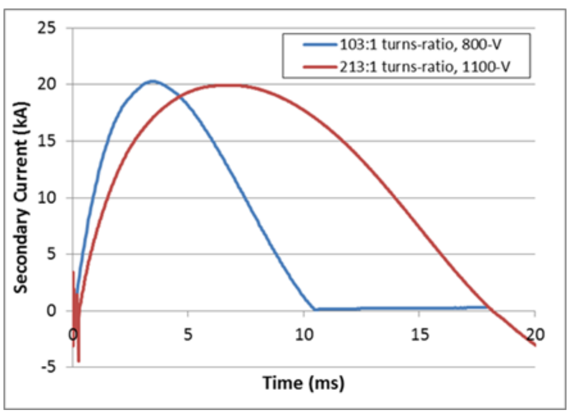


Figure 7. Secondary Current Response for Two Different Windings Ratios using a Film-cap in the Power Supply[1] (charge voltage is adjusted to achieve similar peak currents)

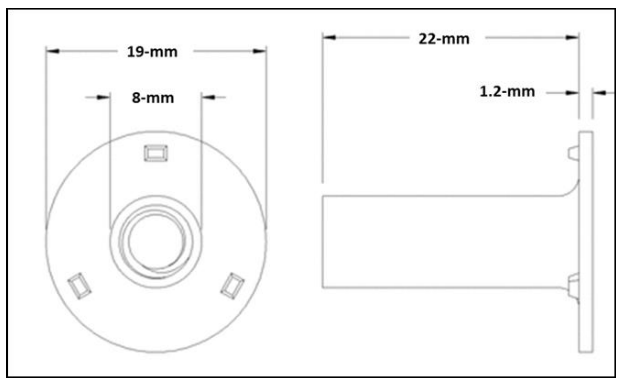


Figure 8. Design of the Weld Nut Used in This Study (weld nuts were of mid steel, with three projections nominally 2.5 mm in diameter and 0.95-mm tall)

Weld quality during these trials was assessed in two ways. Primary quality evaluations were made through push-off testing. This included placing the welded nut assembly in a simple fixture, and pushing the stem through the sheet. Testing was done on a Southwark hydraulic unit. Such testing placed the projection welds in direct tension. The second method was through metallographic assessment. Samples showing best strength values (for the two transformer windings ratios used) were sectioned and prepared using standard metallographic techniques.

Results

Weldability during these trials was assessed through current range testing. During these tests, the weld force was maintained at 3.3 kN, and the charge voltage on the capacitors slowly increased to provide additional current. Voltages were varied from no-weld conditions to metal expulsion. Weld performance was evaluated through push-off testing. Current range testing was duplicated for both the 103:1 and 213:1 turns-ratios. All results are provided in Table 1. As mentioned previously, work was done to parallel previous efforts using a similar size film capacitor[(3)]. The current range results from those film cap trials are also reproduced in Table 1.

Table 1. Current Range Results Using Two Different Transformer Turns-Ratios for both E-Caps and Film Caps (film capacitor data was taken from previous research[(3)])

E-Cap (1320 µF) Current Range Results				**Film-Cap (1280 µF) Current Range Results**			
Trial	**Charge Voltage**	**Current (kA)**	**Push-off Test (kN)**	**Trial**	**Charge Voltage**	**Current (kA)**	**Push-off Test (kN)**
103:1 Turns-Ratio Data				103:1 Turns-Ratio Data			
1	400	8.4	0	9	500	11.7	2.3
2	500	11.2	0.2	10	800	20.4	2.9
3	450	10.4	0.4	11	400	9.3	0.1
4	420	9.6	0	12	250	5.4	0.0
5	600	14	3.1	13	600	14.9	2.7
6	700	16.9	2.4	28	600	15.0	3.4
7	800	19.3	3.2	-	-	-	-
8	250	5.6	0	-	-	-	-
213:1 Turns-Ratio Data				213:1 Turns-Ratio Data			
9	500	6.6	0	19	500	7.3	0.0
10	600	9.1	0	20	600	9.6	0.0
11	700	10.3	1.1	21	700	10.6	2.5
12	800	12.7	0	22	800	11.9	3.4
13	900	14.2	3.8	23	900	14.4	4.1
14	1000	16.7	3.6	24	1000	16.9	3.8
15	1100	18.3	4	25	1100	19.6	4.0
16	1200	19.8	3.9	26	1200	21.4	3.8

The data provided include the charge voltage employed, the resulting peak current (measured using an active integrator and oscilloscope), and the resulting strength observed during push-off testing.

Current/voltage relationships for the two capacitor types at the different transformer turns-ratios are provided in Figures 9 and 10. In both cases, there is clearly a linear relationship between charge voltage on the capacitors and peak secondary currents (through current range testing). It is of note that the slope of the current/voltage dependence is slightly less for the E-cap arrangement. This is assumed due to the presence of the ESR (electric series resistance) associated with electrolytic capacitors. Currents themselves varied from about 5 kA up to about 20 kA through the current range test regardless of capacitor type or transformer turns-ratio. It was also noted that (as described above) the higher transformer turns-ratio required similarly increased charge voltage to achieve equivalent currents. Largely however, the results from the two capacitor types are indistinguishable for differing charge values and transformer turns-ratios.

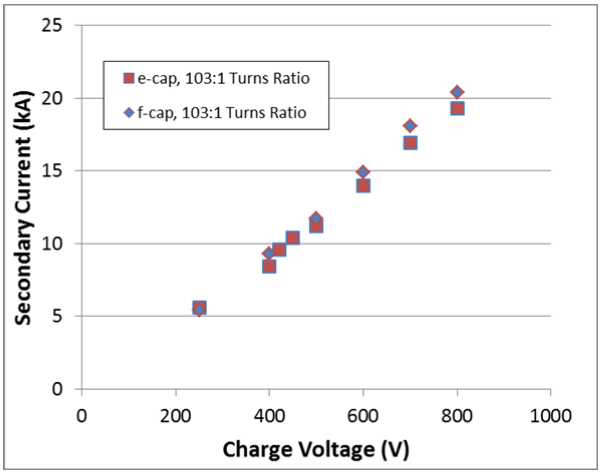


Figure 9. Relationship between Current and Voltage for both E- and Film-Caps Using a 103:1 Transformer Turns-Ratio

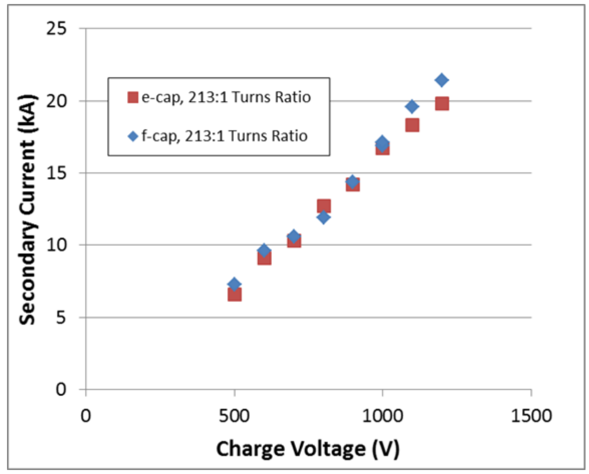
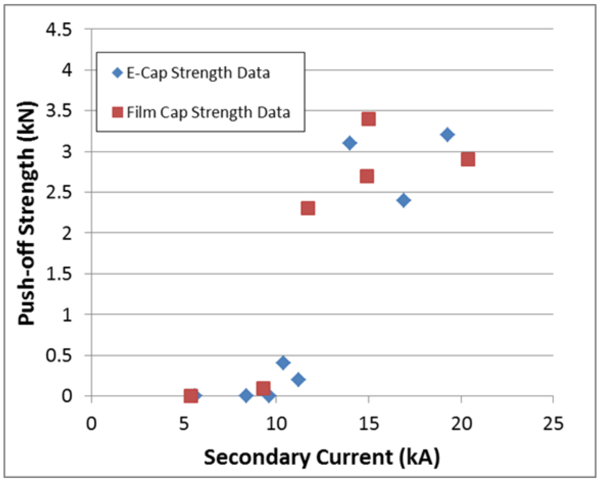


Figure 10. Relationship between Current and Voltage for both E- and Film-Caps Using a 213:1 Transformer Turns-Ratio

Actual current range results are shown graphically in Figures 11 and 12. The actual current range here is defined as the difference between that needed to achieve a minimum strength (taken from AWS-recommended practice documents[5]) and expulsion. Differences in current range response for the two different transformer turns-ratios have been discussed elsewhere[3]. In summary, the 103:1 transformer resulted in peak strengths of about 3 – 3.5 kN, and a current range of approximately 7 kA. Alternately, at a turns-ratio of 213:1 peak strengths increased to between 3.5 – 4 kN, and the current range to about 10 kA. Finally, the level of scatter in these results was much greater at the lower transformer turns-ratio. Of note for this study however, in both figures, it is clear that the joint strength/current relationships for the two capacitor types are identical. The two datasets completely overlap, with similar attributes in both cases.



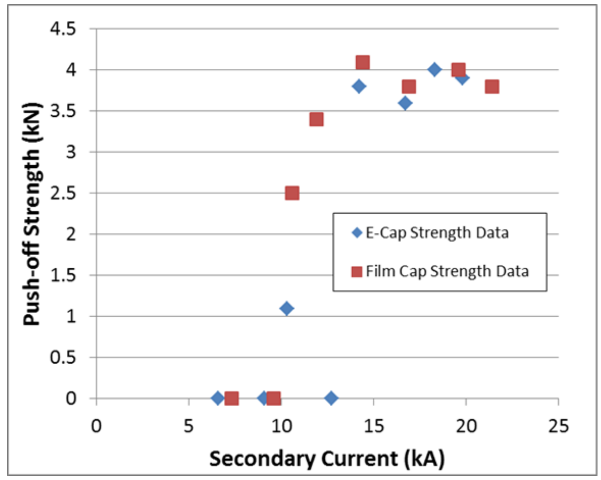
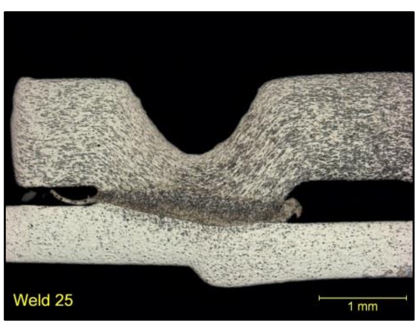


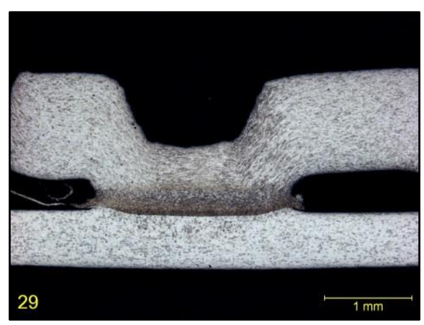
Figure 11. Current Range Results Based on Weld Strength for both E- and Film-Caps Using a 103:1 Transformer Turns-Ratio

Figure 12. Current Range Results Based on Weld Strength for both E- and Film-Caps Using a 213:1 Transformer Turns-Ratio

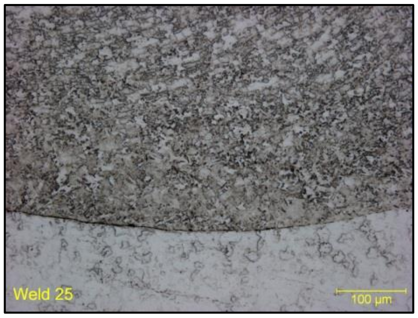
Metallographic sections were then taken from welds made at peak strengths of the current ranges done at the 103:1 and 213-1 turns-ratios. These were then compared to similar results collected previously when using a film capacitor[3]. The electrolytic capacitor results are provided in Figure 13. These results show the macrostructure, and progressively increasing magnifications of the bond line at the weld center. Similar results for a weld made using the film capacitor are provided in Figure 14. As described previously[3], welds made at the 103:1 turns-ratio were characterized by shallow set-downs of the projection, limited effective bond diameters, and heat-affected zones limited to a few hundred microns. In the latter case, duplex (ferrite + transformed austenite) microstructures were observed within 100 μm of the faying surface.



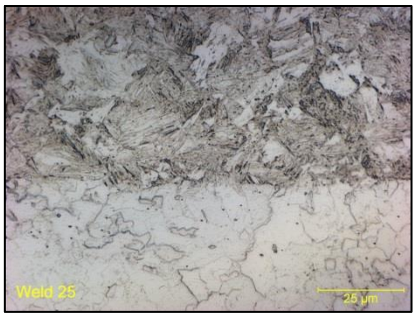
(a) Weld Macrostructure



(a) Weld Macrostructure

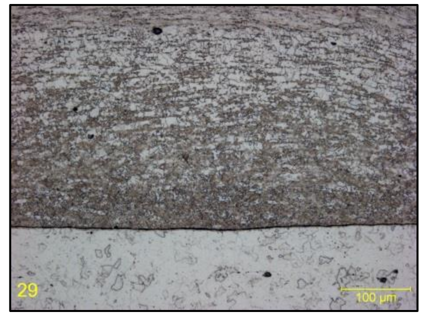


(b) Bondline at Low Magnification

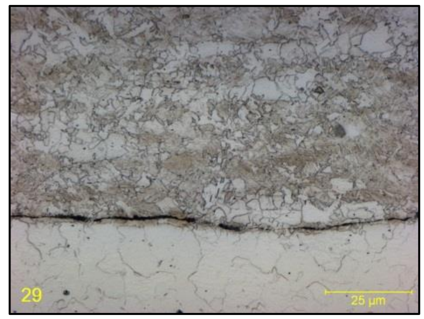


(c) Bondline at High Magnification

Figure 13. Macro- and Micro-structure of a Weld Made at the 103:1 Transformer Turns-Ratio using the E-Cap Arrangement



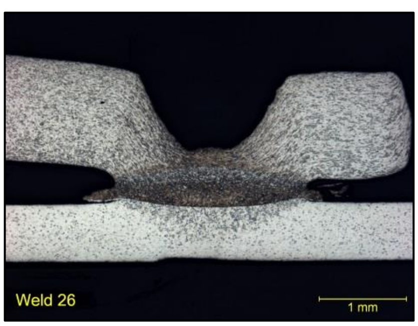
(b) Bondline at Low Magnification



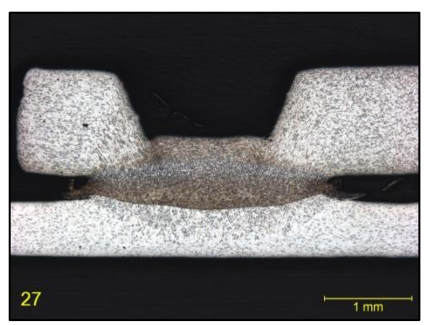
(c) Bondline at High Magnification

Figure 14. Macro- and Micro-structure of a Weld Made at the 103:1 Transformer Turns-Ratio using the Film Capacitor

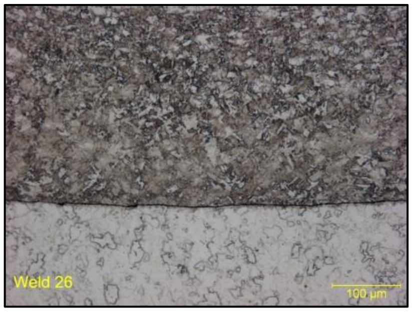
Similar results for the welds made using the E-cap array with the 213:1 turns-ratio are provided in Figure 15. Comparative metallographic data from welds made using the film capacitor[3] are provided in Figure 16. The micro-structural response from welds made with the two capacitor types is again nearly identical. This response (for the film capacitor results) has been described previously[3]. Compared to the welds made with the 103:1 turns-ratio, these joints show greater set-downs of the projection, larger overall diameter welds, and heat-affected zones that fully penetrate both metal thicknesses on both substrates.



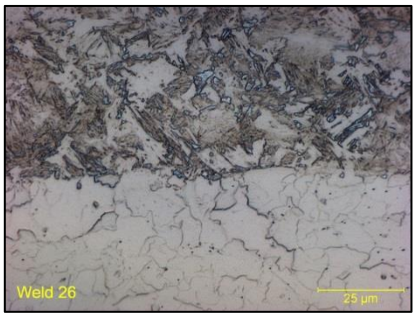
(a) Weld Macrostructure



(a) Weld Macrostructure

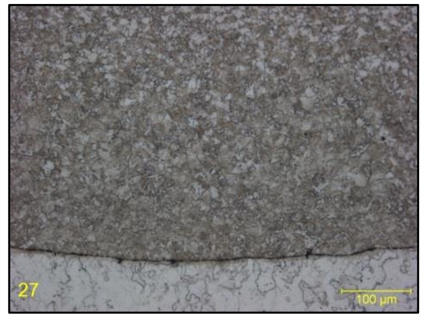


(b) Bondline at Low Magnification

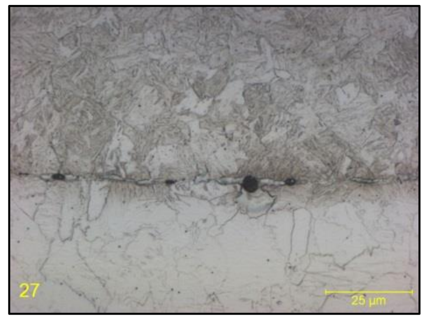


(c) Bondline at High Magnification

Figure 15. Macro- and Micro-structure of a Weld Made at the 213:1 Transformer Turns-Ratio using the E-Cap Arrangement



(b) Bondline at Low Magnification



(c) Bondline at High Magnification

Figure 16 . Macro- and Micro-structure of a Weld Made at the 213:1 Transformer Turns-Ratio using the Film Capacitor

As also described in the previous work[3], it was somewhat surprising that the lower turns-ratio setting (103:1) resulted in lower strengths and less process stability. Lower turns-ratios lead for faster current rise times, which are generally beneficial. This discrepancy was related to achievable mechanical follow-up for the press frame used. Shorter rise times require better follow-up to prevent expulsion and process instability. Longer rise times can accommodate poorer follow-up without such instability. With respect to this study, it is of note that the two capacitor types responded to this rise time/follow-up balance identically.

Discussion

The results presented here indicate that electrolytic capacitors, configured to provide similar charge voltage and energy storage, can yield identical weld performance results. Process, mechanical strength, and metallographic results are all identical for the two capacitor arrangements. It was further of interest that even levels of process stability (reduced for the lower transformer turns-ratios) were also mirrored for the two capacitor types.

Clearly, the use of electrolytic capacitors offers mass and volume advantages over film capacitors. For the application described here, a single 1280-μF film capacitor was replaced with an array of ten 3300-μF electrolytic units. A table providing the performance details of these two capacitor variants is provided in Table 2. Compared to the film variant, the electrolytic array can provide similar performance (capacitance, voltage tolerance, stored energy) at roughly one-third the mass and one-half the volume. Current estimates based on this work are that electrolytic capacitor arrays can be made available at a price point nominally 80% of that for the current film variants.

Table 2. Comparison of Performance Details for the Two Capacitor Arrangements Used in this Study.

	E-Cap Series Module 5 Pieces in Series with 2 Strings of 3,300 uF single cap	Film Capacitor uUit
Capacitance	1320 F	1280 μF
Rated Voltage	3500 V	3600 V
Stored Energy	5.94 kJ	5.76 kJ
Rated Temperature	85°C	50°C
Weight	17.3 kg	51.8 kg
Size	580×213×213 mm	342×170×760 mm
Volume	0.026 m^3	0.044 m^3
Targeting Cost	~80%	100%

The application of such electrolytic capacitor arrays is, of course, not without design considerations. One challenge is the design of arrays that can uniformly balance voltages across series capacitors during repeated charging cycles. In this work, that was accomplished through the use of balancing resistors (~100 kΩ). This balancing must be addressed in any array design. A second concern is the potential (as described previously) for a reverse voltage on the capacitor array. For the work conducted here, this has been avoided by the use of a set of switched biasing diodes across the output leads leading to the primary of the transformer(3). These diodes function to shunt any reflected currents from the secondary (resulting from under-damped matching with the primary). Future designs may include more local protection of the individual capacitors. Finally, developed capacitor arrays must be thermally protected. Initial examinations in this study suggested that some temperature rise (on the order of a degree centigrade) was observed when welds were made at a high rate over a period of hours. This heating is apparently related to the ESR values associated with the individual capacitors. This series resistance, though small, does create thermal transients that need to be managed.

Conclusions

In this study, the suitability of electrolytic capacitor arrangements for use in large-scale CD welding applications was investigated. Baseline for the study was a set-up using a 1280-μF main capacitor. The application was a mild steel weld nut with three projections attached to a similar material substrate. For this study, an array with ten electrolytic capacitors was developed. This array showed similar voltage tolerance and storage capability to the film capacitor used for comparison. The two capacitor set-ups were used with the same welding equipment and workpieces. Performance was evaluated based on current range behavior and metallographic response. Conclusions from this work include:

(1) An array of electrolytic capacitors can be designed that show performance comparable to film capacitors – An array was developed to provide similar voltage tolerance and system capacitance to a standard film variant conventionally used for CD welding.

(2) The designed array must include provisions to allow voltage balancing and prevent polarity reversals during use – This was accomplished using a series of bleed resistors between parallel sets of capacitors and a switched diode array at the output to the transformer.

(3) Secondary current – charge voltage relationships during testing were virtually identical for the two capacitor types – Current range testing including two sets of transformer turns-ratios provided nearly identical responses.

(4) Achievable current ranges for the application were indistinguishable for the two capacitor types - This included not only defined current ranges for each transformer turns-ratio setting, but the individual characteristics (e.g., degrees of scatter, observed peak strengths) of the datasets.

(5) Projection collapse characteristics and resulting micro-structures were also similar for the two transformer types – Defining features relating to current rise times and mechanical follow-up of the system were reproduced for the two different capacitor types.

(6) Array designs must be done in a way to accommodate electrolytic capacitor functionality and response – Features to be considered include balancing the capacitors during charging, preventing reverse voltages during firing, and thermal management for longer-term high-duty cycle use.

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