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Failure Analysis of Pinch Weld Electrodes

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Abstract

Savannah River Site uses brazed copper / tungsten electrodes for a specialized weld referred to as a pinch weld. An alternative method to produce the pinch weld electrodes was sought to improve quality and to reduce the manufacturing steps. Back casting of pinch weld electrodes was selected as such a process. During preliminary testing, deformation of the electrodes was observed. A failure analysis assessment was conducted and the strength of the electrodes was found to be significantly less than required to enable welding of the tubes. This assessment includes compression testing metallographic analysis. The pinch weld electrodes fabricated by back casting do not meet the requirements with respect to strength. In addition, a minimum strength requirement for conventionally prepared electrodes is recommended.

Background

Savannah River Site uses pinch welds, a very specific type of resistance spot weld, to seal hydrogen gas containers. Pinch welding in Type 304L stainless steel is performed by applying a force of nominally 1250 lbs (5560 N) to 0.125" (3.17 mm) Type 304L stainless steel (SS) with a 0.035" (0.89 mm) wall. The force crushes the tubing and brings the surfaces nearly into contact, a schematic of the weld process is shown in Figure 1. A current between 3000 – 4000 Amperes is applied for a total of 12 60 Hz cycles (0.2 seconds). The weld is then formed by dynamic recrystallization and solid-state diffusion across the faying surfaces (1,2). This welding process has been successfully used for this application for nearly 60 years with no field failures (3).

A number of internal pinch welding studies have been conducted to better understand the limits of the process and other effects. For instance, studies have been completed to characterize the effects of control systems (4), stem machine oil (5,6), internal bore scratches (7), internal brushing (8) and weld atmosphere on the bond quality and interfacial contamination (9). The use of constant current vs constant voltage did not reveal any significant difference in appearance of the weld interface, using standard optical metallographic sample analysis methods (4). The stem supplier needed to change vendors for their cutting fluid and due to the high reliability required for the stems, a series of test welds were prepared. Using the established nominal weld conditions, this study indicated that the stems would weld acceptably (5,6). The stems are also inspected using a borescope, the borescope leaves shallow scratch like linear indications in the tube, these periodically seem to have a "visual" depth and are subsequently rejected. While the presence of an actual scratch may result in an undesirable stress riser and be a valid cause for rejection; there was an interest in determining if measurably deep scratches would cause welds to leak. Scratches with depths of 25 µm were created and successfully welded. The deep scratch was evident in the flow lines of the weld, but it had been completely filled with metal and held the requisite pressure. This scratch was significantly worse than what is observed in production and shows the robustness of the process (7). Occasionally, the stem supplier observes surface related defects or debris in the stems. This debris is unacceptable so a rework procedure to remove it entails running a rotating stainless-steel brush through the ID. The effect of this treatment on the weld quality was shown to be somewhat detrimental to the weld interface with the deposits being observed at the weld interface, but the welds held the minimum required pressure (8). The weld atmosphere has also been investigated by flowing either air or nitrogen at 15 psig through the tubes during welding. The concern was that the air in the tube would be sufficient to cause the weld interface to form visible oxides upon inspection; there was an assumption that the level of oxidation between welding in an inert (N_2) environment vice the oxidizing environment could be the difference between continuous or discontinuous oxides. The difference between the atmospheres was not sufficient to be detected using optical microscopy (9).

All the efforts described above demonstrate that properly prepared stems, using the nominal conditions, and good practices for cleanliness lead to acceptable welds. Furthermore, the process is generally robust enough for the weld quality to be inferred as a function of the weld conditions (10). However, there can be challenges in the tube and process preparation steps. For instance, the preparation of the pinch weld electrodes can result in unacceptable electrodes being produced, such as those shown in Figure 2. These electrodes were not prepared per the drawing due to poor manufacturing processes; Fig 2a shows a pinch weld electrode (PWE) where there is a center hole; the center point is not permissible per the drawing. Figure 2 b shows an incorrect braze alloy being used; the vendor selected a “better” braze without consulting the customer. Fig. 2c shows improper cleaning prior to brazing with associated braze skips. Fig. 2d shows a properly prepared PWE after torsion testing indicating that the PWE can accommodate much shear. Due to the failures in manufacturing, a new method of preparing PWE was sought that requires fewer steps than those required for the conventional PWE fabrication. A comparison of the approaches is shown in Fig. 3. Savannah River National Laboratory teamed with the Kansas City National Security Campus to evaluate the use of back casting for PWE fabrication. This project was intended simply to evaluate the functionality of the PWE using the nominal welding conditions used for Type 304L SS and metallographic sample analysis. As the task unfolded, damage to the PWE was detected. This paper describes how the PWE were evaluated and additional steps taken to validate why the back cast PWE (BCPWE) had inferior performance.

Approach

A series of test welds were prepared using voltages from 300 to 400V and forces from 1100 to 1300 lbs. The welds were made on standard Type 304L and 316L SS; typical weld microstructures at the range of currents for the three different electrode types, Short W BCPWE, Long W BCPWE, and CPWE, are shown in Figure 4. As the welds were prepared, there was no indication that anything untoward was occurring. However, when the electrodes were removed so conventional PWE could be tested, it was observed that the PWE were deformed and that there were apparent slip bands on the bore of the PWE. Subsequent testing indicated that the PWE actually deformed during the first weld cycle but did not sufficiently change dimensions to cause weld failures, or indications of weld failures.

The BCPWE were macroetched, sectioned and examined metallographically and compared to conventionally fabricated PWE. Based on the metallurgical and pinch weld testing, compression testing of the PWE was undertaken as well.

Results

Macrographs of the BCPWE blanks are shown in Figure 5. The blanks are cylinders, approximately 80 mm long and 30 mm in diameter. There are two lengths of tungsten inserts, a short 12 mm and a 50 mm. The 12 mm W is consistent with conventionally produced PWE (CPWE) and is the primary subject of this study. The X-rays, Figure 5e & f, indicate the different lengths of the W inserts. In the as machined condition, it is challenging to see the differences between the short W BCPWE and CPWE. A close examination of the W to Cu interface will show the thin braze line, whereas the long W electrodes are obviously different. One reason to avoid the long electrodes was to avoid introduction of change in appearance.

The post weld condition of a single BCPWE is shown in Figure 6. The BCPWE exhibit deformation bands on the reduced section of the barrel, some obvious bending, cracking, and some increase in diameter (barreling). Higher magnification images are shown in Figure 7. A subsequent test indicated that the damage occurred during the first load cycle, which is logical if the compressive yield strength of the material has been exceeded. It was only due to processing multiple welds without inspection that suggested that the BCPWE life was greater than 1.

One failed PWE was sectioned axially, mounted, polished, etched and examined. Contrary to expectation, no grains or other features were observed, except a single grain boundary, as shown in Figure 8a. The wrought microstructure of the CPWE is also shown, Figures 8b and 8C, for comparison. The lack of evident structure was confusing since the expectation was to find multiple grains. Consequently, the BC blanks were macro etched. After this treatment, it was noted that the BC blanks were directionally solidified and had few grains; an unexpected result, shown in Figure 9.

A comparison of the compression properties of the BCPWE and CPWE was conducted using an MTS Criterion screw driven uniaxial test machine. The samples were supported vertically between the compression platens and a compressive load was applied while monitoring in the crosshead displacement and the load. The various diameters of interest were measured and compressive yield values were determined. The configuration of a sample being tested is shown in Figure 10.

The load-displacement curves for selected short W BCPWE, long W BCPWE, and two different vintages of CPWE are shown in Figure 11. It is interesting to note the different properties within the short W BCPWE. There are different load-displacement behaviors for the materials. It is interesting to note that there were no significant differences in the starting dimensions of the samples. The diameter changes for each sample are listed in Table 1 along with the nominal load at deformation, which is also reported as a yield strength. The yield strength is based on the diameter that exhibited deformation at the end of the test. For instance, the BC PWE with short tungsten deformed at diameter “A” while the CPWE and BCPWE with long W at diameter “C”; the locations of “A”, “B”, and “C” are indicated in Figure 12. The yield strength of several conventional wrought alloys are presented for comparison. The comparison reveals that the BCPWE are weaker than all but fully annealed copper.

Conclusions

The BC PWE failed due to inadequate strength. The BCPWE were prepared in such a manner as to produce a directionally solidified structure. The strength of the copper substrate needs to be considered when preparing PWE.

The minimum yield strength of pinch weld electrodes to avoid yielding at the typical maximum load of 7562 N, is 106 N/mm^2. Prudent engineering suggests that the actual yield strength be at least 1.5* YS, so 150 N/mm^2 is suggested.

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Curzio**, * Westinghouse Savannah River Company, Aiken, SC., **Oak Ridge National Laboratory, Oak Ridge TN, "6th International Conference on Trends in Welding Research * 15-19, April 2002 *Callaway Gardens Resort, Pine Mountain, Georgia USA", ASM International

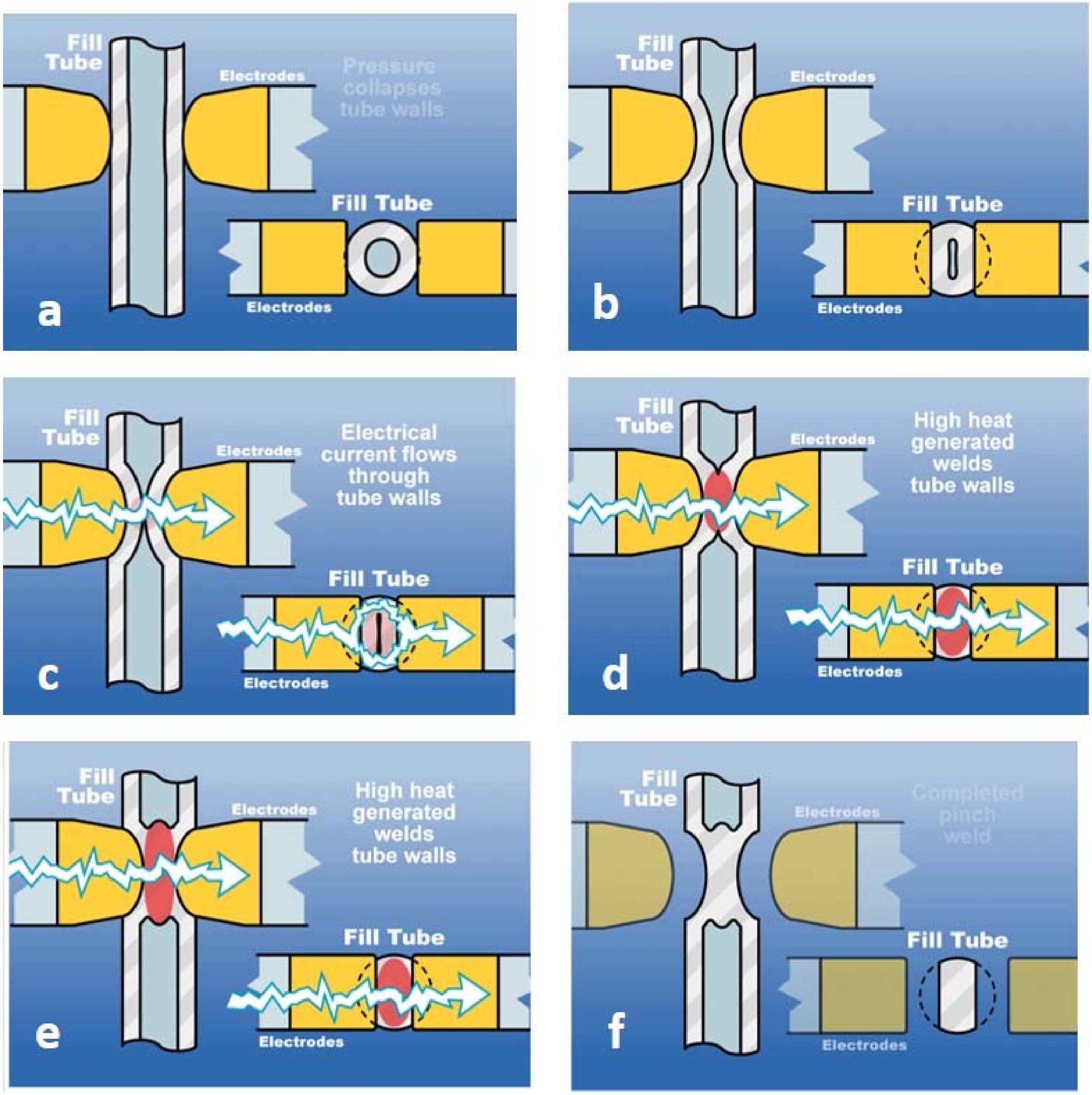

Figure 1. Schematic of the welding process showing the tubing and process evolution, a) tube is placed in the fixturing, b) force is applied to crush the tubing, c) current is initiated to heat the tubing while the force continues to crush the tube, d) faying surfaces heat and diffusion bonding occurs across the interface, e) additional deformation causes extrusion and additional diffusion and grain growth, f) electrodes are retracted.

Fig 2a.

Fig. 2b

Fig. 2c.

Fig. 2d

Figure 2. Condition of electrodes that failed quality inspection a) PWE after torque testing, one sample failed, b) close-up of failed brazed sample after torque testing with failure at the braze joint, c) close-up of failed brazed sample after torque testing with failure at the braze joint and into the W insert d) samples that failed the die penetrant non-destructive test.

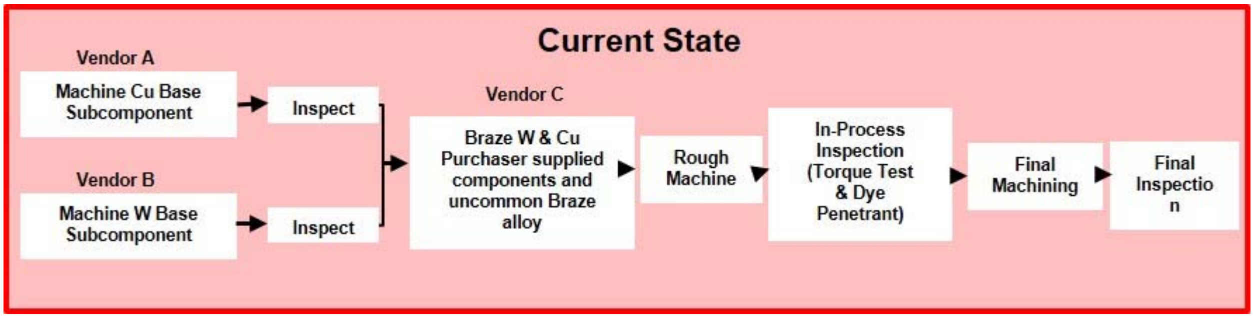

Fig. 3a.

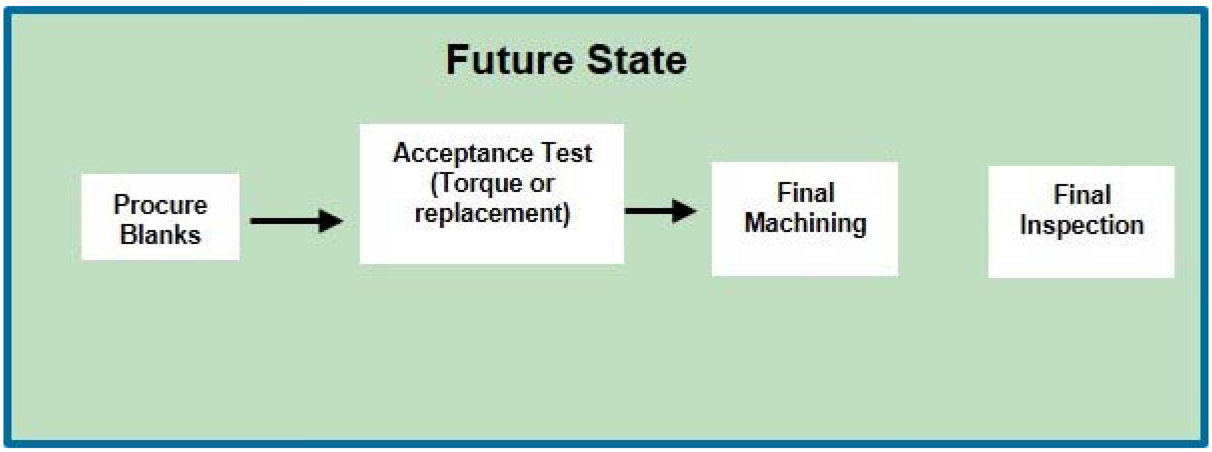

Fig. 3b.

Figure 3. Comparison of the a) current PWE processing state vice b) the proposed processing state.

PWE Microstructure Comparison 1250 lbs, 300V (~3000A), 12 cycles

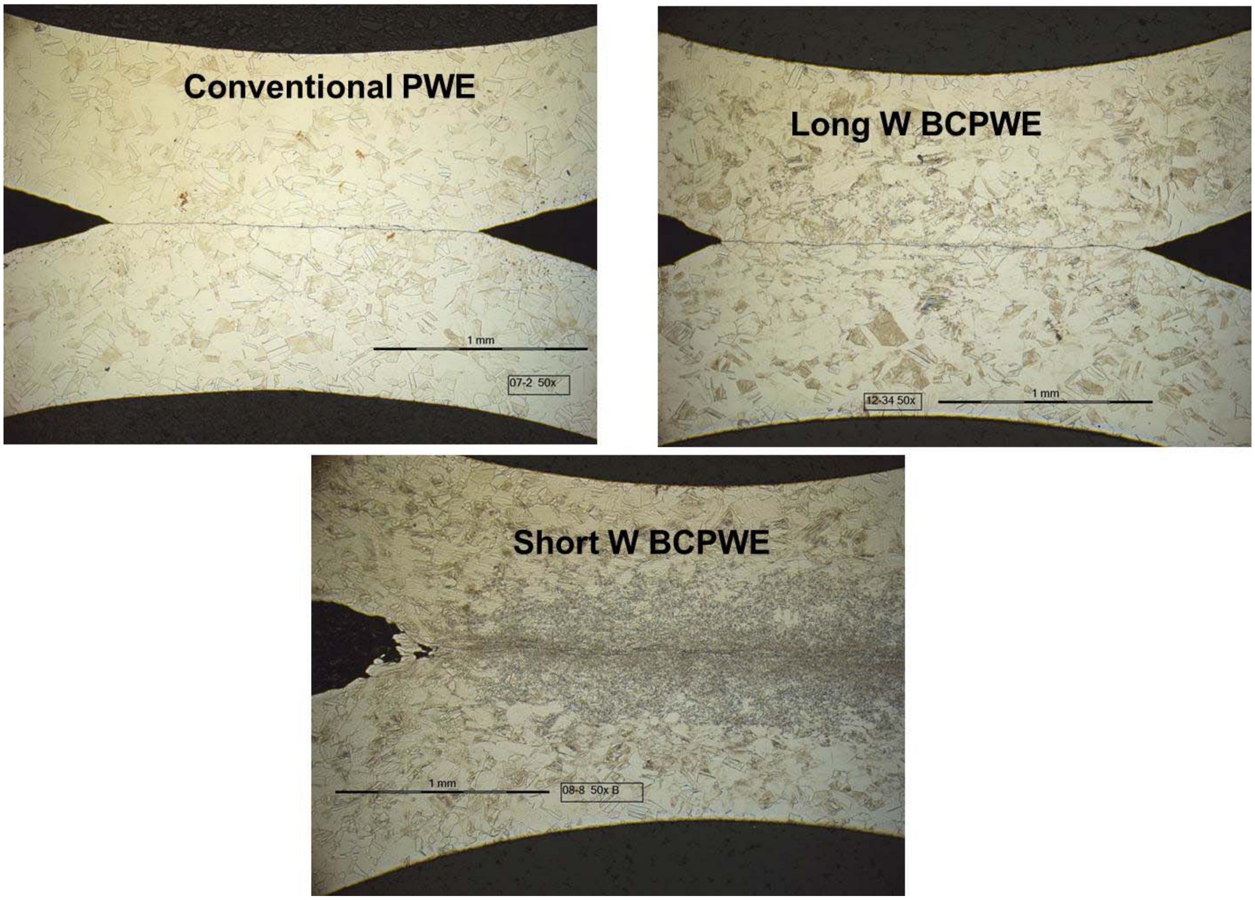

Fig. 4a.

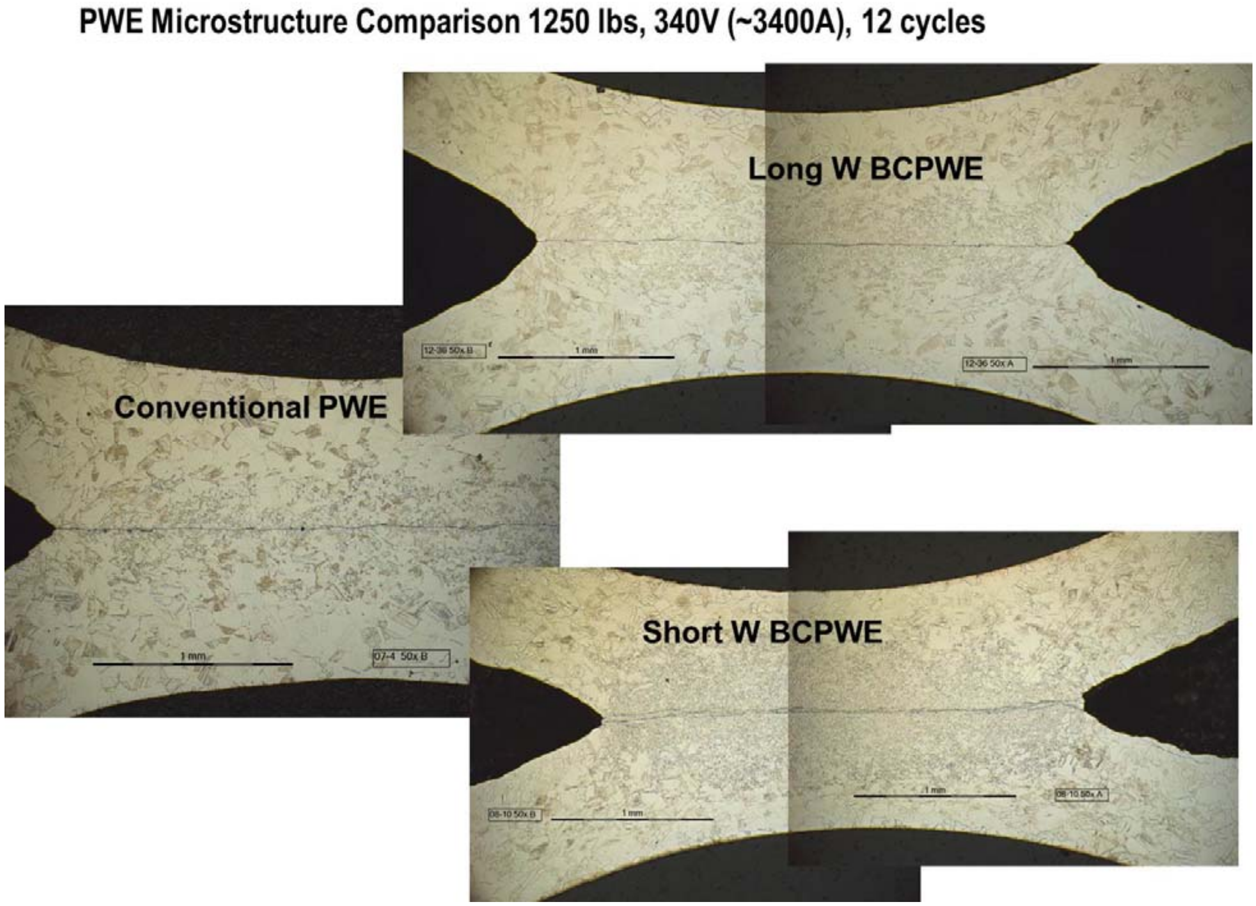
PWE Microstructure Comparison 1250 lbs, 340V (~3400A), 12 cycles
Long W BCPWE
Conventional PWE
Short W BCPWE
12-36 50x B
1 mm
12-36 50x A
07-4 50x B
08-10 50x B
08-10 50x A

Fig. 4b.

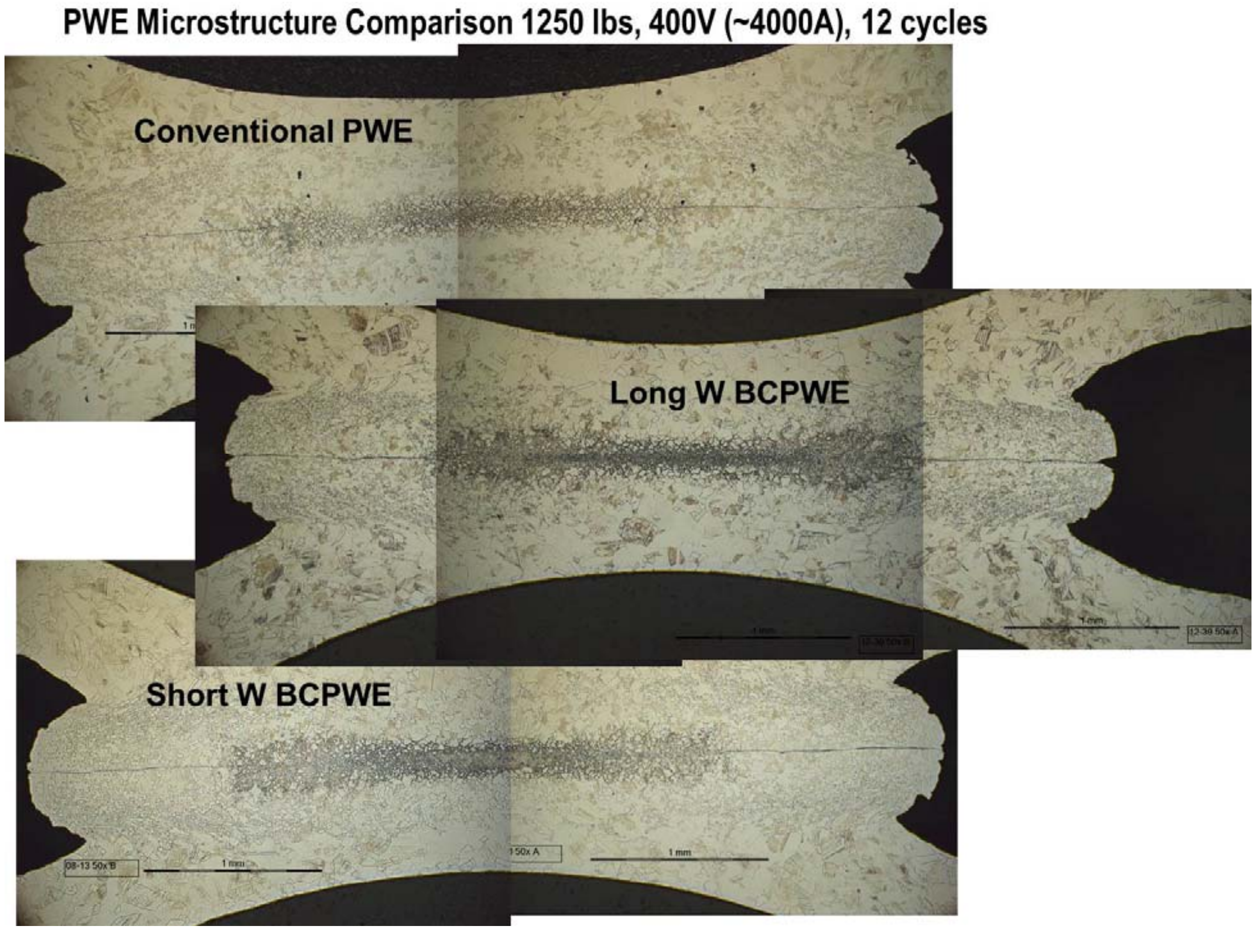

Fig. 4c

Figure 4. Typical pinch welds a) cold ~ 300V b) nominal ~340 V and c) hot welding ~400V at all 1250 lbs force.

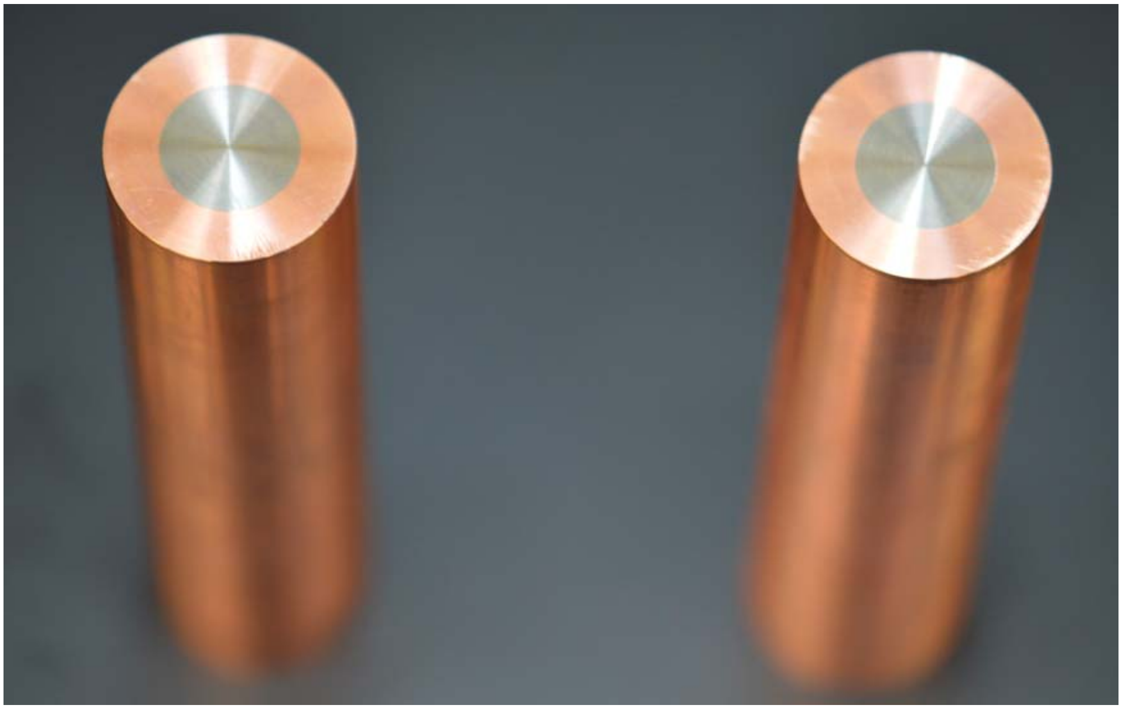

Fig. 5a.

Fig. 5b

Fig. 5c.

Fig. 5d.

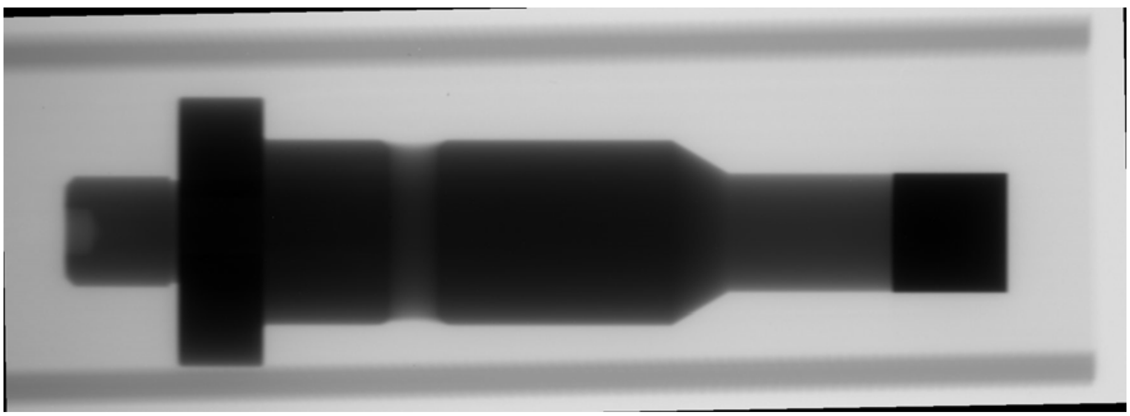

Fig. 5e

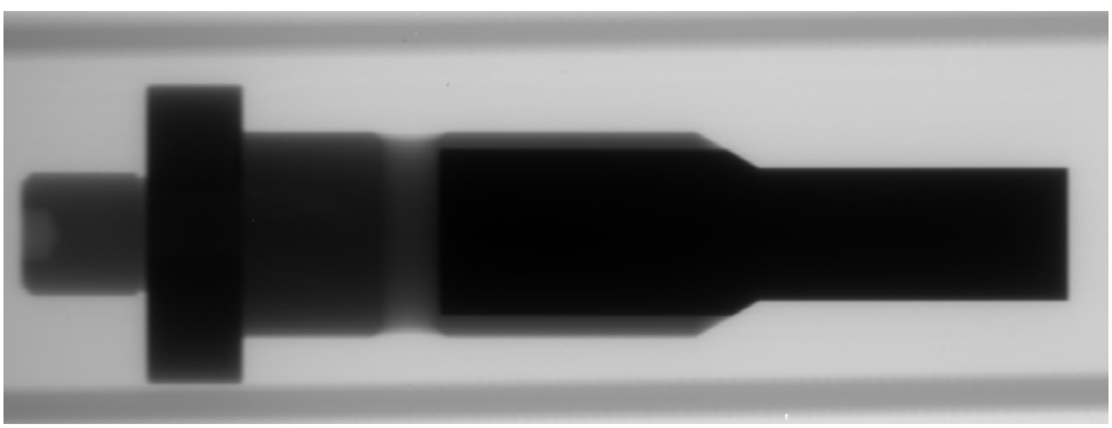

Fig. 5f.

Figure 5. Photo of the a) Back cast slug b) conventional PWE c) machined electrodes BC short W d) BC long W, e) radiograph showing short W and f) long W machined PWE.

Figure 6. Damaged BCPWE after making about 50 pinch welds, note the apparent axial crack in the reduced section and the bending of the PWE.

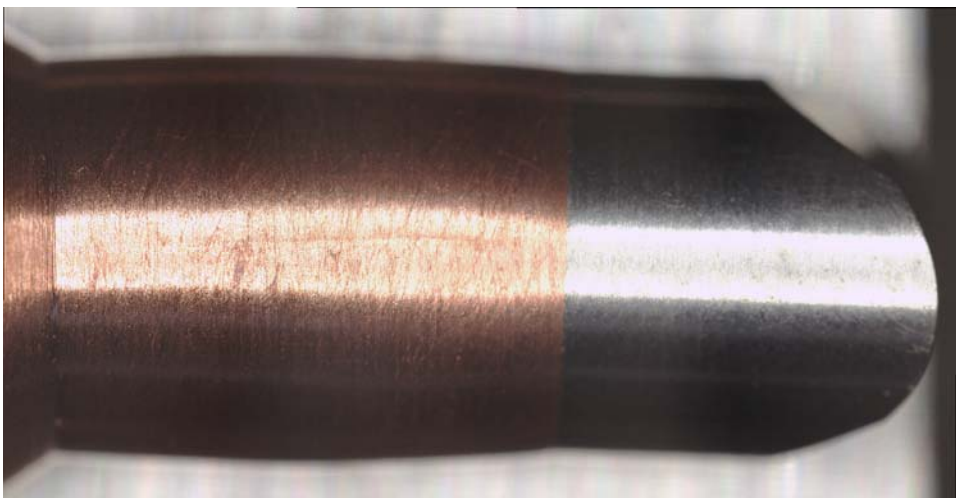

Fig. 7a.

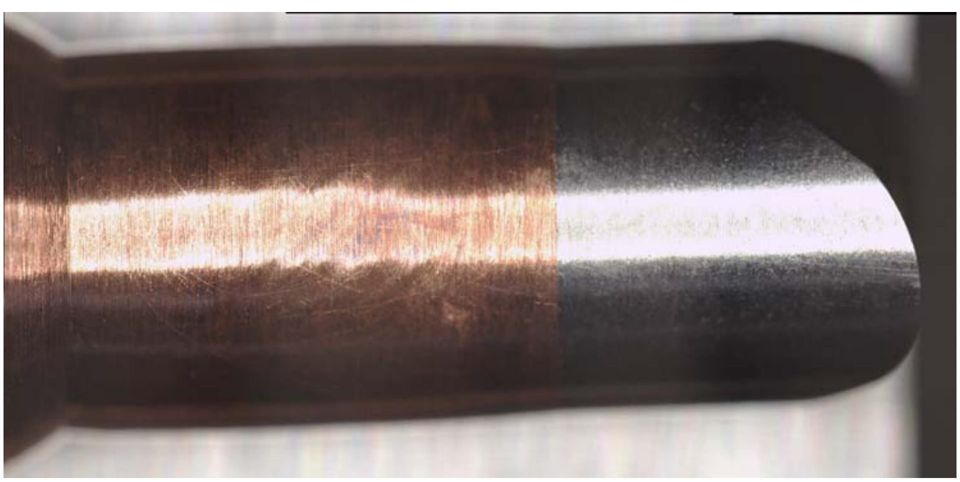

Fig. 7b.

Figure 7. Higher magnification images of damaged BCPWEs a) showing the barreling in the reduced section and b) apparent deformation slip lines.

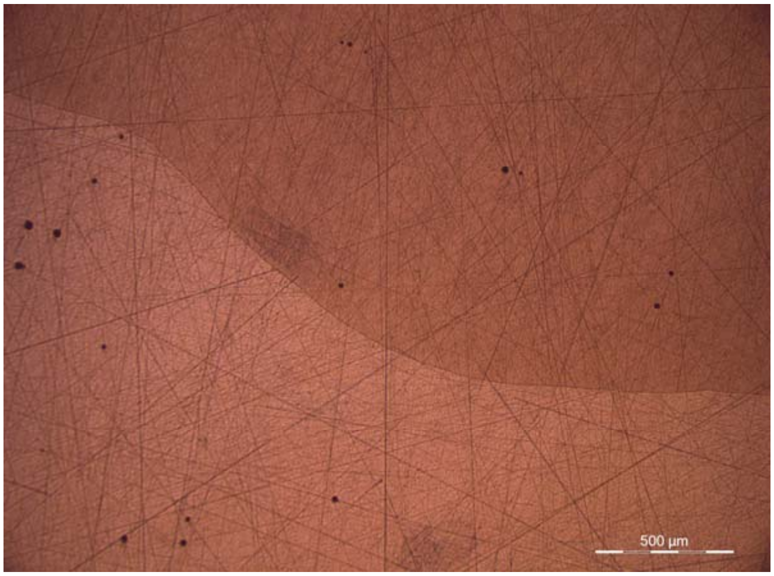

Fig. 8a.

Fig. 8b.

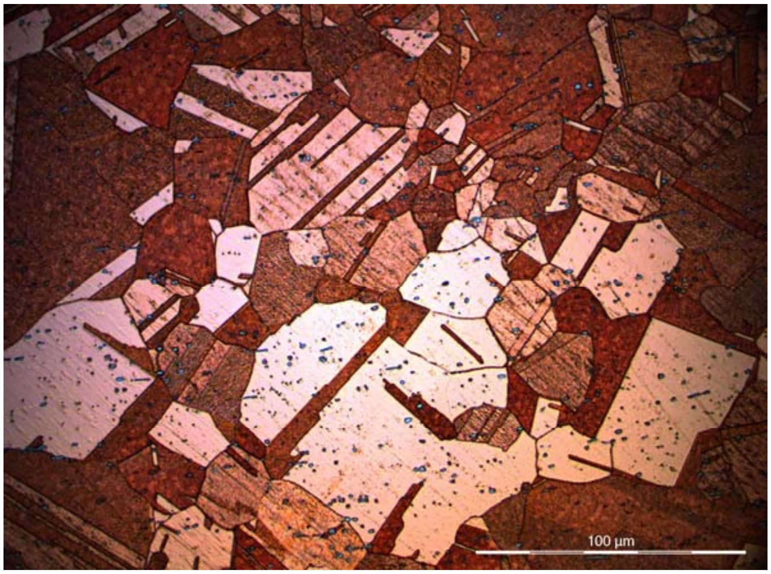

Fig. 8c.

Figure 8. Metallographic cross sections of BCPWE and CPWE, a) BCPWE showing a single grain boundary, b) CPWE showing fine grains at low magnification and c) same view as “b” but at higher magnification.

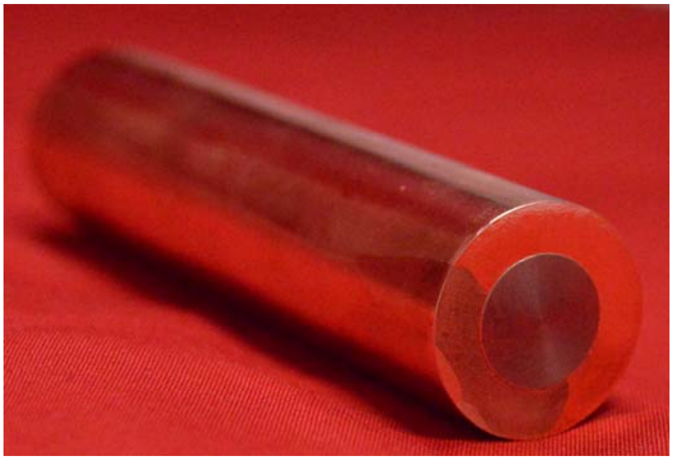

Fig. 9a

Fig. 9b.

Figure 9. Macroetched BC slug showing a) the W insert and three grains and b) the opposite side showing two to three grains.

Figure 10. Fixtures showing the compression testing of a BCPWE.

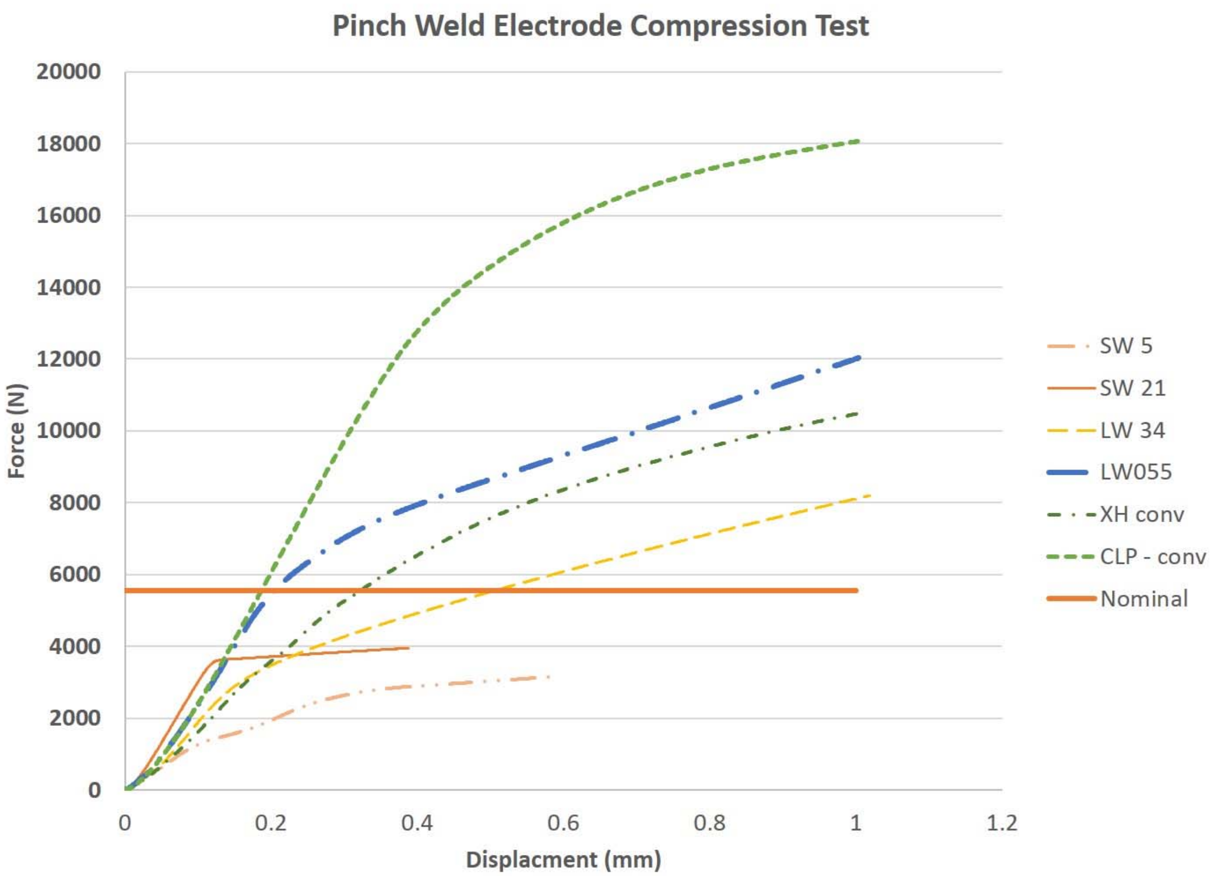

Figure 11. Compression results for a typical PWE in the BCPWE SW, BCPWE LW, and CPWE.

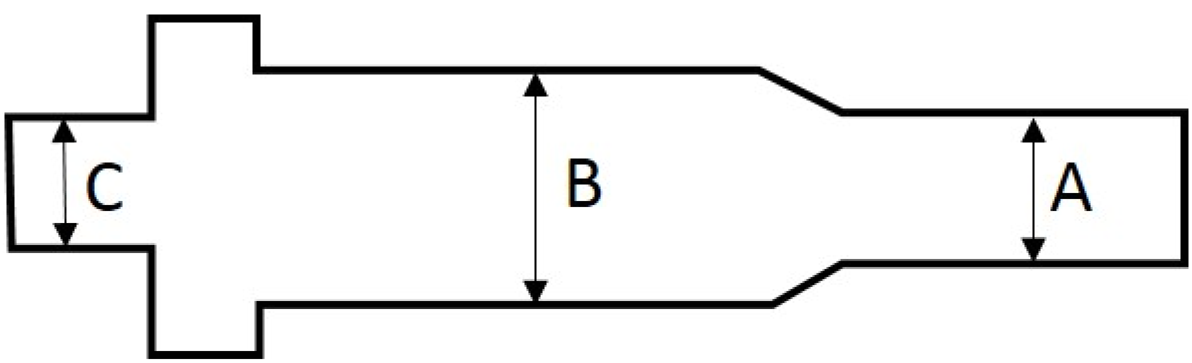

Figure 12. Location of diameter measurements for Table 1.

Table 1. Dimensions (mm) of critical diameters, before and after ‘ (Fig. 12), for the PWE as shown in Fig. 11 with yield load (N) and strengths shown.

Sample	Type	A	B	C	A'	B'	C'	Py	YS
005	PBC SW	10.1	15.7		10.4	15.7		1540	19.3
021	PBC SW	10.1	15.7		10.6	15.7		3660	45.7
043	PBD LW	10.0	15.7	9.5	10.1	15.7	9.8	3520	45.1
034	PBC LW	10.1	15.7	9.5	10.1	15.7	9.8	3713	46.4
055	PBC LW	NA	NA	NA	NA	NA	NA	6450	NA
008 XH	CPWE	10.1	15.7	9.5	10.2	15.7	9.6	6300	78.1
CLP	CPWE	10.1	15.7	9.5	10.3	15.7	9.5	13570	169.1