The PARACAP™ - Longer Electrode Life from a New Geometry, an Innovative Multilayer Coating, and Internal Cooling Fins

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Abstract

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Use of a patented parabolic-shaped electrode (ParaCap™), with a patented nano-ceramic, multi-layer coating (TriCoat™) incorporating internal cooling fins offered longer life and reduced sticking over a comparable, industry-standard, uncoated dome style electrode on zinc coated high strength steels. Electrode tip reconditioning or dressing was performed both on the full face of the electrode as well as only on the side profile of the electrode without touching the weld surface.

A factorial design matrix was constructed and carried out to test the design factors of surface coating, electrode geometry, internal cooling fins, and electrode dressing method. Results of the testing in both laboratory and production environments showed the coated ParaCap™ electrode with cooling fins and side dressing application far outlasted the conventional uncoated domed electrode with full dressing.

Testing methodology was performed using the American Welding Society (AWS) life testing standards on hot dipped galvanized high strength steel with and without a multi-layer Ni/(TiC_P/Ni)/Ni coating on a copper chrome zirconium alloy. The coating itself was characterized by electro-microscopy, energy-dispersive X-ray analysis.

Welding tests showed that the multi-layer Ni/(TiC_P/Ni)/Ni coating acted as a good barrier to decrease alloying between the copper alloy and molten Zn as well as reducing the pitting (or erosion) of the electrode. In addition, the ParaCap™ was found to degrade in a predictable manner, allowing for regular and consistent current stepping. Sticking during the initial phase of the electrode life was reduced and removed any need for electrode conditioning on start-up.

Introduction

Over the last 10 years, research [1-6, 18], and use by major automakers, has shown that titanium carbide coated electrodes lengthen electrode life and reduce sticking. In addition, research and the use in production of internal fins in electrodes have shown improved cooling and longer life. When these attributes were combined with a new multi-layer coating and parabolic geometry, further improvements in life were noted in field testing. This paper is an attempt to validate and measure those improvements.

A series of tests were designed to measure the interaction of parabolic geometry, cooling fins, side dressing and the multilayer coatings in a factorial test performed at the University of Waterloo. These tests were designed and reviewed by the noted metallurgist, John Slaney of Pittsburgh, PA. In addition, life testing was carried using coated ParaCaps™ that were side dressed and uncoated dome style caps, which were conventionally dressed, at the facilities of Allweld Technologies in Chatham, Ont.

A new electrode design developed by Huys Industries is aimed at reducing the degree of ‘mushrooming’ of the electrode similar in character to the domed style nose, while maintaining the longer electrode life enjoyed by the truncated style of electrode. The new parabolic profiled ParaCap™ from Huys is also coupled with a new cooling channel design which utilizes internal “fins” to maximize the heat transfer between the cooling water and the electrode material, enhancing the resistance to softening and deformation. To further boost the performance of the electrode cap, Huys is able to coat the new cap with its newly patented multilayer (TriCoat™) electrode coating for welding of zinc coated steels and aluminum. The multilayer coating enhances the weldability of the electrode for coated steels and can more than double the tip life.

Designing the Next Generation Resistance Welding Electrode

The emergence and adoption of new steels with very complex microstructures and high strengths, and the increased worldwide use of zinc and organic coatings on steels, and combined with the increased demand for lower costs and higher production rates in automotive manufacturing, have created a need for longer lasting electrodes.

In response to these challenges, Huys has developed a new electrode with a number of improvements incorporating a number of new characteristics.

Electrode Geometry

In a study done by the University of Waterloo and General Motors, the effect of various electrode geometries (Figure 1) on the weldability of DP800 steel was shown [7]. This work outlined the subtle differences inherent in each electrode shape leading to varying nugget shapes and sizes seen in Figure 2 as well as changes to the weld lobe for weld current and time of the same steel. Results showed the shape of the electrode cap had influence not only the physical wear and erosion of the electrode, but also the heat flow and resultant weld nugget size and shape produced. It follows then that there should be a design of electrode geometry that will optimize both the wear of the electrode as well as quality of the welds produced.

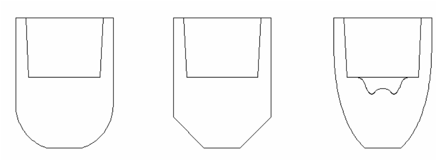
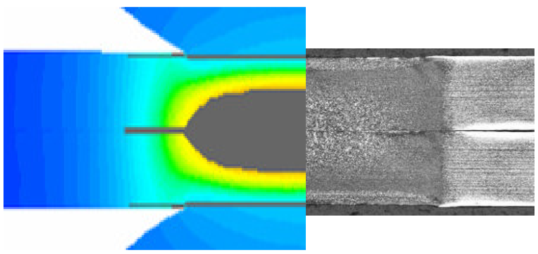
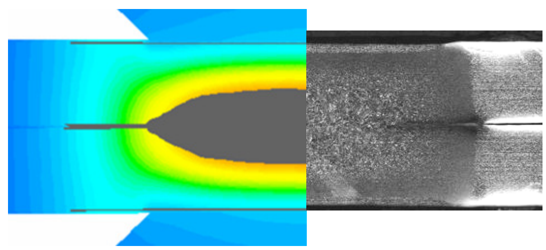


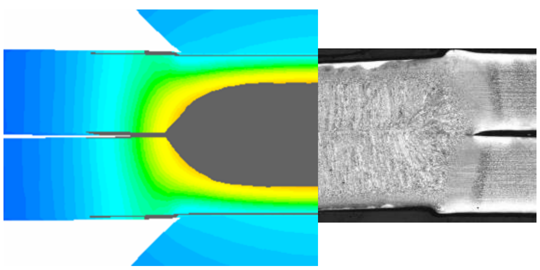
Fig 1: A typical dome (FB), a truncated (FE) and a parabolic (ParaCap™) style electrode



a) FB-25 6.0 mm 6.5 mm nugget



b) FE-25 6.0 mm 6.5 mm nugget



c) ParaCap™ 6.0 mm 6.5 mm nugget

Fig 2: Sorpas®[17] simulations and matching micrographs of welds achieved with different geometries using similar welding schedules. [7]

The domed electrodes are known to resist the tendency for gross surface deformation or mushrooming rather well; however the shape of the tip yields a large increase in weld surface area for a small decrease in electrode length [8-10]. The truncated cone electrode, with its sharp geometry, is much more prone to gross deformation; however, the weld face area increase due to length reduction is less, resulting in overall longer life. The new parabolic geometry incorporates benefits from both of these standard geometries and results in an electrode that is both able to withstand physical stresses and at the same time provide a consistent weld face, mitigating the effects of electrode wear.

Electrode Coating

The next generations of steel coatings for corrosion protection are incorporating organic compounds in addition to the zinc particles for cathodic protection. A metal matrix composite coated on the surface of the electrode is able to protect the electrode from the chemical attack of the zinc in the steel coating as well as change the thermal properties of the electrode enough to allow it to form good weld nuggets on these new coated steels [1]. The next generation of coated electrodes developed by Huys Industries incorporates a multilayered coating with improved surface smoothness and longevity.

Huys Industries has developed a new, patented, multilayered coating with improved surface smoothness, adhesion and longevity [2]. This welded coating is made up of an initial bonding coat of nickel, followed by proprietary coating of titanium carbide, followed by a finishing coat of a nickel. With increased surface uniformity, reduced porosity and discontinuities, the new coating outlasts and outperforms the first generation of titanium carbide coating.

Compared to the previous generation of coated electrodes, the new coating is more uniform across the surface of the electrode with fewer defects as seen in Figure 3.

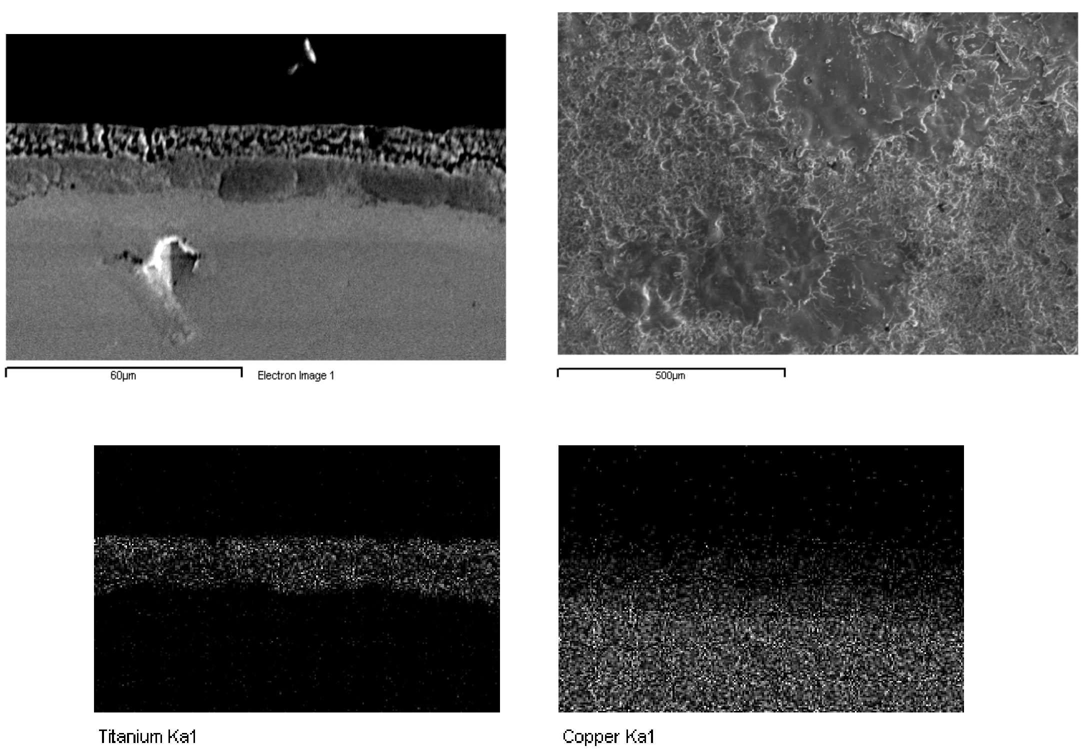


Fig 3: SEM surface and cross section of new multilayer coating (Tricoat™). EDS elemental mapping of Ti, Ni, and Cu are shown to exhibit coating thickness and consistency.

Electrode Cooling

The extraction of heat during the resistance welding process has also become a more complex problem with new steels and the related new coatings that require, and benefit from, multi-pulse welds as well as pre- and post-heating pulses [11]. Controlling the cooling rate of the weld metal can be critical in controlling the final microstructure of the weld. With the additional thermal load being put on the welding electrodes, the need for improved cooling has been addressed with the development of internal cooling channels or 'fins' to increase surface area and total heat flux.

As Hirsch, Masters and Yeung note [12-14], improvement in water cooling temperature and flow can improve electrode life and help maintain weld quality and consistency during the rapid temperature increase at the electrode's weld face during welding. Unpublished automotive research, previous finned electrodes available in the 1970's and recent tests have illustrated the advantages of internal fins to assist in the rapid dissipation of heat.

However, the cost of cold-forming, inserting, or machining internal fins has to be offset against the concomitant saving in longer electrode life. For this study, small, inexpensive, 'cruciform' fins were chosen to be evaluated, as they are the easiest and cheapest to manufacture. Figure 4 shows samples of fins currently available, from least expensive to the more expensive.

Fig 4: Internal fins, 'cruciform' at left to deep and deeper 'cathedral roof' designs, right.

Electrode Tip Dressing

Redressing or machining of the electrode cap after some use is a widely accepted method of prolonging electrode life and ensuring weld quality and size. This practice has been used in industry all over the world and functions by returning the electrode face to the original design specification where the current density is high, generating enough heat for a quality weld.

The benefits of using a coated cap have previously restricted the use of electrode tip dressing as any machining of the surface of the coated electrode would remove the coating itself. With developments in the electrode coating process and electrode tip dressing techniques, a special 'weld face only' coating has been introduced which can be dressed, returning the electrode face to its original size and geometric profile, without damaging the coating on the electrode. Figure 5 shows an example of this coating and dressing blade used.

Chatterjee et al. [15] has shown that variations of dressing only the side of the electrode profile can improve weld quality by leaving the Cu-Zn alloy layers on the surface of the electrodes intact. These layers are formed during the early stages of welding on a bare electrode and eventually allow the electrode to reach a 'steady-state' of welding as the brass layers form and become lost to the sheet. When these layers are removed by traditional full dressing operations, the electrode must once again 'reform' them requiring additional 'break-in' periods after dressing, thus affecting weld quality and consistency.

Fig 5:, A parabolic male cap and a side dressing blade.,

Experimental Design

Laboratory Testing

To study the effectiveness of each of the new features described above, a factorial experiment was designed to evaluate the contributions from, and interactions between, design changes from geometry, coating, cooling and tip dressing. The variables for each of the factors are listed in Table 1.

Table 1: Electrode Design Factors and Variables

Design Factor	+	-
Surface Coating	TriCoat™	Uncoated
Electrode Geometry	Domed, 8mm radius	Parabolic
Internal Cooling	Finned	Unfinned
Tip Dressing	Side Dressing	Full Face Dressing

Because there were 4 factors to be investigated, a factorial experiment was chosen to be used for the investigation. A full factorial design for 4 factors at 2 levels would call for 2 to the 4^{th} power, or 16 test runs, which would measure all possible interactions. Clearly, this would be unnecessary and wasteful of resources. In such a circumstances, fractionating twice would reduce the testing regimen to a 2 to the (4-1) power = 2 to the 3rd power, or 8 runs. This design provides 8 test runs. Such an approach would provide:

- Estimates of the mean of the experiment
- Estimates of the effect of each of the 4 factors, clear of effective interactions, and
- Estimates of 3 pairs of 2-factor interactions

Further fractionating would only provide 4 runs which would not be sufficient to estimate the mean and the 4 effects.

The chosen design yielded the experimental matrix given in Table 2 below. The electrodes for each of the runs were manufactured at Huys Industries and tested at the University of Waterloo. Test runs were performed in a random order for three replications and consisted of 250 welds with a new set of electrodes at which point the electrodes were dressed with their respective dressing operation. Welding then continued for another 250 welds. This concluded the initial test run, and further study was done on select electrodes by repeating the dressing operation and welding for another 500 welds, while monitoring the button size and tip growth. Electrode weld face diameter and peel button size was recorded every 50 welds. Electrode length was recorded at the beginning and end of the test as well as before and after tip dressing.

Table 2: Factorial Design Testing Matrix

Design Run	Surface	Geometry	Cooling	Dressing
1	Uncoated	Parabolic	Unfinned	Full
2	TriCoat™	Parabolic	Unfinned	Side Only
3	Uncoated	Domed	Unfinned	Side Only
4	TriCoat™	Domed	Unfinned	Full
5	Uncoated	Parabolic	Finned	Side Only
6	TriCoat™	Parabolic	Finned	Full
7	Uncoated	Domed	Finned	Full
8	TriCoat™	Domed	Finned	Side Only

Welding at the University of Waterloo was performed on an AC single phase 250kVA pedestal welder with constant current control and 76% power factor. All welds were made on 0.7mm HDG 60G HSLA 350. The steel is typical of the type used in North American automotive applications, and has a heavy and relatively uneven zinc coating which is known to be the worst for electrode life. Weld schedules for laboratory testing are given in Table 3. The weld current was the only parameter that required a change from the coated to the uncoated electrodes. This was due to the coating and was explored in previous works [1-4]

Table 3: Laboratory Testing Weld Schedules for Coated and Uncoated Electrodes with 4.8mm weld face

	Weld Current	Weld Time	Weld Force
	(A)	(cycles)	(lbf)
Uncoated	9200	11	445
Coated	8500	11	445

Electrodes dimensions were the RWMA industry standard for North American use, being .625” (16 mm) in diameter, with a .190” (5 mm) weld face for both the ParaCap™ and the domed FB25. All electrodes were machined from the same bar of copper chromium zirconium (CCZ). Figure 6 shows samples of the caps used in testing.

Fig 6: Images of caps to be used in testing. ParaCaps™ at left, domed at right.

Life Testing

Based upon the results of the factorial design test, two virgin sets of electrodes were selected for life testing without dressing. This was performed to evaluate the performance of the electrode designs, as selected by the DOE test, in a single run weld life test without electrode dressing. The best forming design features (coated ParaCap™ with cooling fins) were tested against the poorest performing (uncoated domed electrode without cooling fins). Electrode weld face diameter was tracked as well as peeled button size until the failure of the electrodes.

Production Testing

Production electrode life testing of uncoated, standard, CCZ, FB25 6 mm weld face domed electrodes and 6mm weld face multilayer-coated ParaCaps™ with stamped cruciform internal fins was performed at Allweld Technologies Inc., Chatham, Ont., using a standard Huys 120 kVA pedestal welder with WTC Technitron S24 weld controller. Secondary current was monitored with a Weldscope WS20 coil on the lower weld arm. The electrodes selected for testing were of similar design to the life tests run in the laboratory except for the weld face diameter of 6mm to accommodate the thicker gauge steel being used here. The test was run with dressing operations to test the ultimate electrode life in a production environment. All domed electrodes were fully dressed, while ParaCap™ electrodes were only side-dressed. This was done to mimic the current state of industrial production versus the new electrode design and dressing technique. Figure 7 shows the electrodes selected for ultimate life testing in their unused state.

Fig 7: Left, Prepared uncoated 6mm CCZ FB25 domes. Right, 6mm weldface ParaCaps™ with small cruciform fins

Due to the frequent inaccuracy in production weld cell automatic tip dressers, both in terms of the amount of material removed, and in the accuracy and consistency of the new weld face machined, electrodes were removed and carefully machined on a Hardinge Cobra 42 CNC lathe, removing between 0.125 to 0.250mm per dressing operation. When reinstalled, they were oriented and placed in their original position.

A series of three tests were performed. These tests were designed to evaluate when dressing was required, what interval between dressings was required, and what the final weld count would be before failure. All welds were made on 1.2 mm HDG 60G HSLA 350 steel supplied by Dofasco. Weld schedules for all production tests are given in Table 4 below. Tests were performed in compliance with the AWS D8.9-97 [16] test standards. Coupons were peeled at 100 weld intervals, and dressings performed when weld buttons peeled dropped below 6mm.

Table 4: Production Testing Weld Schedules for Coated and Uncoated Electrodes with 6mm weld face

	Weld Current	Weld Time	Weld Force	Dress Type	Dressing Frequency
	(A)	(cycles)	(lbf)		
Uncoated	11500	13	900	Full	250 welds
Coated	10500	13	900	Side Only	varying

Results and Discussion

Laboratory Testing

The DOE experimental work was designed to test the possibility of using short welding tests of the order of 500 welds to predict the behaviour of welding electrodes. The factors to be tested were given in Table 1 above while measuring the tip growth and button size every 50 welds. Two sets of 8-run experiments measuring Tip Growth and Button Size were performed. The results of the experiments are given below in Table 5.

Table 5: Factorial Design Analysis Results Matrix

TIP GROWTH								
Design Factor		1	2	3	4	Interactions		
-	Experimental	Uncoated	ParaCap	Unfinned	Full Dress	1 with 2	1 with 3	2 with 3
+	Result	Coated	Domed	Finned	Side-Dress	+ 3with 4	+ 2 with 4	+ 1 with 4
Mean Tip Size Set 1	5.5675							
Mean Effects of Factors		-0.0400	-0.0800	-0.0550	0.0050	0.0750	-0.1400	-0.1200
Mean Tip Size Set 2	5.5775							
Mean Effects of Factors		-0.0150	-0.0650	-0.1150	-0.0850	-0.1250	-0.0250	-0.0850
Mean of Experimental Results	5.5725							
Standard Deviation of Mean Value	0.0071							
Mean Effect of Factors		**-0.0275**	**-0.0725**	**-0.0850**	**-0.0400**	**-0.0250**	**-0.0825**	**-0.1025**
Standard Deviation of Factors		0.0176	0.0106	0.0424	0.0636	0.1414	0.0813	0.0247
BUTTON SIZE								
Design Factor		1	2	3	4	Interactions		
-	Experimental	Uncoated	ParaCap	Unfinned	Full Dress	1 with 2	1 with 3	2 with 3
+	Result	Coated	Domed	Finned	Side-Dress	+ 3with 4	+ 2 with 4	+ 1 with 4
Mean Button Size Set 1	5.6475							
Mean Effects of Factors		-0.3100	-0.2050	-0.0100	-0.2950	-0.1200	0.0350	-0.1900
Mean Button Size Set 2	5.6500							
Mean Effects of Factors		-0.3350	-0.3600	0.0800	-0.5450	0.2050	-0.2150	-0.2900
Mean of Experimental Results	5.6488							
Standard Deviation of Mean Value	0.0077							
Mean Effect of Factors		**-0.3225**	**-0.2825**	**0.0350**	**-0.4200**	**0.0425**	**-0.0900**	**-0.2400**
Standard Deviation of Factors		0.0177	0.1325	0.0636	0.1768	0.2298	0.0813	0.0707

Important values from the analysis of the results are given as the mean effect of factors. The numerical values represent the change in either the tip growth or button size when moving from one setting of the factor to another. For example, for design factor 1 in tip growth, a move from uncoated to coated electrodes will yield a mean change in tip diameter of -0.0275mm. Below this number is displayed the standard deviation of the mean effect.

In the case of Tip Growth, the smaller the value the better as tip growth leads to a drop in current density and decreased weld size. A negative value for the mean effect then indicates that the (+) factor is the better of the two. A positive value for the mean effect indicates that the (-) is the superior of the two. An electrode which is *coated, domed in geometry, finned, and side-dressed* would yield the lowest rate of tip growth.

For the button size analysis, a negative value for the mean effect of the factor denotes that the button size has dropped when moving from the (-) value to the (+) of the factor indicating that the (-) is the preferred of the two for larger weld buttons. This suggests that an *uncoated, parabolic, finned and fully dressed* electrode would yield the largest weld buttons.

As the results of the DOE analysis were somewhat ambiguous indicating only that a finned electrode would perform better for both tip growth and weld button size, isolation of specific variables was performed for evaluation. For the surface coating factor, the coated electrode was indicated to give a lower tip growth rate, but slightly smaller buttons than the uncoated electrode. Figure 8 shows the average button size curves for all of the electrodes that were coated (regardless of the other factors) for Set 1 and Set 2 versus the uncoated electrodes in the matrix. The coated electrode button size is consistently smaller than that of the uncoated electrode; however, due to the thermal and electrical properties of the coating, the weld current was set much lower than that of the uncoated electrode to ensure the similar welding characteristics. The figure also shows the button size of the coated electrodes as slightly more consistent than the uncoated electrodes. This characteristic of the coated electrode would be better suited for a tip dressing application where consistent button size is valued over larger buttons at the expense of consistency. For this reason, the coated electrode was chosen as the improved option for life testing.

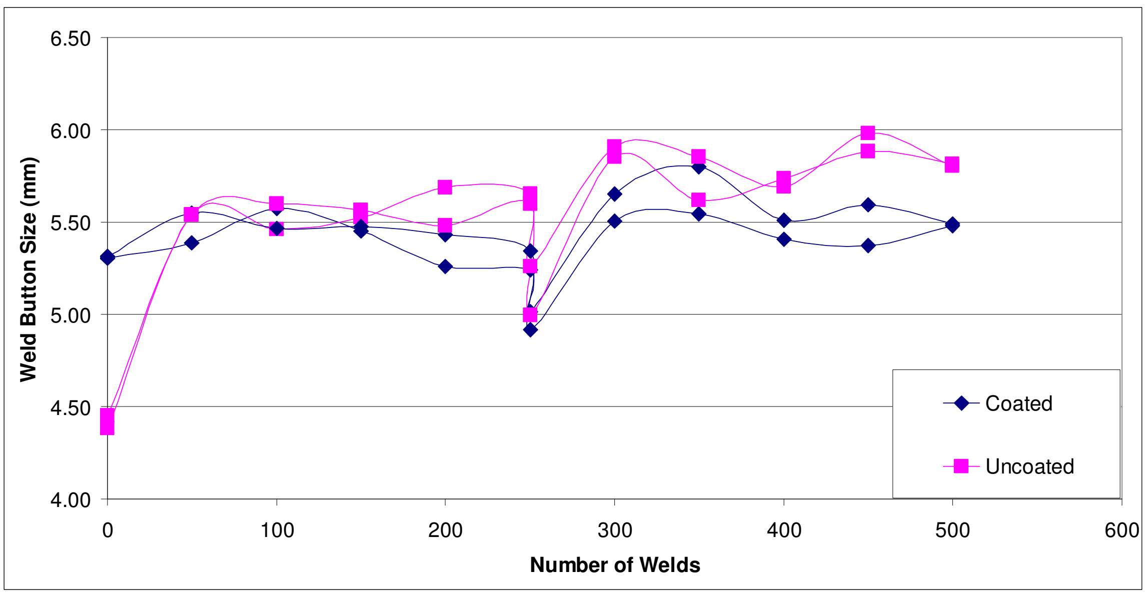


Fig 8: Weld peel button size vs. number of welds for uncoated and coated electrodes

For the geometry factor, the analysis has shown the domed electrode to be better for tip growth, yet the parabolic electrode for weld button size. Figure 9 shows the average tip growth charts for all of the parabolic ParaCap™ and the domed electrodes in the DOE testing matrix. Both electrode geometries have similar tip face growth rates and both are consistent and predictable. The ParaCap™ design is somewhat more susceptible to physical deformation, as it has less reinforcement close to the weld face, and therefore shows greater signs of mushrooming.

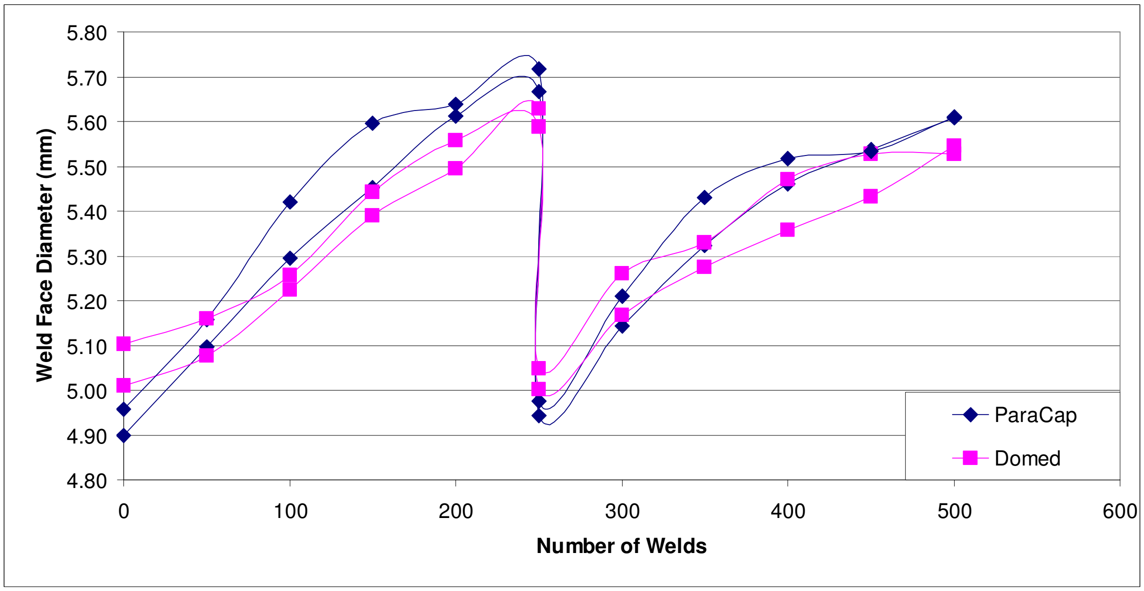


Fig 9: Tip growth for parabolic and domed electrodes

Comparing the weld button sizes for the two electrode geometries shown in Figure 10, the ParaCap™ is able to maintain a larger weld button with less fluctuation especially after the dressing operation at 250 welds. This consistency is preferred for electrode tip dressing operations to ensure weld quality between dressing operations. Tip dressing is also able to remove any mushrooming that has occurred and so the parabolic ParaCap™ geometry was chosen as the improved option for further testing.

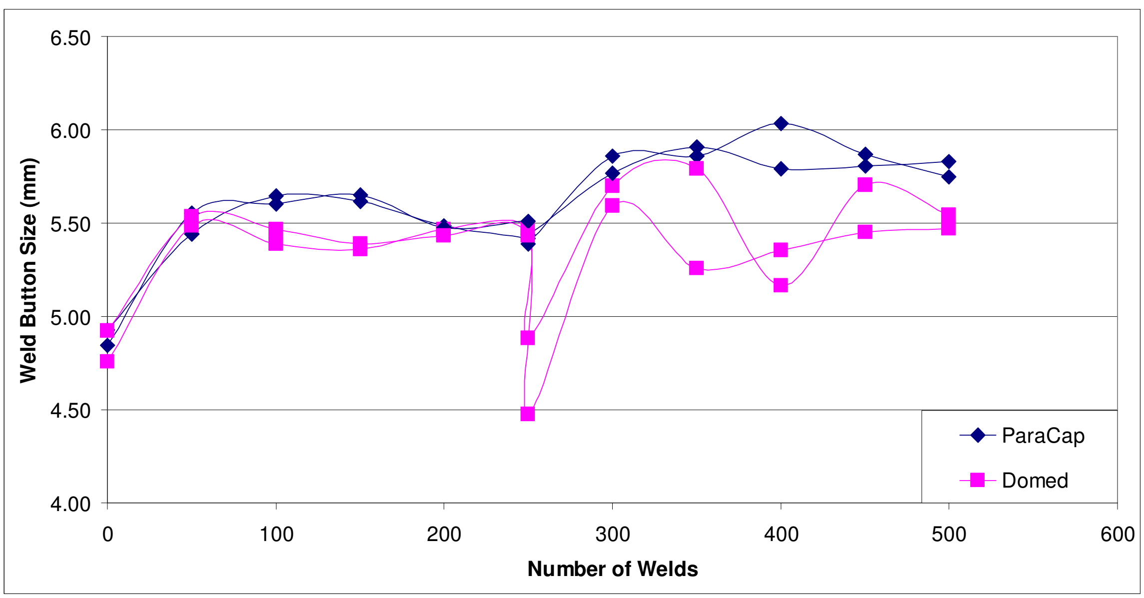


Fig 10: Weld button size for parabolic and domed electrodes

Electrode tip dressing the full geometric profile of the electrode is able to remove any alloy layers and zinc buildup on the surface, returning the electrode to a 'like-new' condition. This process, however, shortens the electrode with each operation and can cause a sudden drop in the weld button size as seen in Figure 11. As it is impractical to condition the electrodes after each dressing operation, weld systems and schedules must be robust enough to accept this weld size drop. The side-dressing operation does not remove any material from the weld face, and so does not change the interface properties once the electrode has developed alloy layers. Additionally, the side dressing process does not shorten the electrode by much, if at all, as only material around the periphery is removed to reshape the tip. As seen in the figure, the weld size increases after tip dressing due to the increase in current density. When using a coated electrode, side dressing can be employed as the surface is not damaged. For further testing, side-dressing will be used as the improved factor.

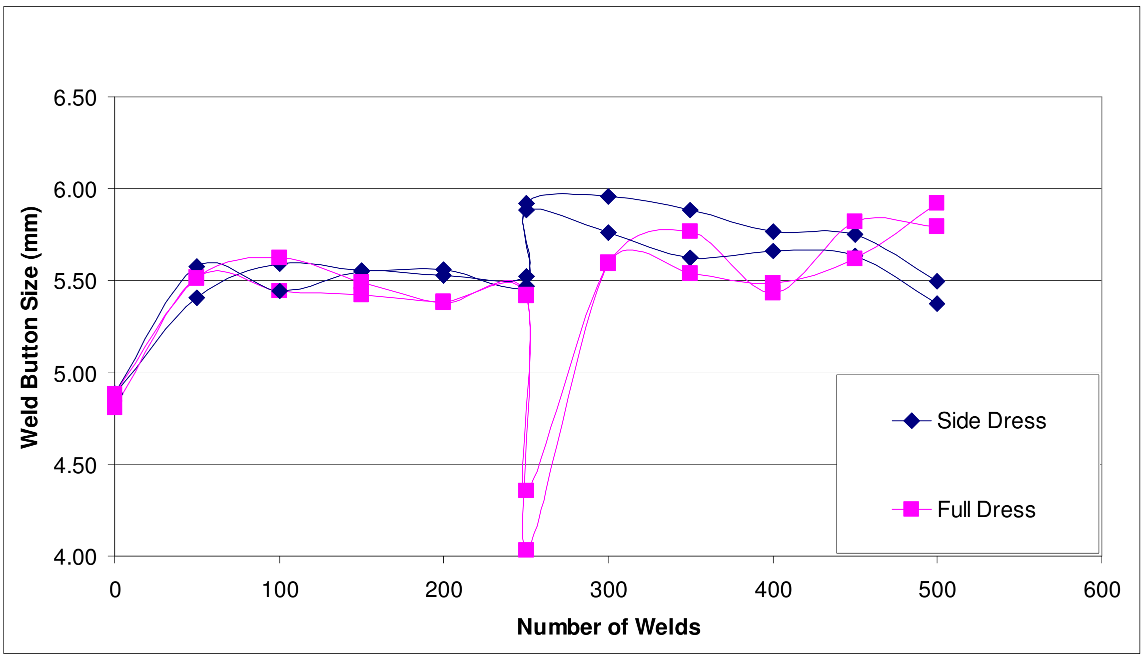


Fig 11: Weld button size increase after side dressing only compared to sudden weld size drop after full dress. Dressing operation at 250 welds

Further testing of the design factors will utilize two electrodes specified by the DOE analysis above. The improved electrode will be of parabolic geometry, with the new TriCoat™ surface coating, equipped with internal cooling fins and will be side-dressed where applicable. The baseline electrode will be an uncoated domed electrode with no cooling fins and will be fully dressed where applicable.

Life Testing

Electrode life testing of the selected electrodes is shown in Figure 12. The parabolic electrode with the coated weld face and internal cooling fins experiences a much longer life than the uncoated domed electrode without cooling fins. As seen in previous studies [1-4], the coated electrode is able to form larger nuggets in the beginning of life without the need for conditioning. The weld size is maintained for more welds with the parabolic electrode. It can be seen that in the region of 400 to 1000 welds, the electrode is able to maintain a steady weld quality where the domed electrode experienced a drop in weld size and rapid failure shortly after.

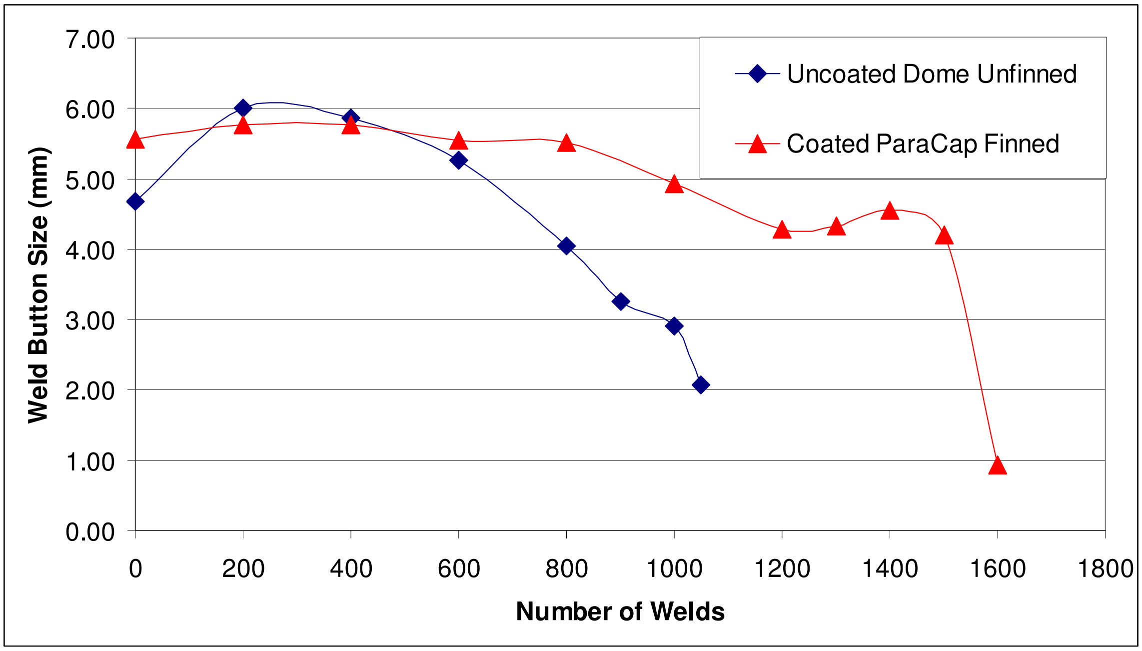


Fig 12: Electrode life test results for Improved electrode design (coated, parabolic, finned and side dressed) compared to conventional (uncoated, domed, unfinned and fully dressed) electrode design.

Failure of the uncoated-domed-unfinned electrode occurred at 900 welds. Failure of the coated-parabolic-finned cap occurred at 1600 welds. The life extension realized by the parabolic electrode is due to the collective influences of the geometry, surface coating and the internal cooling fins. The ability to form satisfactory welds at a longer life is primarily due to the preservation of the weld face diameter to maintain current density. When current density is maintained, the heat input to the system is focused and able to create a good weld. Figure 13 shows the progression of the weld face diameter during the life testing. As can be seen from the figure the initial tip growth rate of the parabolic electrode is slower than that of the domed electrode. The electrode weld face diameter at the point of failure is also slightly larger for the parabolic electrode. This was due to the presence of the multilayered electrode coating acting as a thermal barrier increasing the electrical efficiency of the weld while welding at lower weld current.

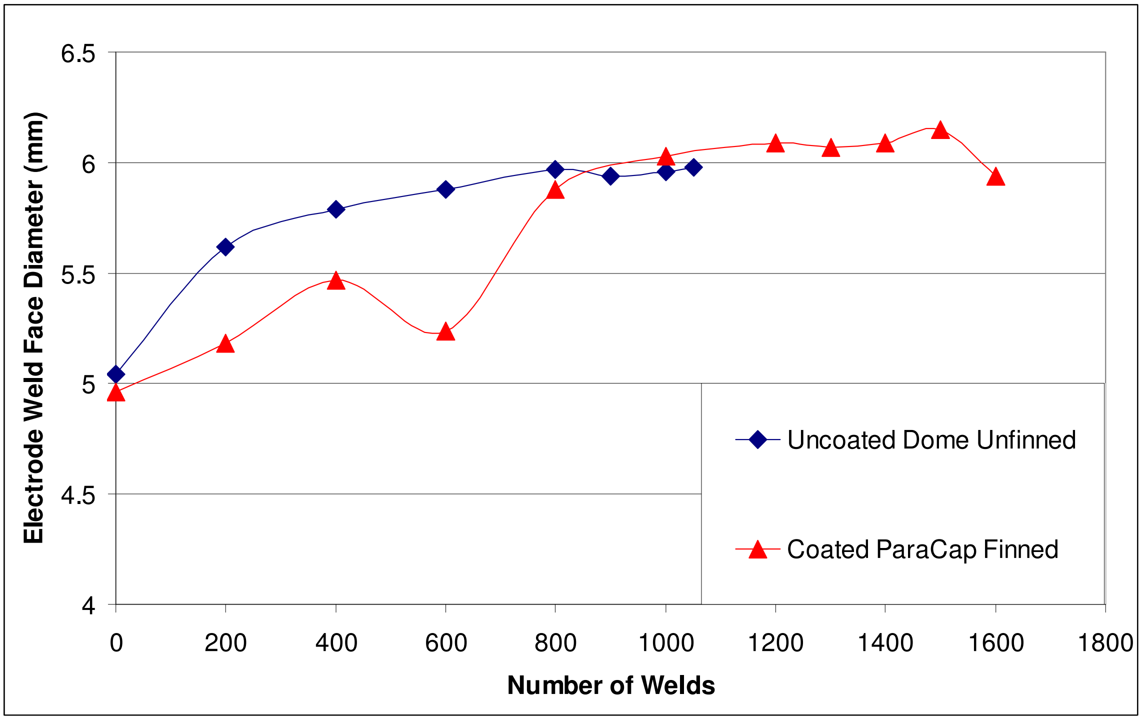


Fig 13: Weld face diameter growth curves for improved and conventional electrode designs

To investigate the reason for the improvement in weld face diameter growth rate, the electrode length can be used. Tracking the overall length of the electrode at the beginning and end of the life will indicate the collective processes of erosion and deformation of the electrode. Table 6 shows the average length of the top and bottom electrodes for both domed and ParaCap™ tests as well as the length reduction in mm.

Table 6: Electrode length as measured before and after life testing

Electrode Length (mm)	Domed	ParaCap™
Before	22.37	22.41
After	22.20	21.87
Length Reduction	0.17	0.54

The length reduction of the parabolic electrode is more than double that of the domed electrode. This was expected as the domed electrode is known to have very good resistance to physical deformation due to the geometry. Although the length reduction experienced was greater for the parabolic electrode, the geometric growth rate was much less resulting in a much lower weld face diameter growth rate. From the DOE study, the effect of the cooling fins was not significant in the rate of length reduction and deformation of the electrodes.

Production Testing

As outlined above, the domed electrodes were tested as conventional production electrodes, being dressed over the entire weld face and profile at regular intervals. The ParaCap™ electrode was tested as a new state of the art electrode system with side-dressing only at irregular intervals to maximize the life of the electrode while maintaining good weld quality by utilizing the latest multi-layer TiC surface coating from Huys. Three tests were conducted to explore and evaluate the new system compared to the conventional domed electrodes. All tests were conducted using weld schedules found in Table 4.

Production Test Run One

The first production environment test was run to 1500 welds. This initial test was designed to determine the dressing interval for the coated ParaCap™ electrode. As seen in Table 4, the dressing frequency for the conventional domed electrodes was every 250 welds to ensure weld quality. The coated ParaCap™ electrodes are able to maintain excellent quality welds for longer than the domed electrodes, so a threshold weld size of 6.0mm was set for dressing. Welding results are shown in Figure 14. The first dressing operation was not required until 1000 welds. After this initial dressing operation, the electrodes were able to form welds over 6.0mm until 1600 welds.

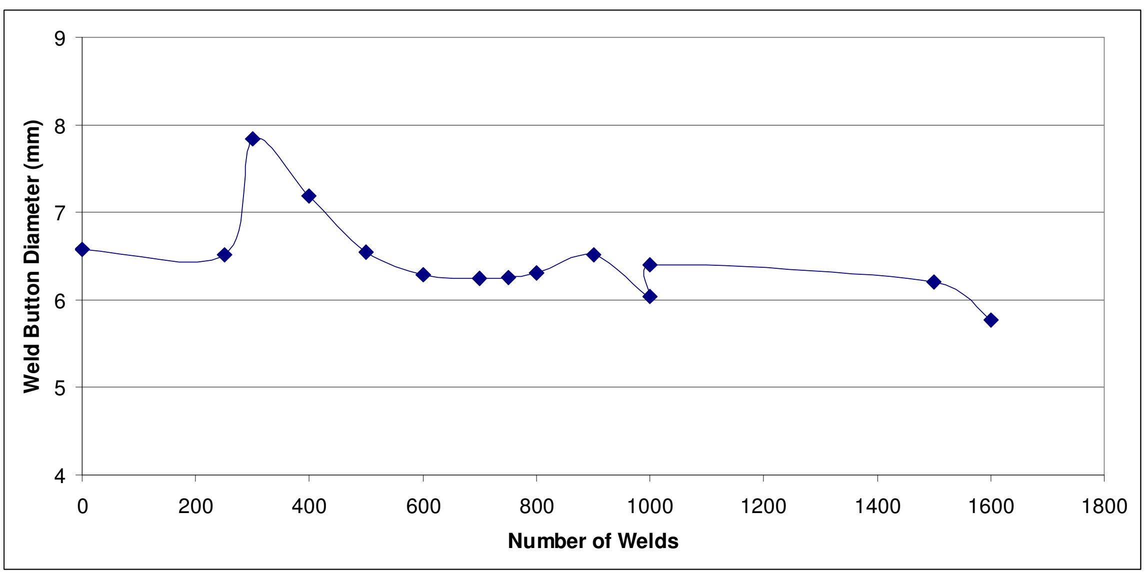


Fig 14: Weld button size vs. number of welds for production test one. Dressing was performed whenever button size dropped below 6.0mm.

As the dressing threshold was 6.0mm and the minimum button size was 4.38mm according to $4(\sqrt{t})$, the dressing frequency was selected as 500 welds for the coated ParaCap™ to ensure that the welds would be larger than the minimum. Although the coated ParaCap™ was able to last longer then 500 welds in the initial unused state, it was decided to dress every 500 welds for consistency to compare against the conventional domed electrode.

Production Test Run Two

Test run two consisted of full production runs with for both the uncoated domed electrode and the coated ParaCap™ electrode. Weld schedules as shown in Table 4 were used with a dressing frequency of 500 welds for the ParaCap™. The test would be terminated when either of the electrodes would fail due to undersized welds before the dressing period or the dressing limit was reached on the electrode (no more copper is able to be removed without compromising the function of the electrode). Weld peel coupons were prepared before and after each scheduled dressing operation. Figure 15 shows the resultant weld button sizes for both the uncoated domed and coated ParaCap™ electrodes. The button sizes are maintained well above the minimum weld size of 4.38mm for both electrodes. The use of side dressing at a less frequent dressing interval, compared to the full dressing of the uncoated dome, is able to maintain a better weld quality standard while consuming less electrical power with the new coated ParaCap™. The test was terminated at 4000 welds due to the domed cap reaching the dressing limit. At this point, the ParaCap™ was measured at 20.5 mm and was still able to weld and undergo further dressing operations to maintain weld face diameter and weld quality.

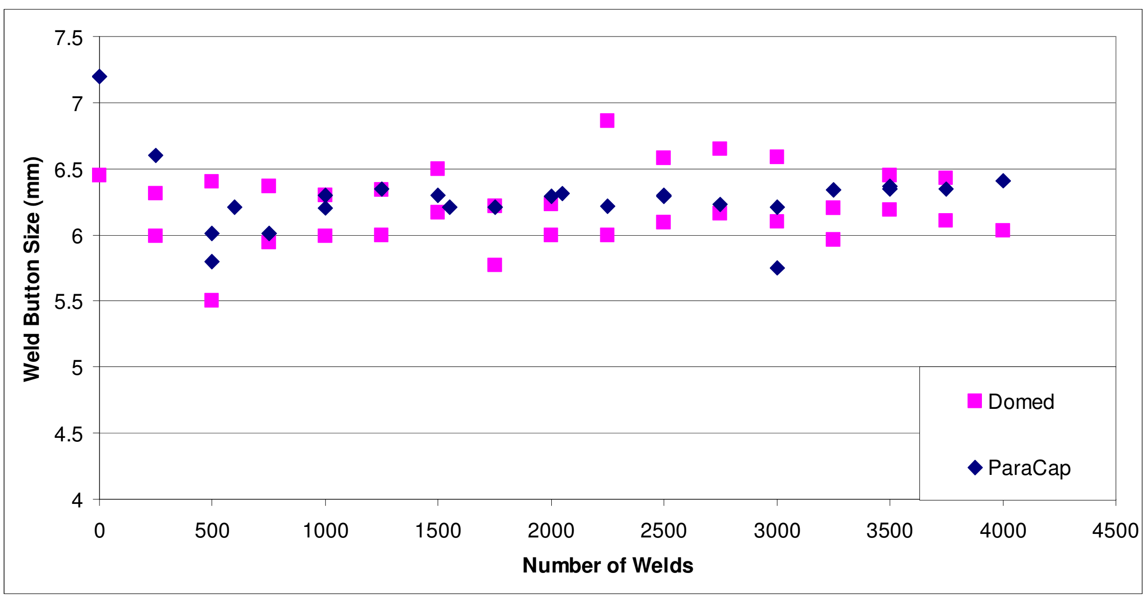


Fig 15: Weld button size vs. number of welds for production test two with dressing every 250 welds for domed electrode, and every 500 welds for ParaCap™.

Figure 16 shows the electrode length tracked with each dressing operation. As the side dressing operation only removes electrode material from the sides of the electrode and not directly from the weld face, electrode shortening is much less severe after each dressing operation. At the end of the test, the domed electrode had reached the physical limit for dressing at a length of 16.5mm. The slope of the length reduction is very consistent from the dressing operations and so the wear of the electrode and performance of the electrode can be predicted. For this reason, the combination of the ParaCap™ geometry and surface coating which is able to last longer than the conventional uncoated domed electrode coupled with the side-dressing technique has been shown as the superior resistance welding electrode system.

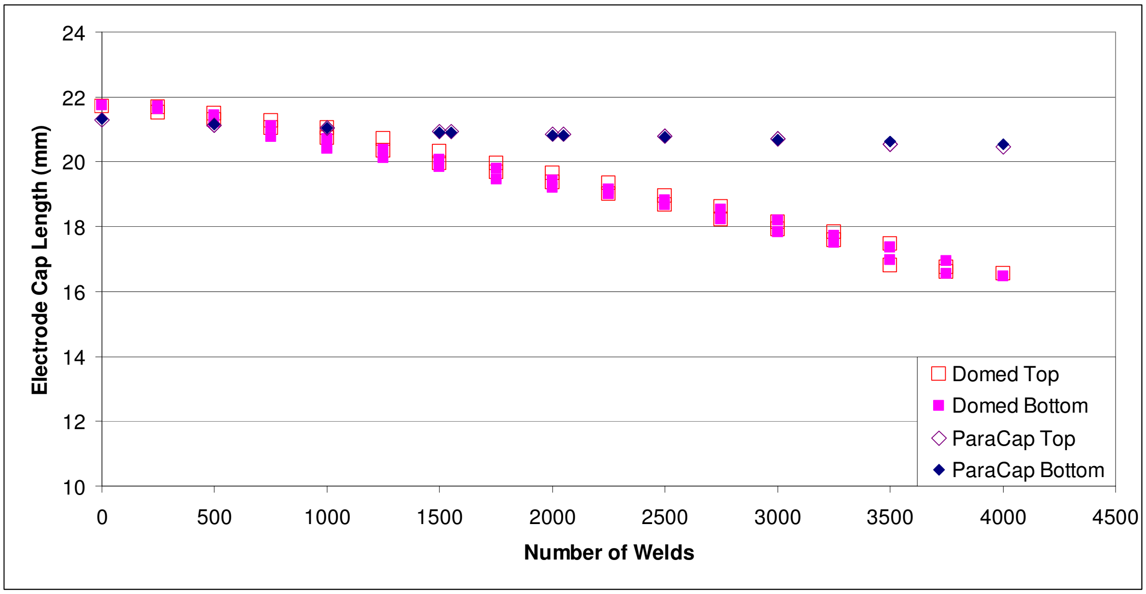


Fig 16: Electrode length measurements at each dressing interval for Production Test Run Two.

Figure 17 shows images of the used electrodes after the test compared to a new electrode. The reduction in length due to the dressing operations can clearly be seen. The ParaCaps™ in Fig. 17b also show the degree of mushrooming that occurs during the life of the electrode. It is this mushrooming that causes the length reduction in the cap, as the side-dressing process does not remove any material from the surface. After dressing, both electrodes have a geometric profile identical to when the electrodes are new.

During the course of this test, it was noted that one set of coated ParaCap™ electrodes experienced a large amount of pitting. Weld button sized dropped causing failure due to this; however, button size increased again when the weld current was stepped or increased to compensate. Welding continued for a short time to gauge the consistency of the system with current stepping as well as tip dressing. Results looked promising; however, this investigation was outside the scope of this work. The test was terminated and discarded. It was believed that the alloy layers on the surface of the weld face were able to attack the base copper of the electrode due to damage to surface coating during a dressing operation. As the electrodes used in the production tests were machined on a CNC lathe and not a traditional dedicated tip dressing press, it was difficult to determine if this issue would occur again. In a traditional tip dress press, there is a normal force applied to the electrode which would ensure the weld face is cleaned somewhat without damaging the coating.

a)

b)

Fig 17: a) Uncoated domed electrodes after 4000 welds before dressing compared to new electrode. No further dressing operation could be performed. b) Coated ParaCap™ electrodes after 4000 welds before dressing compared to new electrode. Further dressing operations and extended tip life can be performed.

Production Test Run Three

A final production test run was performed to allow the coated ParaCaps™ to weld until ultimate failure. For this test, weld schedules as shown in Table 4 were used for the coated cap with a dressing interval which varied. Dressing was again performed only when peel buttons dropped below 6.0mm. Because of the variable dressing frequency, peel coupons were made every 100 welds to ensure weld quality was maintained. Figure 18 shows the weld button size of the coated ParaCap™ compared to the previous domed electrode of Test Run Two.

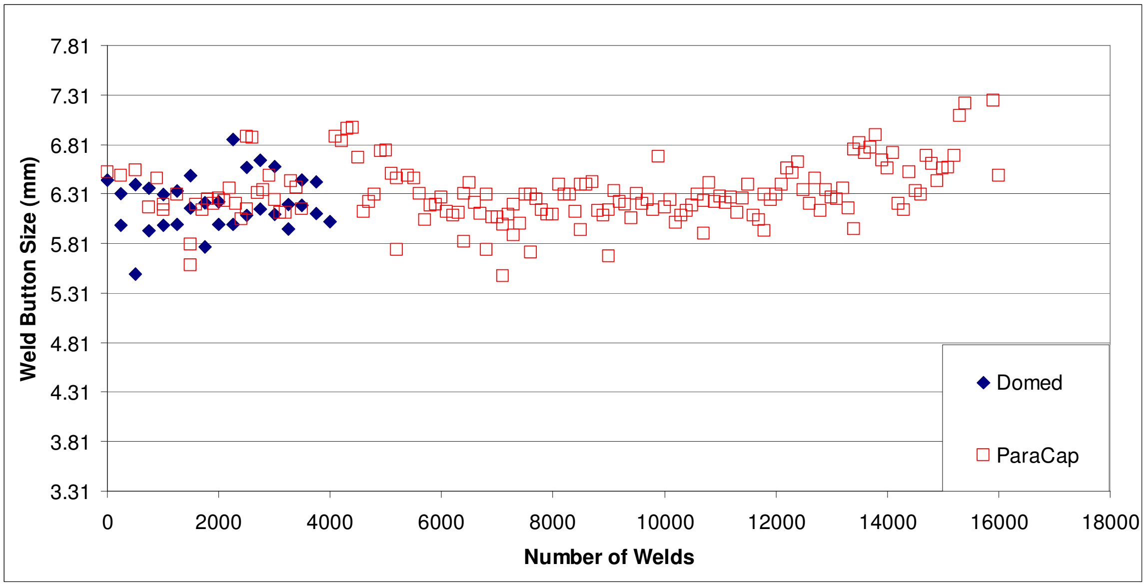


Fig 18: Weld button size vs. number of welds for production test three. ParaCap™ results are compared with domed electrode results from production test two

As the dressing frequency of the test was not regular, the weld button sizes may have varied more than normal. Note that the termination of the test is at 16000 welds when the weld button size is still over 6.3mm. Weld quality was maintained throughout the weld test while showing that a single pair of electrodes combined with the side-dressing technique was able to perform 16000 welds on HDG steel.

Conclusions

Factorial experiment results showed that for reducing tip growth, an electrode which is coated, domed in geometry, finned, and side-dressed would be best. For the largest weld buttons, an uncoated, parabolic, finned and fully dressed electrode would be best. Further analysis of the factors and considerations for production processes and weld quality standards indicated that a *coated, parabolic, finned and side-dressed* electrode would be the best improvement over an uncoated, domed, unfinned and fully dressed electrode commonly found in production environments.
Further testing of the electrodes in both laboratory and production environments showed that:

1. Parabolic ParaCaps™ with a multilayer TriCoat™ coating last longer than comparable standard dome shaped electrodes.

2. Internal cooling fins can reduce the weld tip growth rate and preserve current density to yield larger and more consistent welds.

3. Side Dressing maintains the Cu-Zn alloys on the surface of the electrode, which can assist in maintaining weld button size and consistency of quality while not

shortening the electrode, and can thus extend the ultimate usable life of the electrode in a tip dressing application.

4. Coated ParaCaps™ require less frequent dressing than uncoated domes, and can be returned to their original state by side dressing more times than a complete dressing of uncoated domes.

5. Additional testing needs to be done in determining the effectiveness of combining current stepping and side dressing in the use of parabolic ParaCaps™. It is our belief that such a combination would significantly improve electrode performance and life.

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