Quality and Electrode Life Improvements to Automotive Resistance Welding of Aluminum Sheet

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ABSTRACT

Commentators have suggested that the need for better fuel economy will see a resurgence in the use of aluminum in the North American automotive sector. Recent advances have put aluminum back into mainstream automobile production, and pressure for more efficient vehicles will lead to increased use of aluminum where possible. Aluminum, however, is still considered difficult to weld, which hampers its acceptance against competitive materials. The thermal and electrical properties of aluminum make resistance welding difficult, requiring high current and short weld times to generate the necessary heat to form the nugget before the heat is dissipated through the work sheet. Conventional uncoated domed-face electrodes are able to weld aluminum sheet but suffer from short electrode lives. The interaction between copper and aluminum is several times stronger than that of copper and zinc, making the degradation of copper alloy electrodes more severe when welding aluminum than coated steels. Recent testing of a new, specifically designed electrode geometry, incorporating the use of a newly patented electrode coating, was able to control the typical wear process of copper alloy electrodes when welding aluminum alloys. The formation of the weld nugget was seen to be easier due to the presence of the electrode coating which acted as a layer to generate heat as well as thermally insulating the growing nugget from the cooled electrodes, thus allowing the nugget to grow larger. In addition, both electrode life and the consistency of the welds were found to be significantly increased and improved. The wear characteristics of the electrode were shown to be uniform and predictable, allowing the force distribution over the weld area to remain even, facilitating predictable weld nugget growth. Traditional pitting of the electrode and loss of current and force density was not seen with the new electrodes. Transformer weld current stepping was easily applied as the wear character of the electrodes was predictable.

1. Introduction

The continuing need for better fuel economy is pushing forward a trend to increase the use of aluminum in the North American automotive sector. Recent advances have put aluminum back into mainstream automobile production, and pressure for more efficient vehicles will lead to increased use of aluminum, where possible. Implementation of aluminum in automobile hoods and trunk lids can save weight while maintaining safety standards and ease of manufacturing. These applications employ aluminum alloy sheets, which are processed and manufactured in a similar manner to automotive sheet steel, and can also be stamped and cut in a similar manner. The difficulty and deterrent for the use of aluminum is its weldability. During the initial boom of aluminum in the automotive industry, resistance spot welding of the lightweight and corrosion resistant material was extremely difficult and costly. Electrode life was drastically short, and weld quality was difficult to maintain at production speeds. This hurdle was primarily responsible for hampering acceptance other against competitive materials.

The thermal and electrical properties of aluminum make resistance welding difficult, requiring high current and short weld times to generate the necessary heat to form the weld nugget before the heat is dissipated through the work sheet [1]. Conventional uncoated domed-face electrodes are able to weld aluminum sheet but with short electrode lives. The interaction between copper and aluminum is several times stronger than that of copper and zinc, making the degradation of copper alloy electrodes more severe when welding aluminum than coated steels.

Electrode coatings have been presented as a means by which to extend electrode life. Dong and Zhou [4] have shown that a TiC coated electrode (TiCAP™, a trademark of Huys Industries Limited, Ontario, Canada [7]) can extend the life of micro-resistance welding electrodes. Their tests found the coating to increase tip life by approximately 70 percent by reducing the amount of local bonding between electrode and sheet. Although the use of the patented coating for electrode life improvement in resistance spot welding of aluminum sheet has been suggested, presently, there is no detailed experimental evidence as to the validity of this claim.

In the present work, the effects of the TiC coating on the electrode tip life were explored when welding aluminum alloy 5182. Tip life trials were conducted and tip diameter and surface profile data were recorded. This study is aimed at understanding the performance, degradation and failure mechanisms of the coated electrode.

2. Technical Background

The weld nugget is formed by the passing of current through the electrodes and the worksheets. Heat is generated by the contact resistance at the interfaces and bulk resistances in the workpiece governed by the equation $H=I^2Rt$, where H is the total heat, I the weld current, R the total circuit resistance, and t the weld time. The quality of the weld formed is directly dependant on the localized heat generation, or H/A, where A is the area of the contact face of the electrode. This is in turn influenced by I/A known as current density. With the weld current set and held constant, the quality of the welds is related to the contact area. As the electrode degrades, the current density decreases due to tip face growth until nuggets are no longer formed due to inadequate heating. The rate of tip face growth may be tracked with carbon tip imprinting and can be used to compare the wear rate of electrodes.

The low electrical resistance and high thermal conductivity of aluminum alloys inherently make resistance welding difficult. Based on the governing equation above, when the resistance of the work sheets are low, and the heat input to the system is dissipated quickly, the weld time must be short and the weld current very high to generate the required heat to form a weld [1-3]. With the shortened weld time and rapid cooling of aluminum, the weld nugget is formed and solidifies in a very short amount of time. As the weld occurs in a much shorter time than for similar steel welds, the need for proper electrode alignment and force distribution as well as electrode backup force is critical for weld consistency and quality. Spinella et. al. [1] has shown that there is a certain force threshold that must be met to produce consistent welds. This force is that which is needed to break the oxide layer and allow uniform distribution of the weld current through the cracks of the broken oxide layer. For this to occur, the force must not only be at a certain level, but must also be uniformly distributed across the entire weld area.

With the added complexity of the tenacious aluminum oxide layer at each of the interfaces in the weld area, resistance spot welding can become very erratic and hard to predict. The localized heating at the electrode work interface, coupled with the rapid heating and cooling cycles of each weld, lead to very rapid electrode wear and the pitting phenomenon that is unique to aluminum resistance welding [1-3]. The erosion process typically starts with pitting caused by the brittle fracture of local bonds formed at the intermetallic phases. Once this pitting has occurred, a secondary pitting process has been presented by Lum et.al. [2] where small amounts of molten copper from the electrode are transferred in the liquid state. This process was said to have been brought about due to the intense heating and increased contact resistance at the location of existing pits, causing localized melting of the copper alloy welding electrode. These pits in the electrodes have been shown to appear in as little as 20 welds. Once a sufficient number of small pits have formed on the electrode surface, further welding serves to bring the pits together to form a large central pit in a process termed cavitation. Once this has occurred, the weld force and current are restricted to only a small ring on the outer periphery of the large pit. At this point, weld quality and consistency are extremely impaired. Lum et. al has summarized the electrode degradation of conventional copper alloy electrodes when welding AL5182 in four steps: 1) aluminum alloy pickup, 2) electrode alloying with aluminum, 3) electrode tip face pitting, 4) cavitation.

3. Experimental Procedure

Welds were made on 1.5mm thick AA5182-H111 (Table 1) using a 170-kVA MFDC pedestal resistance spot welding machine. No cleaning of the surface was performed prior to welding. All tests used Class 2 CuCrZr copper alloy electrodes with a modified tip geometry. Some of the electrodes employed a TiC-MMC coating which covers the entire weld face as well as some of the surrounding electrode face.

Table 1: Chemical Composition of AL5182

Aluminum alloy AL5182 worked and heat treated Chemical composition						
Element	Si	Fe	Cu	Mn	Mg	Al
Wt%	0.08	0.19 0	0.05	0.32	4.71	Bal.

The electrodes used in this study have been designed by Huys Industries Ltd. and are shown in Figure 1. These electrodes are very similar to a truncated cone E-nose style body with a slightly curved weld face with a set diameter. Both coated (Al-Capp(TM)) and uncoated variations of this electrode were used in this study. The coating employed is not the same as the TiCap(TM) coating employed for resistance welding of steel alloys.

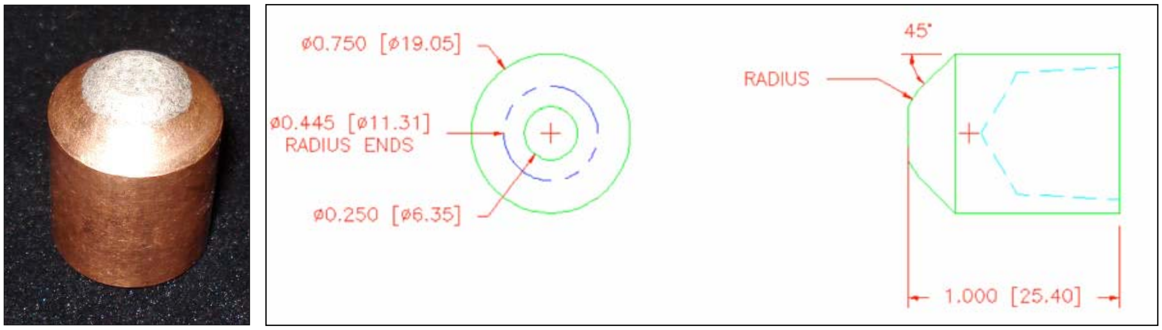

Figure 1: Electrode geometry

Nugget Formation Testing

Weld current window testing was conducted by allowing each electrode type to make a weld at a starting weld current of 20kA and increasing the current incrementally up to 26kA. All other weld parameters such as weld force and time were held constant. This test was conducted to show the difference, if any, between electrodes in the 'new' condition without any pre-conditioning in terms of their ability to form adequate sized weld nuggets on aluminum. As the electrode degradation process occurs very quickly with aluminum, a new pair of electrodes were used for each trial. Each trial was repeated twice for a total of three runs, with two welds made at each weld current.

Electrode Life Testing

Electrode life testing was conducted for both electrodes using equal welding parameters for each electrode without current or force stepping. Weld parameters were held constant and determined by the weld current window testing conducted. Peel button coupons and tip imprinting was performed every 50 welds. The test was ended when the nugget diameter fell below 4.8mm from guidelines set out by Spinella et al. [1] for commercial aluminum applications.

4. Results

Nugget Formation Testing

Weld current window testing for both the coated Al-Cap(TM) and the uncoated electrode were conducted with results shown in Figure 2. The figure shows the trend of the Al-Cap(TM) being able to produce larger nuggets at each level of weld current. For this thickness of material, a target of 6mm pull out nugget was the target according to ISO 18595 2007E as well as Spinella et al.[1]. This target was reached approximately 2kA sooner with the Al-Cap(TM) than the uncoated electrode, showing the reduction in utility costs and the higher efficiency benefits of the coated electrode.

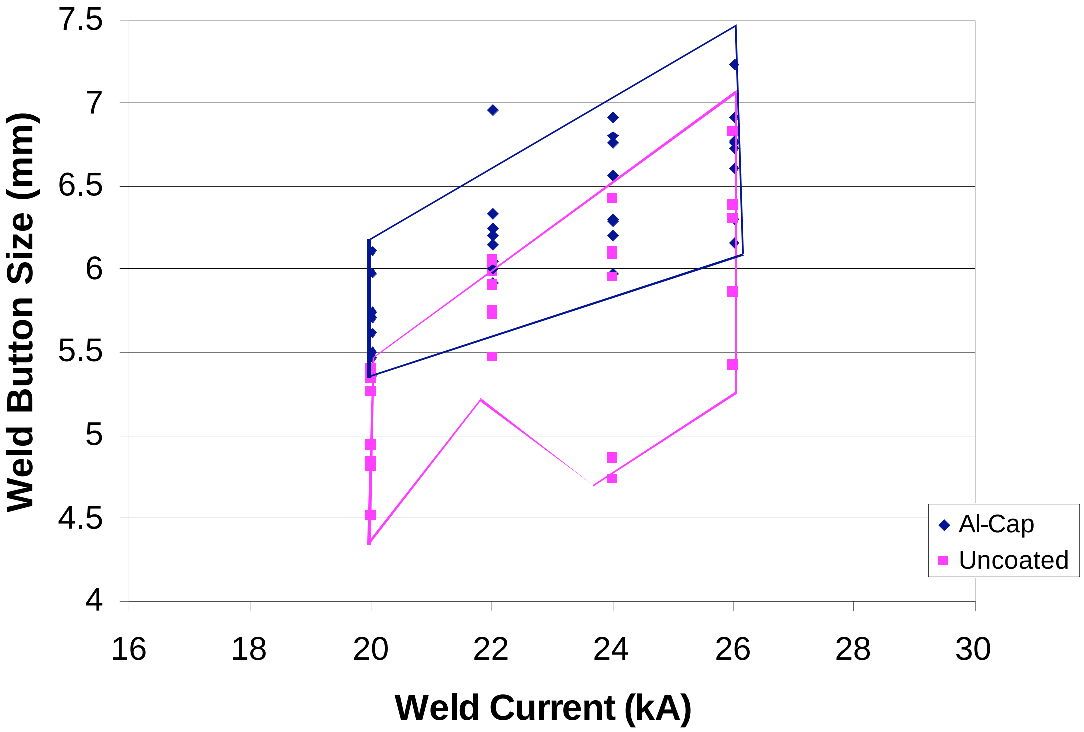

Figure 2: Weld current windows for the coated AlCap(TM) and uncoated electrode

Figure 3 (below) shows the welds as peeled from the test. For each electrode, pull-out buttons were achieved and both were dimensionally sound and of good appearance. The level of indentation from this geometry of electrode is slightly higher than that of a fully domed electrode of a larger weld face diameter; however, it is well within quality standards. As the electrodes remained in the very early stages of electrode life and degradation during this test, the nuggets remained well formed with the weld diameter being the major change in character as the weld current was changed. It can be noted, however, that the uncoated electrode did start to yield some slightly oval buttons near the middle of the test, unlike the coated electrodes.

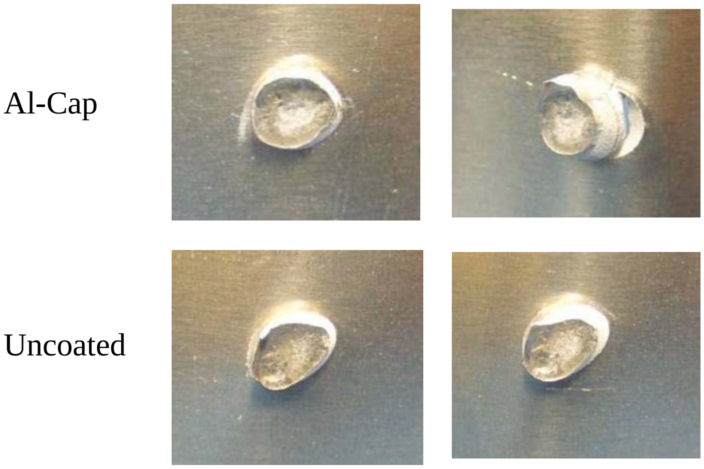

Figure 3: Peeled Weld Buttons from Weld Current Testing at 24kA

Cross sections of welds made at 20kA and 24kA were taken to compare the development of the weld nugget for each electrode type. Figure 4 shows very clearly the shapes of the cross sectioned nuggets. At the lower weld current, both electrodes were able to produce pull out buttons. In the figure it can be seen that the interfacial nugget diameter is similar, however due to the shape of the nugget, the Al-Cap(TM) weld was able to pull a larger diameter button. The same can be seen for the welds made at 24kA, with a similar shape in the nuggets.

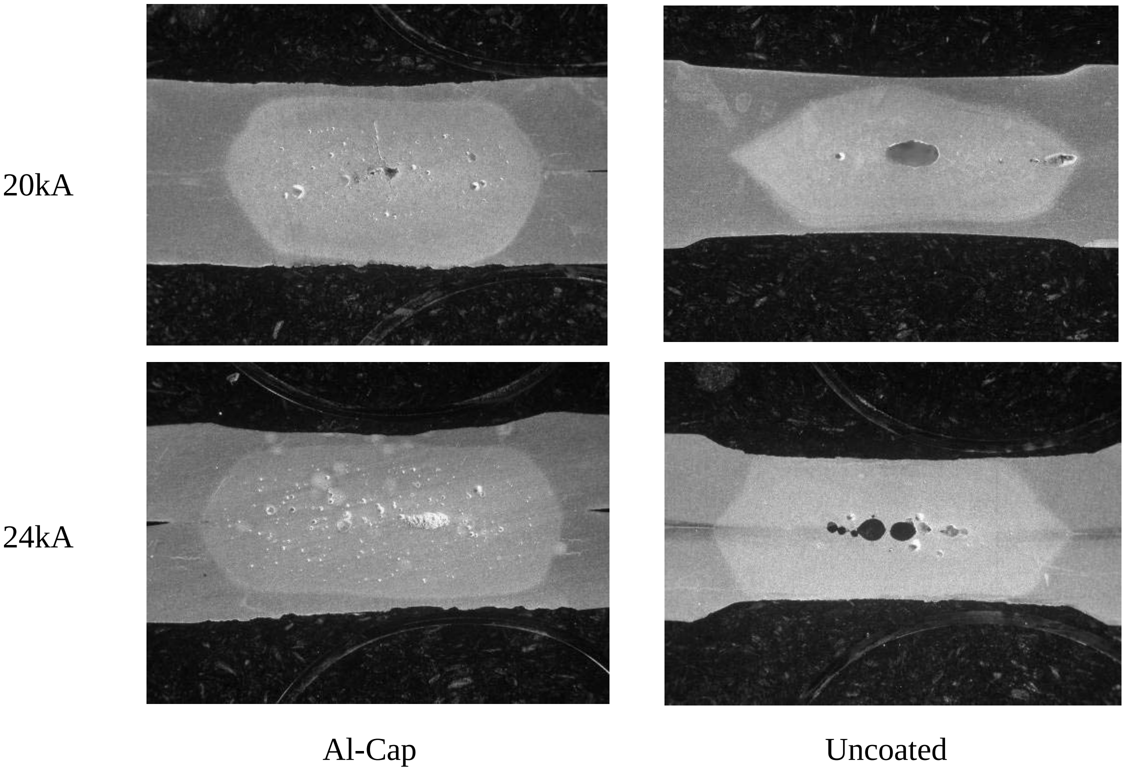

Figure 4: Cross sectioned aluminum welds at 20kA and 24kA of the Current Test

Electrode Life Testing

Electrode life testing using a non-stepped single current was conducted for both electrode types using the weld parameters shown in Table 2.

Table 2: Electrode Life Testing Parameters

Squeeze	25 cycles
Weld Time	5 cycles
Hold Time	6 cycles
Force	930 lbf
Current	24 kA
Welding Rate	20/min

Results for the life testing of the electrodes are seen in Figure 5 below. The curves for the button size with increasing weld number show that the Al-Cap(TM) electrode is able to form acceptable welds for a longer period than the uncoated electrode without any weld schedule modification. Also, the effect of the nugget formation character is seen as both electrodes were tested at the same weld parameter schedule, and it is clearly seen that at the beginning of the test, the Al-Cap(TM) has a larger weld diameter.

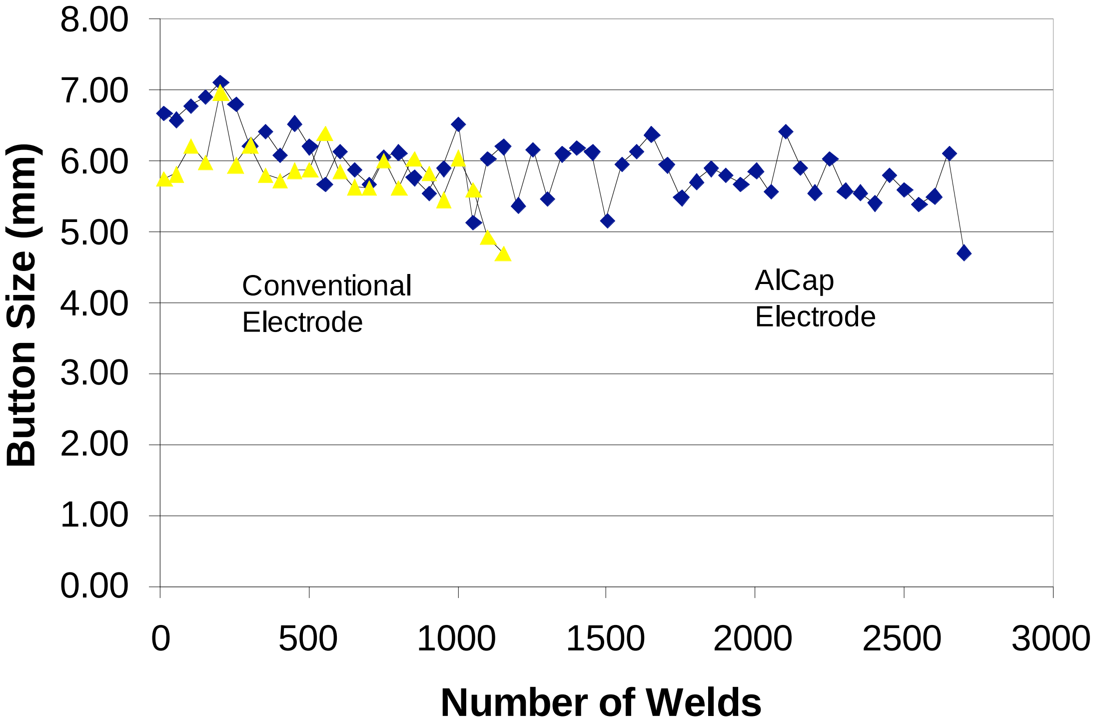

Figure 5: Electrode life test results

Carbon tip imprinting was performed at each weld peel interval to track the growth of the electrode tip face of the upper electrode. The resultant tip growth curves for the life test are shown below in figure 6.

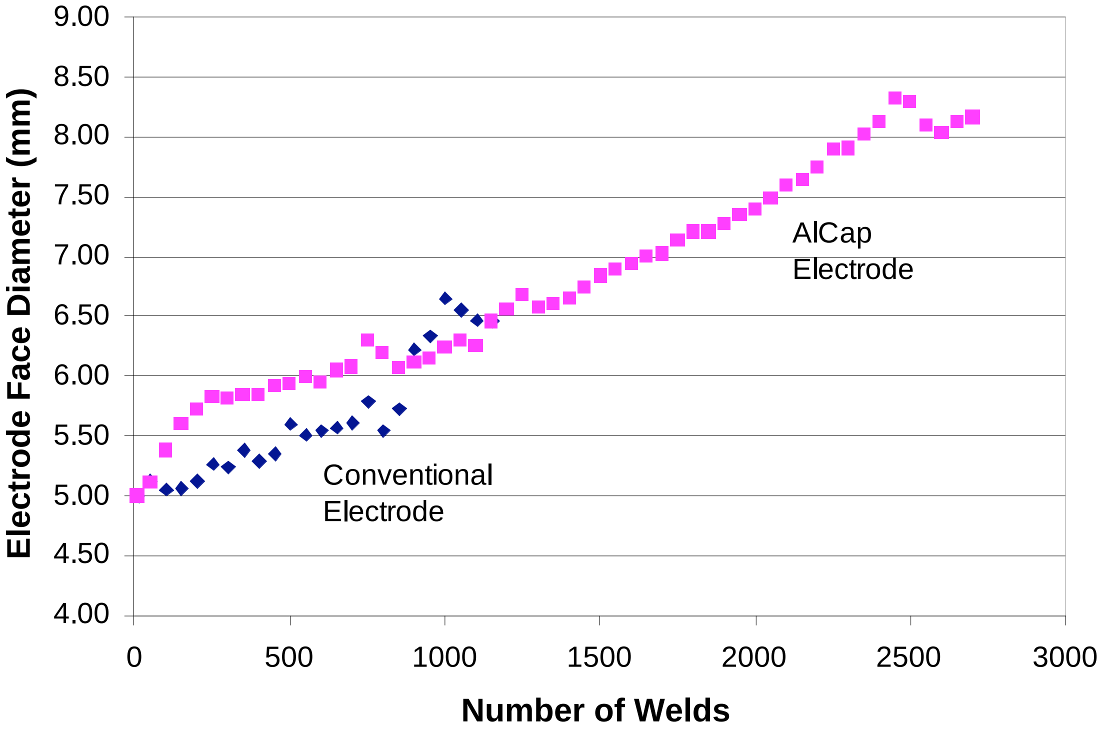

Figure 6: Electrode tip face diameter growth curves for the conventional uncoated electrode and the Al-Cap(TM) for life testing results.

5. Discussion

Nugget Formation Characteristics

From the figures shown in Section 4, it was seen that the Al-Cap(TM) electrode was able to form larger nuggets than the conventional electrode using the same welding parameters. The weld current window yielded larger nuggets and would be expected to be wider as well. The shape of the peeled buttons was also more consistent and round. This was due to the presence of the TiC electrode coating serving as an additional layer of electrical resistance, as well as a thermal insulator [5]. As the electrode work interfaces are much more critical in terms of determining the final size of the nugget when welding aluminum [1], the presence of the slightly higher resistance coating on the Al-Cap(TM) allows for better use of the weld current and more consistent weld nuggets. This is seen directly in Figure 4, as the shape of the nuggets clearly shows the rounder, more evenly developed nugget when using the Al-Cap(TM). The inherent issues of low electrical resistance and higher thermal conductivity are directly addressed by the Al-Cap(TM).

Electrode Life

From the data shown in Section 4 on life testing, it is seen that the Al-Cap(TM) is able to produce acceptable welds for a longer period of time without any current or force modification. As the number of welds increases, both electrodes begin to wear as seen in Figure 6. The weld face diameter grows quickly for the Al-Cap(TM) and then levels off to a slower growth rate. The uncoated electrode shows a steady increase in the growth rate until failure. As previously discussed, the nugget formation characteristics have been changed using this style of electrode, and it is believed that this change has also greatly contributed to the extended life performance as the Al-Cap(TM) is able to form acceptable welds even after the weld face diameter has grown larger than that of the failed uncoated electrode. Another large factor in the electrode life behaviour of the electrodes is the character in which they wear. It has been noted in literature that when welding aluminum sheet, the uncoated electrodes pit very easily and these pits coalesce to form a large central pit which is detrimental to the current and force density. The following section looks closely at the wear character of the electrodes.

Electrode Wear Profile

The results from the previous sections suggest that there is a mechanism in the wear character of the electrodes that is contributing to their weld performance. Analyzing the way the electrodes degrade through the use and interaction with the aluminum work pieces repeatedly, we can gain insight into why the electrode performs the way it does.

In addition to the electrical and thermal character of the Al-Cap(TM) electrode being changed, analysis of the used electrodes showed that the shape of the electrode surface was changed. The traditional large central pit was not formed on the Al-Cap(TM), thus allowing the force and current distribution to be maintained throughout the electrode life. The typical stages of electrode wear when welding aluminum have been changed due to the presence of the coating and need further study to fully characterize. As the weld face does grow larger with increasing welds, and no significant mushrooming was seen, it can be assumed that alloying and erosion through material transfer is occurring. It is likely that with the coating present, the secondary pitting as reported by Lum et.al.[2] is no longer possible as areas of exposed copper alloy are no longer present. With a barrier between the copper and the aluminum surface, the pitting has been reduced and the surface of the electrode remains flat and able to produce acceptable welds.

In a production environment conducted by an industrial partner, the Al-Cap(TM) was able to last consistently to 5000 welds with a MFDC current stepper in use. Figure 7 shows the progression of the upper (positive) electrode tip and its carbon imprint over the course of the electrode life during actual production runs at a major automotive manufacturer that has chosen to remain anonymous. The figure shows the progression of the electrode face diameter growing with increasing number of welds. The tip imprint images which correspond to the electrodes also show that although there is considerable growth of the electrode surface, the contact profile remains flat and able to transmit the required force to form a sound weld. A pitted electrode would yield a carbon imprint with a blank center, where the electrode was not able to make contact with the carbon paper due to the pit as seen in work done by Fukumoto et al [3]. As the erosion of the electrode progresses, the surface remains flat and is able to conduct the weld force and current evenly across the weld zone. It is this feature of the coated electrodes that contributes to the ease of use and longevity of the cap when used with a current stepping profile.

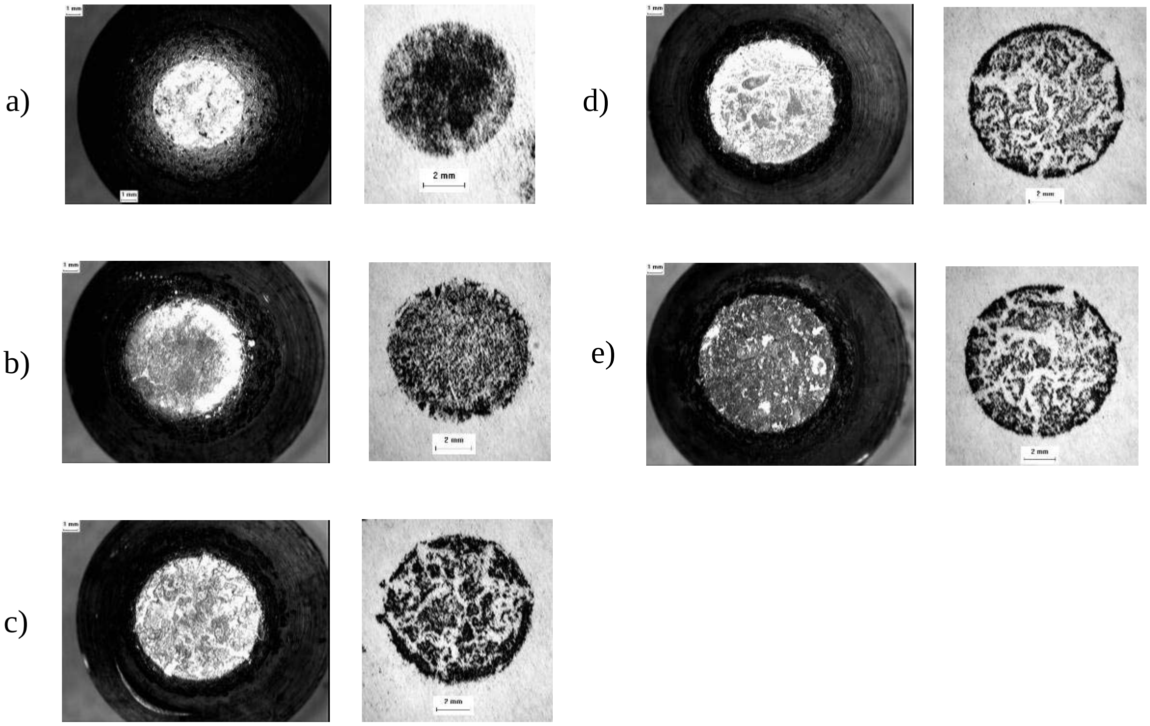

Figure 7: Upper Electrode images and tip imprints from production testing results taken at various weld number intervals: a) 0 welds, b) 500 welds, c) 1000 welds, d) 3000 welds, e) 5000 welds.

From the cross sections of these electrodes, the surface profile and any concavity of the surface can be seen. Figure 8 shows the electrodes as seen in figure 7 in cross section. As the number of welds increases, the surface of the electrodes does get rougher as shown also in figure 7. The overall profile though remains relatively flat, and we do not see the large central pit or gradual concavity that would lead to an uneven or ring distribution of the weld current and force.

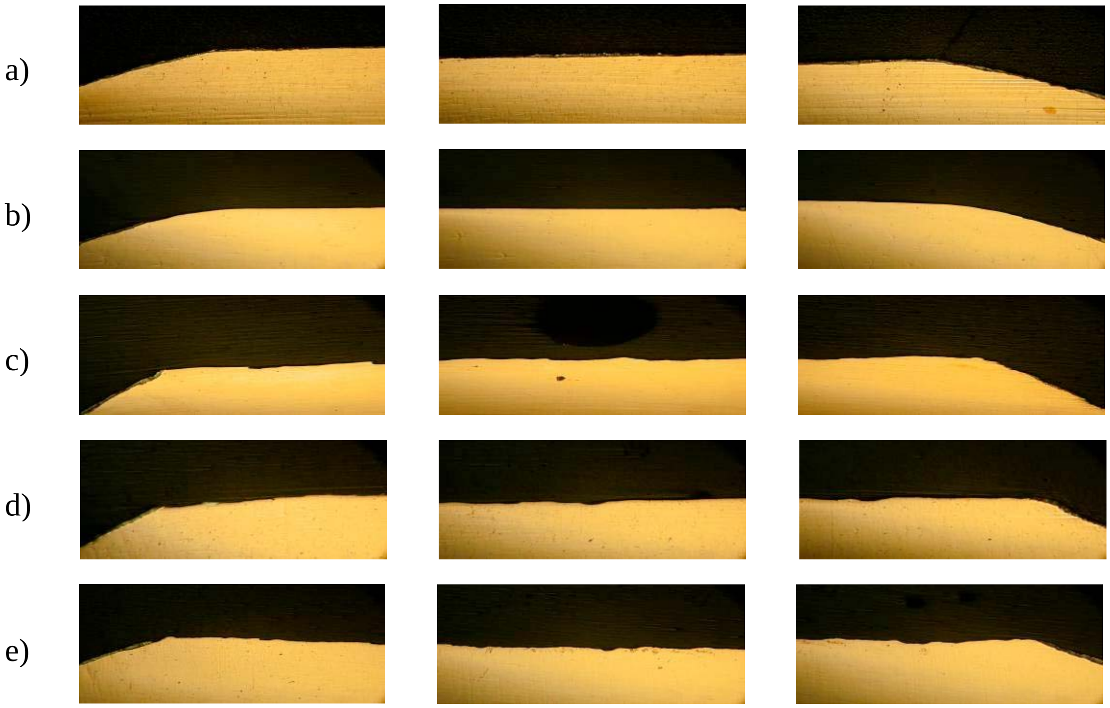

Figure 8: Upper Electrode cross sectioned images from production testing results taken at various weld number intervals: a) 0 welds, b) 500 welds, c) 1000 welds, d) 3000 welds, e) 5000 welds.

6. Conclusions

This study has been able to show that the TiC coated electrode was able to form larger welds than a traditional uncoated electrode at the same welding parameters yielding a larger welding window making it more robust for production. The resultant welds were also seen to be more round and consistent in nature when peeled and cross-sectioned versus the uncoated electrode. This was due to the TiC electrode coating acting to serve as an additional interfacial layer providing additional electrical resistance and thermal insulation.

The electrode life for a static weld current and force test was approximately double that of the uncoated electrode. In a production environment with current stepping, the coated electrode was able to reach 5000 welds consistently. Upon study of the electrodes at intermittent stages in life, it was seen that the wear profile of the electrodes remains flat, and large pits and concavity as described in literature do no exist. It is this feature that allows the force and current to continue to reach the aluminum worksheet and form acceptable welds. The mechanism by which the TiC electrode was able to wear differently requires further study, but was theorized to be related to the function of the TiC coating acting as a physical barrier between the copper alloy electrode and the aluminum to mitigate alloying and secondary pitting as well as providing a hard wear and impact resistant coating to protect against mushrooming and localized melting of the copper.

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