Solutions for Welding Zinc Coated Steels

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ABSTRACT

A broad overview of the different process solutions for joining galvanized steels for automotive applications is provided which will include both arc welding and laser welding processes. With the increasing conversion of automotive chassis components to hot dip galvanized steels to improve corrosion resistance and the transition to thinner advanced high strength steel to meet the demands of increased fuel efficiency, finding suitable welding solutions for coated materials has assumed higher significance. However, welding coated steels has always been a critical issue with conventional processes and consumables. Three major problems with welding zinc coated steels are high spatter amount, poor bead appearance, and high internal porosities. In addition, the residuals left after welding on the surface of the plate can affect the corrosion resistance by interfering with the coating process. The fundamental mechanisms and the essential variables controlling spatter, porosity and productivity while welding over zinc coated steels are discussed. Two novel approaches to welding coated steels are explored. Intentional alloying through the core of a tubular wire to affect zinc evolution time and a welding process that uses an advanced power source to enable stable droplet transfer using an AC waveform is shown to enable the cored wire to be used at high travel speeds without affecting critical weld attributes. The effect of residuals on the weld surface due to post welding e-coating processes was also evaluated. This process is compared to other existing solutions to show the advantages and concerns for welding over zinc coated materials for automotive applications.

INTRODUCTION

With the increasing conversion of automotive chassis components to hot dip galvanized steels to improve corrosion resistance and the transition to thinner advanced high strength steel to meet the demands of increased fuel efficiency, finding suitable welding solutions for coated materials has assumed higher significance. The common standard process for welding chassis components is to use a GMAW process. For coated components this solution has produced very inconsistent results. However, welding coated steels has always been a critical issue with conventional processes and consumables due to the low boiling temperature (906°C) of zinc. Vaporized zinc is trapped during weld solidification generating both internal and external porosity. In addition, increased arc turbulence due to the zinc vapor causes an abnormal increase in spatter and affects the directionality of the arc thus affecting the bead shape. These visual and internal defects significantly reduce the mechanical properties of the weld joints and could potentially cause pre-mature failure of components[1]. In addition, the residuals left after welding on the surface of the plate can affect corrosion resistance by interfering with the coating process.

From manufacturers' point of view, several criteria, including productivity, mechanical properties, e-coating ability, and base material properties, are essential to evaluate the galvanized welding processes. The general perception is that the productivity often decreases with zinc coating thickness due to the generation of the zinc induced external and internal porosities in the weld deposit requiring rework time. One common approach to reduce porosity is by reducing the welding speed, which leads to a lower productivity. Past work also shows dramatic reduction in the load carrying capacity of the joint when internal porosity is larger than 10% of total weld bead area[2]. Most arc welding processes will evaporate the zinc on the plate leading to corrosion in the weld area and in the backside of the bead. In order to minimize corrosion, a post welding protective coating, e-coating, is usually required. Traditional e-coat processes can be affected by spatter and slag on the surface. Coating manufacturers are developing cleaning methods to improve the e-coat coverage on welded galvanized steels.

The base material properties, such as heat affected zone (HAZ) sizes and penetration depth, are associated with welding heat input and process parameters. Welding with higher heat input is more likely to have high potential of burning through thin sheets. There are several potential welding solutions for welding galvanized sheets in automotive industry, including commonly used pulsed GMAW processes and self-shielded flux cored arc welding processes. This work details the development of a new welding process with a specialized metal cored wire and a specialized AC pulse waveform (Solution B). This welding process uses an advanced power source to establish stable droplet transfer by an AC waveform and is shown to enable the cored wire to run at high travel speeds without affecting critical weld attributes. The advantages and disadvantages for each galvanized welding solutions are listed in **Table 1**.

The new process (Solution B) will be compared to other processes to benchmark weldability, productivity, internal and external porosity. Some initial results on the corrosion resistance of the weldments after e-coating will also be presented. Solution C which is a commercially available solution for welding over coated steels will be discussed purely for comparative purposes with Solution B. In addition, the benefits of using the AC waveform in conjunction with the metal cored wire will be highlighted by comparing it to a solution where the metal cored wire is used with a constant voltage power source operated in negative polarity. Finally, some preliminary results on the

Table 1. Advantages and Disadvantages for Different Galvanized Welding Solutions

	Process Detail	Pros	Cons
Solution A	GMAW with DCEP Pulse	· Standard equipment · Standard solid wire · No clean-up needed	· High porosity · Spatter · Burn through · High repair rate · Low travel speed
Solution B	Metal cored wire with AC waveform	· Minimum porosity · Low spatter · Flexible with gap · High travel speed	· Investment on new equipment · Silica islands on the surface
Solution C	FCAW-S wire with DCEN	· Standard equipment · Minimum porosity · High travel speed	· Slag clean-up · Fume cleaning · May not e-coat well
Solution D	ER70S-6 Laser Hot Wire	· Minimum porosity · No clean-up needed	· High equipment cost · Additional training required

effect of post weld e-coating on the corrosion rates using standardized test protocols will be presented. The laser hot wire is a superior solution for automotive industry capable of producing porosity free welds with minimal surface residuals at high travel speeds. However, the high cost of the equipment, efficiency and the difficulties of adopting the technology to the current process will remain the laser hot wire solution for future development and investment.

EXPERIMENTAL

The experiments were conducted with two discussed solutions. The 1.1 mm (0.045 in.) diameter AWS ER70S-6 wire, and a 1.0 mm (0.040 in.) diameter AWS E70C-GS (Metalshield® Z™) wire were used in solution A, and B, respectively. All the welds were produced by FANUC robotic welding system, with the Lincoln Electric Power Wave® S350 and Advanced Module. 2.0 mm (0.080 in.) thick DP 980 advanced high strength galvanized steel sheets with 60 g/m^2 coating amount (ASTM A653 60G/60G) were used as the base material for the weldability evaluations. For the corrosion testing, the steel sheets conformed to the 55CR01 MS-6000 Chrysler specification. The welds

Table 2. Testing Parameters for Each Solution

	Solution A	Solution B
Wire	1.1 mm (0.045 in) ER70S-6	1.0 mm (0.040 in) E70C-GS
Waveform	Advanced Pulse	AC waveform (Rapid Z™)
Shielding Gas	90% Ar and 10% CO_2	
CTWD (in)	1/2 - 5/8	
Travel Speed	16.9 - 21.2 mm/sec (40-50 in/min)	
Welding Position	2F Lap	

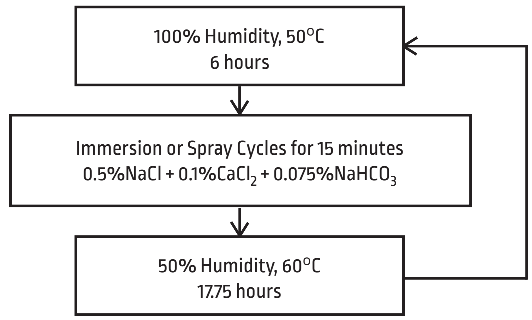
were deposited to galvanized sheet at 2F lap joint in single pass. The gap between two base sheets was fixed on the specialized fixture to maintain no gap condition during welding. The mixed gas of 90% argon and 10% CO_2 was used as the shielding gas at 1.13 m^3/hr (40 ft^3/hr) flow rate. All the experiments were performed at 16.9 mm/sec (40 in/min) travel speed. The detail welding parameters for each solution are shown in **Table 2**.

Chemical compositions for the weld deposits were examined by an optical emission spectrometer (OES). The internal porosity was examined by X-ray radiography after welding. ImageJ was used as the imaging software for calculating the porosity sizes, numbers and areas from radiography images. The number of each data point is the average result of three welded sheets. Metallography samples for light optical microscopy were prepared with standard procedures. Post welding e-coating experiments is in progress with major OEMs.

Corrosion Testing

Accelerated corrosion testing of the welded samples used the SAE J2334 cyclic corrosion test method[3] and an accelerating solution. This test method exposes samples sequentially to a hot 100% humidity atmosphere for six hours followed by immersion/spray environment for 15 minutes and then a hot 50% humidity atmosphere over

Figure 1. Standard SAE J2334 Cyclic Corrosion Cycle



the course for a 24 hour cycle as shown in **Figure 1** above. Due to the constraints of the corrosion cabinets used in this work, the accelerating solution was sprayed on fifteen times (5 seconds every minute) to ensure the samples are soaked with the accelerating solution for the entire 15 minute period. Testing was conducted for 80 cycles with observations and pictures taken every 20 cycles. The benchmark for comparing the two solutions was samples of uncoated and coated steels that were spot welded at the edges.

RESULTS

Chemical Analysis

Table 3 shows the chemical compositions of the weld deposit from solutions A and B respectively.

Table 3. Chemical Composition of Weld Deposit

	%C	%Si	%Mn	%P	%S
A	0.08	0.08	1.52	0.006	0.008
B	0.12	1.03	1.65	0.008	0.01

Porosity

Solution A is the process with the 0.045 in. ER70S-6 wire and the advanced pulsed DCEP waveform. **Figure 2** shows the radiography images at 16.9 mm/sec (40 in/min) travel speed. The amount of internal porosity is 3 per inch weld, and the area of the porosity is 8% of total weld area at 16.9 mm/sec (40 in/min) travel speed.

Figure 2. Radiography Images of Solution A at 16.9 mm/sec

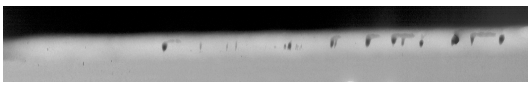


Figure 3 demonstrates the radiography image of Solution B at 16.9 mm/sec (40 in/min) travel speed. Solution B shows promising results of controlling zinc porosity to a minimum level in the weld deposit. The amount of internal porosity is 0.1 per inch weld, and the area of the porosity is 0.04% of total weld area. This data is calculated based on data from welds made in triplicate and averaged. The effect of travel speed on the internal porosity is also summarized in **Figure 4**.

Figure 3. Radiography Images of Solution B at 16.9 mm/sec (40 in/min) Travel Speed

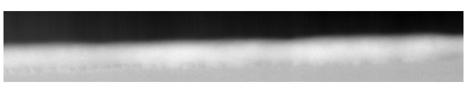
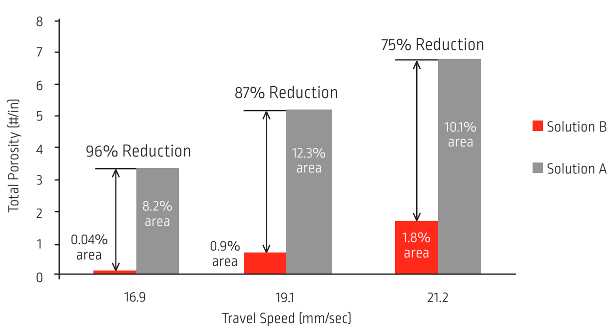


Figure 4. Comparison of Total Internal Porosity Counts/Areas for Different Solutions at 16.9-21.2 mm/sec Travel Speed



Bead Profile

The bead profiles with the indication of HAZ and penetration depth of Solution A and B are shown in **Figure 5 and 6.** Deeper bead penetration is commonly observed from the DCEP welding process. The penetration depth is 1.24 mm and the HAZ size of the bead is 8.28 mm while traveling at 16.9 mm/sec (40 in/min) with Solution A in comparison to Solution B which had a penetration depth of 0.83 mm and HAZ size of 7.56 mm. This data is summarized in **Table 4. Figure 7** shows the porosity in radiography images for Solution A and B at different travel speed. As the travel speed increases, more internal porosity can be found in the weld bead. The procedures at the three different travel speeds were adjusted so as to deposit the same size weld bead.

Figure 5. Effect of Travel Speed on Bead Shape and Penetration Profiles When Welded with Solution A

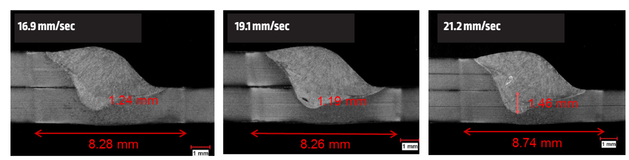


Figure 6. Effect of Travel Speed on Bead Shape and Penetration Profiles When Welded with Solution B

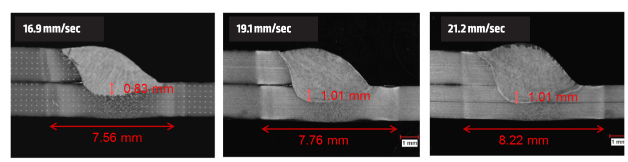


Table 4. Penetration Depth and HAZ Size for Different Solutions at 16.9 mm/sec (40 in/min) Travel Speed

	Solution A	**Solution B**
Penetration Depth (mm)	1.24	0.83
HAZ Size (mm)	8.28	7.56

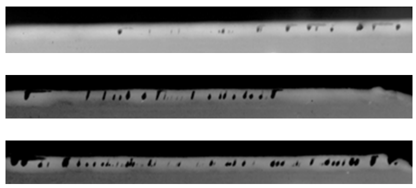
Figure 7. Radiography Images of Solution A and B at 16.9 to 21.2 mm/sec Travel Speed

Solution A:

16.9 mm/sec

19.1 mm/sec

21.2 mm/sec

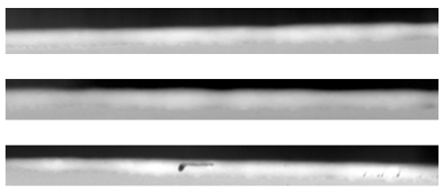


Solution B:

16.9 mm/sec

19.1 mm/sec

21.2 mm/sec



Corrosion Tests

All tests coupons were scribed before the beginning of testing. The affected weld areas maximum width affected by corrosion, formation of red rust and paint loss/ blistering in the weld was estimated. The increase in the weld area covered with rust was similar for Solution A and Solution B after 60 days. However, visually the Solution B seemed to have lesser red rust than Solution A. **Figure 8** from Solution B shows lesser of the red rust than Solution A. In comparison, the benchmark samples from coated/ spot welded samples did not show any sign of rusting and the cold rolled samples showed the most extensive edge and scribe rusting. Future work will show the results after 80 days and quantitative measurements of rust coverage and affected weld areas.

Comparison of Solution B with and without the AC waveform:

Spatter

A metal cored wire when welded on DCEN has the highest spatter amount. The Solution B running with AC waveform significantly reduced the amount of spatter by 36% than running with negative polarity. The amount of spatter while welding with and without the AC waveform is shown in **Figure 9**. The spatter was collected from three welds each six inches in length welded with each solution at 16.9 mm/sec (40 in/min). The spatter amount for Solution B is 3.3 g with AC waveform and 5.2 g with negative pulse waveform. It is clear that the welding with AC waveform can significantly reduce the amount of spatter.

Figure 8. Interim Results of Corrosion of Welds Made with (a) Solution A and (b) B Compared with Control Samples. (c) Coated and Spot Welded Sample and (d) Uncoated/Spot Welded Base Material with No Arc Weld

(a) (b) (c) (d)

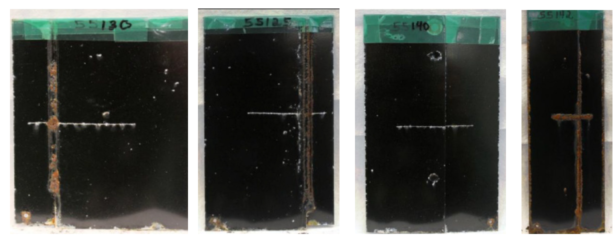
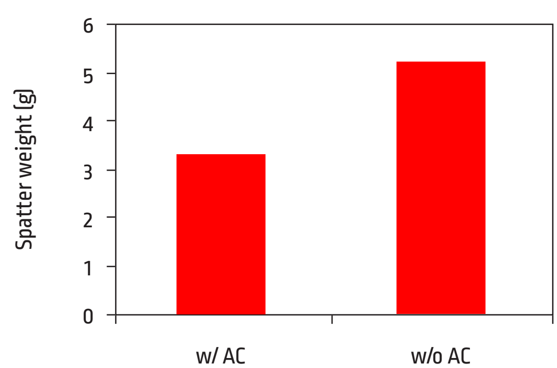


Figure 9. Spatter Weight for Solution B With and Without the AC Waveform



Operating Range

The differences in operating range between Solution B with and without the AC waveform are schematically shown in **Figure 10** below. This also shows the change in penetration and HAZ size as a function of bead size (WFS).

DISCUSSIONS

Porosity

One major concern of welding coated steel is the porosity. As mentioned in the background work, the negative effects of internal porosity can dramatically reduce the fatigue life and tensile strength of the welded components. The target of all new solutions for welding galvanized sheets is to effectively reduce the external and internal porosity of the weld deposit.

One of the approaches to reduce porosity is to lower the solidification temperature of weld deposit. In an arc welding process, the arc superheats the weld pool to temperatures around 2500°C which is well above the melting point of steel and boiling point of zinc. As the weld pool cools down, the zinc continues to evolve out of the weld pool, interacts with the oxygen and forms zinc oxide. The zinc oxide is distinctively seen as a white residue either along the edges of the weld pool (coldest regions) or in cases where the zinc is trapped by the solidification front, as a white residue on the surface of external pores of the weld. The trapping of zinc within the weld occurs when the solidification is complete before the evolution of the trapped zinc. The lower solidification temperature will keep the weld pool at liquid phase for a longer time in order to extend the time for zinc to escape from the weld deposit. The solidification temperature can be influenced by the additive chemicals in the core. Solidification temperatures of the weld metal with different levels of alloying levels in the wire core are calculated with Thermo-Calc®[4]. The Scheil solidification simulation module was to calculate the solidified mass fractions. Carbon, manganese, aluminum, and silicon are included in calculation. The temperature corresponding to 95% solidified mass is given in **Table 5**. The solidified mass fraction of 95% is chosen due to the zinc vapor is most likely to be trapped in weld metal towards the completion of solidification. Table shows that the weld bead of Solution A has a higher solidification temperature than Solution B. With lower solidification temperature, zinc vapor has more time to escape from or dissolve into the weld pool, and hence lower tendency to form porosity. This is also consistent with the longer crater size of welds made with Solution B in comparison with Solution A as shown in **Figure 11**. As the travel speed is constant, a longer weld pool indicates that it takes longer time for weld metal to solidify.

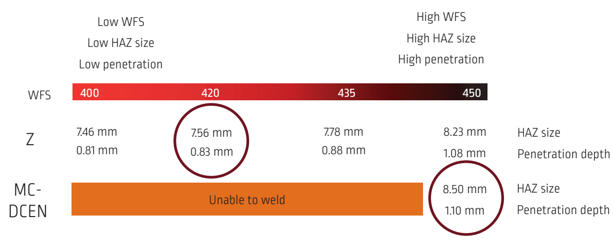


Figure 10. The Operating Range for Solution B With (Z) and Without (MC-DCEN) AC Waveform at 16.9 mm/sec (40 in/min) Travel Speed

Another approach for zinc porosity reduction is by controlling the waveform. Welding at positive polarity has the advantage of focused arc at the end of the wire to minimize unnecessary surrounding zinc interaction and high localized pinch force for better droplet transfer as illustrated in **Figure 12 (a)**. On the other hand, welding at negative polarity can reduce the penetration depth of the weld deposit and the zinc interaction volume as shown in **Figure 12 (b)**. This effect of using an electrode negative polarity cored wire has been successfully used with commercial self-shielded cored wire solutions to weld over coated steels. The disadvantages of using a self-shielded cored wire for welding over coated steels has to do with the residual slag/scum on the surface of these weld deposits. This surface oxide that forms on top of the weld metal if not completely removed could result in issues during the post-weld surface treatment for corrosion protection e-coat process.

Table 5. Temperature of 95% Solidified Mass from Simulation

	Solution A	Solution B
95% solidification temperature (°C)	1456	1440

Figure 11. Crater Sizes from Solution A and B Deposited at 16.9 mm/sec [40 in/min] Travel Speed Indicating the Differences in the Weld Pool Solidification Times

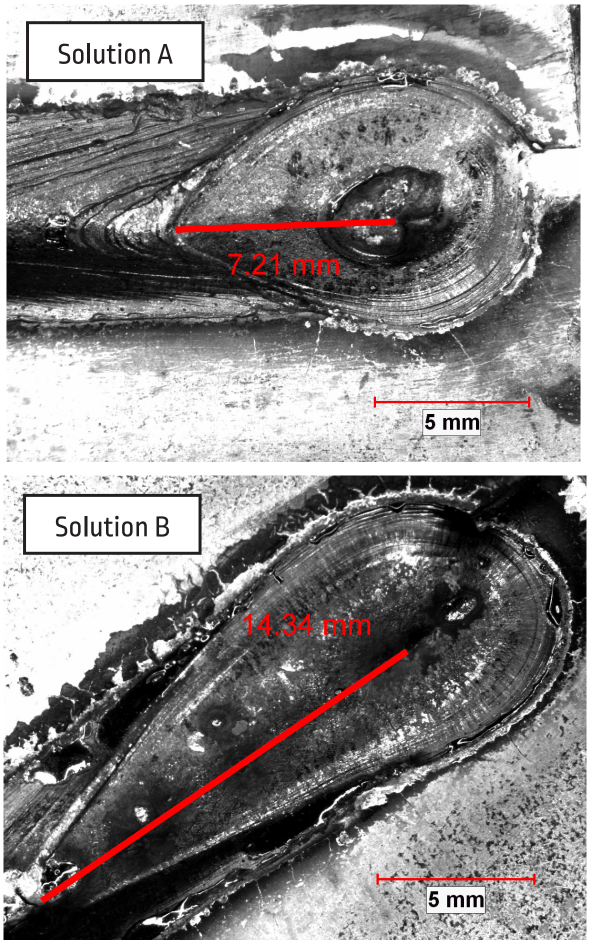
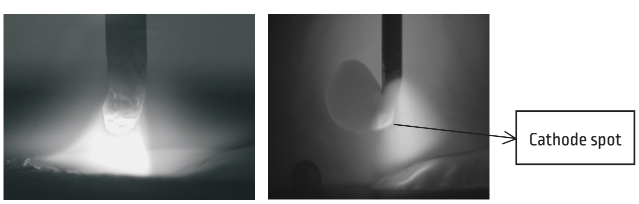
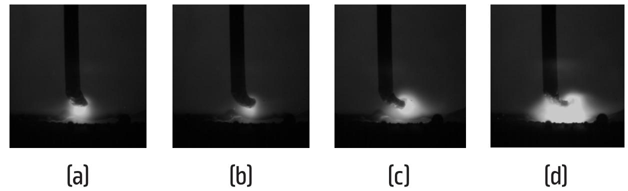


Figure 12. Illustration of the Droplet Transfer at [a] Positive Polarity and [b] Negative Polarity



[a] [b]

Figure 13. A Series of Snapshots of Droplet Transfer Welding in DCEN. [a]-[g] Comprises of Snapshots of the Arc Taken Over 260 mseconds



[e] [f] [g]

A secondary issue of using a cored wire in negative polarity is the instability of the cathode spot which is now located on the tip of the electrode instead of being right under the root of the arc plasma on the substrate in the case of DCEP welding[5]. This cathode spot now tends to move around the electrode tip creating an arc plasma that is less directed and forceful than its DCEP counterpart. **Figure 13** shows several snapshots of a wire welded under negative polarity illustrating the unfocused nature of the arc and irregular droplet detachment process. It indicates the unstable tether being formed and the inability of the droplet to form/detach from the electrode tip. This is due to the arc plasma climbing the wire and encompassing the entire droplet, decreasing the current density along the axis of the wire thus leading to a lower pinch force for droplet detachment. This lack of arc focus while producing a shallower penetration profile beneficial for welding over zinc interaction in the root of the weld, also increases the possibility of zinc interaction along the edges of the weld bead. This also results in requiring a larger weld bead to fill a joint of variable gap usually encountered in field applications thus potentially increasing the heat affected

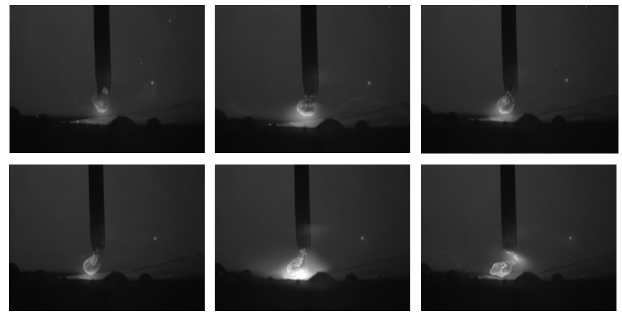
Table 6. Major Aspects for Welding Galvanized Sheets at Negative and Positive Polarity

DCEN	DCEP
· Wandering cathode spot · Unfocused arc · Shallower penetration profile · Low Zn interaction	· Stationary cathode spot · Focused arc · Higher pinch forces · Finer droplet transfer

zone size and deterioration in base material properties achieved through thermo-mechanical treatment as shown in the **Figure 10**. **Table 6** summarizes the positive and negative aspects of welding with either polarity. In order to minimize the impact of a wandering cathode spot on droplet transfer and the resulting instabilities, a specialized AC waveform that comprises of a negative background and a positive peak has been developed to achieve a one droplet per cycle transfer mode. In this specialized waveform developed for welding over coated steels in conjunction with a specialized wire with additives for increased zinc evolution time, the wandering of the cathode spot is minimized by switching polarity from negative background to positive to force the arc to be rooted to the bottom of the electrode/droplet before it has a chance to overheat the wire and cause a secondary initiation of the arc from a different position on the electrode tip. Once the droplet is delivered on the positive cycle, the polarity is switched again to build the droplet in the negative cycle thus minimizing the zinc interaction in the root of the joint. **Figure 14** shows snapshots of the droplet delivery during this process.

Solution A used the most common conventional ER70S-6 welding wire with an advanced pulse waveform in positive polarity. The solution was able to create weld deposit without external porosity. However, there are still much internal porosity inside of the weld deposit and deeper penetrations.

Figure 14. A Series of Snapshot of Droplet Transfer Welding with Solution B Showing the Droplet Formation and the Necking of the Droplet Due to the Pinch Force Allowing for Stable and Focused Droplet Delivery



Solution B runs with an AC waveform, which combines the advantages from both positive and negative polarity and eliminate the negative effect on both sides. Radiography images clearly show that Solution B has the lowest overall internal porosity.

With the combination of new consumable and waveform design, Solution B has the cleanest weld deposit with up to 99% reduction of porosity number or area.

Corrosion

Visual appearance of the welded regions after 60 days suggests that Solution B has a qualitatively lower amount of red rust and general corrosion around the weld area.

Quantitative metallography and measurements are underway and will be completed after the 80 day exposure is completed.

Overall

Table 7 shows an overall comparison between three solutions. +++, ++ and + represent the best, better and normal result in each category, respectively. In general, Solution B has the best overall results.

CONCLUSIONS

With the trend of moving into thin and galvanized thin sheets in automotive industry, welding on galvanized thin

Table 7. Overall Comparison

	Solution A	Solution B
Porosity	+	+++
Spatter	+	++
Penetration	+	+++
Overall	+	+++

sheets brings serious concern on the effects zinc porosity. Many efforts and attempts were made to effectively reduce the numbers of the porosity and still maintain the high productivity. In this study, two solutions for welding galvanized thin sheets without gap has been thoroughly examined and presented. Solution A, the conventional ER70S-6 wire with the advanced pulse waveform is compared to Solution B, a newly developed Metalshield® Z™ cored wire with a specified Rapid Z™ AC pulse waveform. The Solution B shows the best result in porosity and spatter, and remains a better penetration profile. The AC waveform also increases the usable operating range of the process and minimizes burn through and size of the heat affected zone that could be critical to performance of AHSS.

The approach of developing a solution for welding galvanized thin sheets using a specialized metal cored wire with an AC waveform has shown promising results. The intentional alloying additions in the core wire successfully elongated the weld pool and increased the evolution time to partition the zinc away from the weld deposit. The ability to tailor the waveform to achieve stable and consistent droplet transfer and low zinc interaction volume has been demonstrated. This newly developed solution with adequate penetration, minimal HAZ and porosity, but still remaining high productivity and quality shows promise for welding over hot dip galvanized zinc coated steels. The effect of welding over coated steels and post weld e-coat treatment on corrosion has been qualitatively estimated.

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