Metal-Cored Gas Metal Arc Welding Electrode for Producing Welds in Zinc-Coated Steels with Minimal Porosity

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Abstract

The trend toward lightweight, coated steels in the automotive industry has created unique fabrication challenges, especially in the welding process. Gas metal arc welding (GMAW) using solid wire in short-circuit or pulse transfer mode has long been the joining method of choice in these situations, however GMA welds are frequently laden with porosity. The presence of porosity can reduce joint strength and poor weld integrity. The problem is solid wires, such as American Welding Society (AWS) ER70S-3 and ER70S-6, do not contain any ingredients to counteract or neutralize the reactions that take place in the weld pool, which are a result of the vaporization of the zinc coating. Self-shielded flux-cored arc welding (FCAW-S) electrodes have met with success in terms of reducing the amount of porosity, however the process has some disadvantages. The operation of self-shielded FCAW electrodes can be harsh and some types tend to produce high levels of weld spatter and fumes. They also leave a slag coating on the weld that the welding operator must remove before the parts can be painted or put into service.

Hobart Filler Metals has recently introduced a metal-cored welding electrode designed for constant voltage GMAW. Unlike solid wires, this metal-cored wire contains small amounts of fluxing ingredients, which help to counteract the effects of the zinc or other coating materials. The wire is uniquely formulated to operate on direct current, electrode negative (DCEN), which reduces the amount of heat going into the base plate and with it, the likelihood of burn-through. Extensive testing of the new wire, both at Hobart and at customer locations, shows that porosity is significantly lower with the new wire as compared with solid wires. Furthermore, research finds that welds produced with the new wire had only negligible amounts of porosity over the entire range of travel speeds tested. Welds that contained greater than about 6% porosity failed at significantly lower loads than those that contained only minimal amounts of porosity.

Acknowledgement

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Introduction

The trends in automotive manufacturing over the past 40 years have been toward the use of lighter-weight materials to manufacture vehicles with improved fuel economy. Replacing traditional steels with advanced high strength steel (AHSS) with a reduced thickness is one approach to decreasing the weight in chassis applications. With the reduced thickness, however, come concerns about corrosion resistance. One solution to the corrosion problem is to use a zinc (Zn) coating in concert with e-coating for chassis applications.[1] Utilizing Zn for these applications does present a joining concern, however. Solid wire GMA welding of hot-dipped galvanized (HDG) steel has traditionally been fraught with difficulties due to increased spatter, internal porosity, arc instability, and throughput degradation. Flux-cored arc welding (FCAW) has been proven to be successful to reduce porosity.[2,3] Tower International and others have successfully welded HDG steel using FCAW for many years.

The typical solid wire GMAW consumable (e.g., ER70S-3 or ER70S-6) does not contain any ingredients to counteract or neutralize the reactions that take place in the weld pool. The boiling point of zinc is lower than the melting point of steel, so as the base material is heated to its melting point, the zinc coating vaporizes, which leads to porosity. One way to reduce the porosity is to reduce the travel speed, which gives the zinc vapor more time to escape before the molten steel solidifies. As the travel speed is reduced, however, the chances of burn-through increase, making it very difficult to produce a sound weld.

Another difficulty associated with welding galvanized and other coated materials is that welds that appear to be sound during visual inspection may actually contain extensive sub-surface porosity. Figure 1 shows an example of a weld produced using solid wire GMAW at a travel speed of 1 m/min. The weld fully met visual acceptance requirements, despite the fact that it had extensive internal porosity. Several studies have found that roughly 20% of welds produced using solid wire GMAW exhibited unacceptable levels of sub-surface porosity *even though* the welds fully met the visual inspection requirements.

Figure 1. **Example of weld produced with solid wire GMAW that passed visual inspection. The weld had gross internal piping porosity, as indicated in red.**

Another major challenge associated with welding galvanized or other coated materials is that the thickness of the coating may not be consistent. Figure 2 shows a steel substrate that is zinc-coated. Within one very small area, the thickness of the zinc coating ranges from 3.4 to 21.6 μm (0.13 to 0.85 mil). This variation in coating thickness means that the welding consumable needs to manage a wide range of zinc contents with little or no variation in arc action and weld quality. While it may be possible to "dial in" the welding parameters for a solid wire for a specific coating thickness, if that thickness varies, the welding operation and integrity will likely deteriorate.

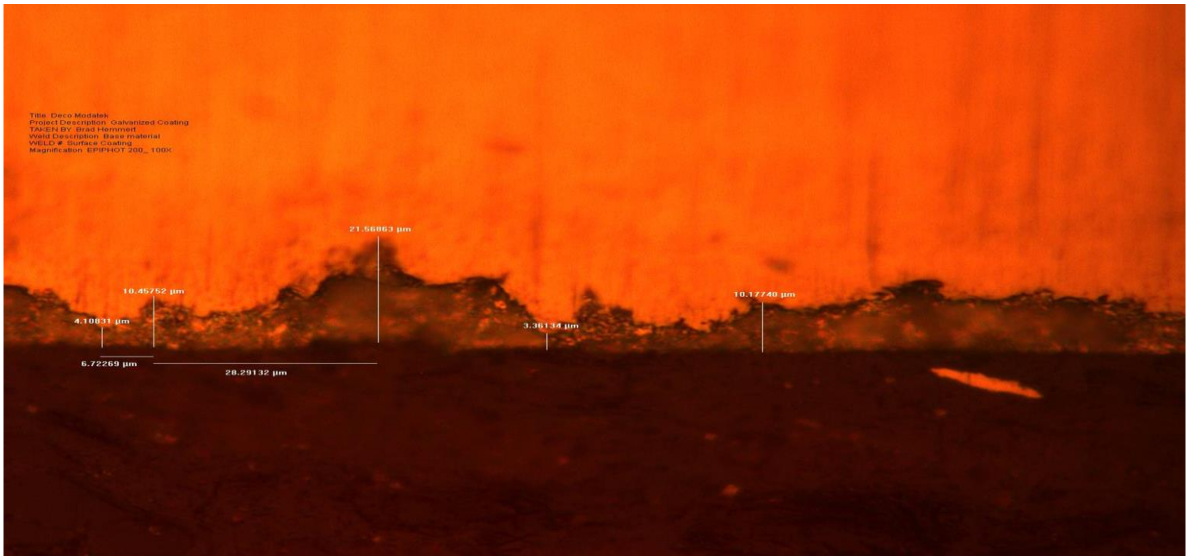

Figure 2. **Typical variations in thickness of zinc coating on hot-dipped galvanized steel.**

New Product Development

Hobart Filler Metals recently took on the challenge of producing a metal-cored arc welding (MCAW) electrode that could be used on light-gauge coated steels at faster travel speeds with minimal porosity and burn-through. Thin gauge and coated steels are typically welded either with a small diameter solid wire or self-shielded flux-cored arc welding (FCAW) electrodes. There are two problems with these solutions. Solid wires do not contain ingredients to react with the volatile coating materials, which can result in porosity-laden welds. Self-shielded FCAW electrodes, on the other hand, often include ingredients that react with the coating materials to reduce or eliminate porosity, however the operation of these electrodes can be harsh and in some cases they can produce high levels of smoke and weld spatter. They also leave a slag coating that needs to be removed before the parts can be painted or put into service.

In order to prevent burn-through on thin, coated steels when traveling at a speed that produces acceptable weldments, it is necessary to direct the heat away from the workpiece. An electrode that is usable with direct current electrode negative (DCEN, or negative polarity) offers a solution. The majority of flux-cored, metal-cored and solid wires operate on direct current electrode positive (DCEP, or straight polarity). In DCEP, the welding gun is connected to the positive terminal of the welding machine, and the workpiece is connected to the negative terminal. This means that the current flows from the electrode to the workpiece, which focuses the heat on the part being welded. In DCEN, the welding gun is connected to the negative terminal of the welding machine, which causes the current to flow from the workpiece to the electrode. The result is that the heat is focused at the electrode rather than on the base plate, providing a less penetrating arc. The difference between DCEP and DCEN is shown schematically in Figure 3. Because there is less heat going into the base plate when utilizing DCEN, there is less chance of burn-through and a reduced amount of weld distortion.

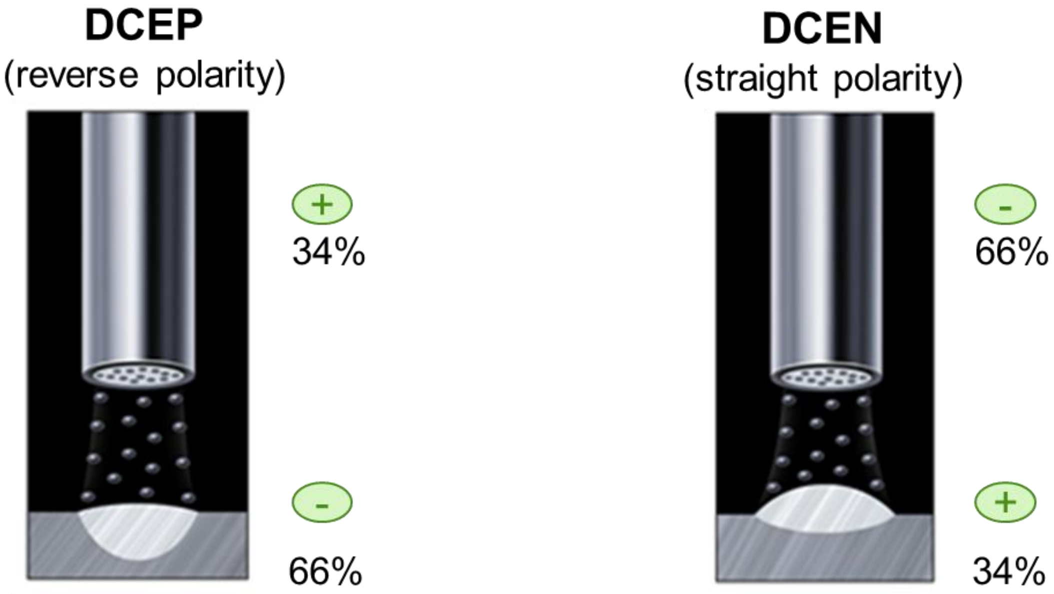

Figure 3. **Schematic showing how polarity affects the heat distribution and penetration profile in FCAW and MCAW.**

Traditional GMAW with solid and metal-cored wires utilizes DCEP because the arc tends to be very unstable in DCEN. High levels of spatter and poor weld quality are also typical with GMAW using DCEN.

The new product from Hobart Filler Metals — FabCOR® F6® metal-cored wire — has been specially formulated with a proprietary blend of arc stabilizers to operate smoothly on DCEN with minimal weld spatter. Besides utilizing negative polarity, the FabCOR F6 wire also includes a small quantity of fluxing ingredients that interact with the zinc, causing it to gas out earlier, when the weld pool is still very fluid. These fluxing ingredients also act to focus the arc, leading to a smaller spot size, which acts to further improve the weld bead contour.

Tower International Testing[*]

Tower International recently undertook extensive testing of various welding consumables in order to better understand the factors that affect weld quality and robustness. The welding consumables tested included ER70S-6, ER80S-D2, E71T-14 and FabCOR F6 (E70C-GS). Welds were produced at three different travel speeds and were radiographed to determine the level of porosity. The amount of porosity was evaluated using PAX It!™ image analysis software. Engineers also tensile tested welds, and cross-sectioned, polished and tested other welds for micro-hardness in the weld metal, heat-affected zone (HAZ) and base metal.

The material tested was 3.0 mm (0.12 inch) thick 550-MPa (80-ksi) high strength low alloy (HSLA) steel with a hot dipped galvanized (HDG) coating produced to Fiat/Chrysler Automotive Specification MS.50002-LAH550Y620T GI 60/60 U. Lap welds were produced in the 3-o'clock position (2F) at three

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[*] Data and statistical analysis provided by Tower International

different travel speeds. Five welds were made at each travel speed/wire combination for a total of 60 welds. The welding conditions are summarized in Table 1. The parameters were set so as to provide a similar bead profile for each product/travel speed. The plates were clamped so that there was no gap. The plate orientation and details are shown in Figure 4.

Table 1. Parameters used for producing test weldments.

Wire	Travel Speed cm/min (ipm)	WFS cm/min (ipm)	Heat Input kJ/cm (kJ/in)	Travel Angle	Work Angle	Targeting	Sample Nos. Settings
ER70S-6 GMAW-P 3/8" ESO DCEP 85/15 Shielding	64 (25)	699 (275)	4.0 (10.2)	5° Push	40°	1.5mm high	***S6-S10*** 194A/22V
	89 (35)	864 (340)	4.0 (10.0)	5° Push	40°	3mm high start 2mm high weld	***S1-S5*** 247A/23.7V
	114 (45)	1143 (450)	3.6 (9.3)	15° Push	40°	1.5mm high	***S11-S15*** 283A/24.7V
ER80S-D2 GMAW-P 3/8" ESO DCEP 85/15 Shielding	64 (25)	724 (285)	4.9 (12.5)	15° Push	45°	1mm high	***D6-10*** 224A/23.2V
	89 (35)	826 (325)	3.9 (9.9)	5° Push	40°	2mm high	***D1-D5*** 244A/23.6V
	114 (45)	385 (9.8)	3.7 (9.5)	5° Push	40°	1mm high	***D11-D15*** 281A/25.3V
E71T-14 FCAW ¾" ESO DCEN Self-shielded	64 (25)	864 (340)	7.9 (20.4)	10° Drag	35°	In the joint	***F6-10*** 348A/24V
	89 (35)	1143 (450)	6.7 (17.0)	10° Drag	35°	In the joint	***F1-5*** 397A/25V
	114 (45)	1461 (575)	6.3 (16.0)	10° Drag	45°	In the joint	***F11-15*** 445A/27V
FabCOR F6 GMAW 5/8" ESO DCEN 85/15 Shielding	64 (25)	737 (290)	6.8 (17.2)	10° Push	40°	1.5mm high	***M6-10*** 323A/22.2V
	89 (35)	1118 (440)	6.1 (15.6)	10° Push	40°	1.5mm high	***M1-5*** 383A/23.7V
	114 (45)	1461 (575)	5.7 (14.6)	10° Push	40°	1.5mm high	***M11-15*** 441A/24.8V

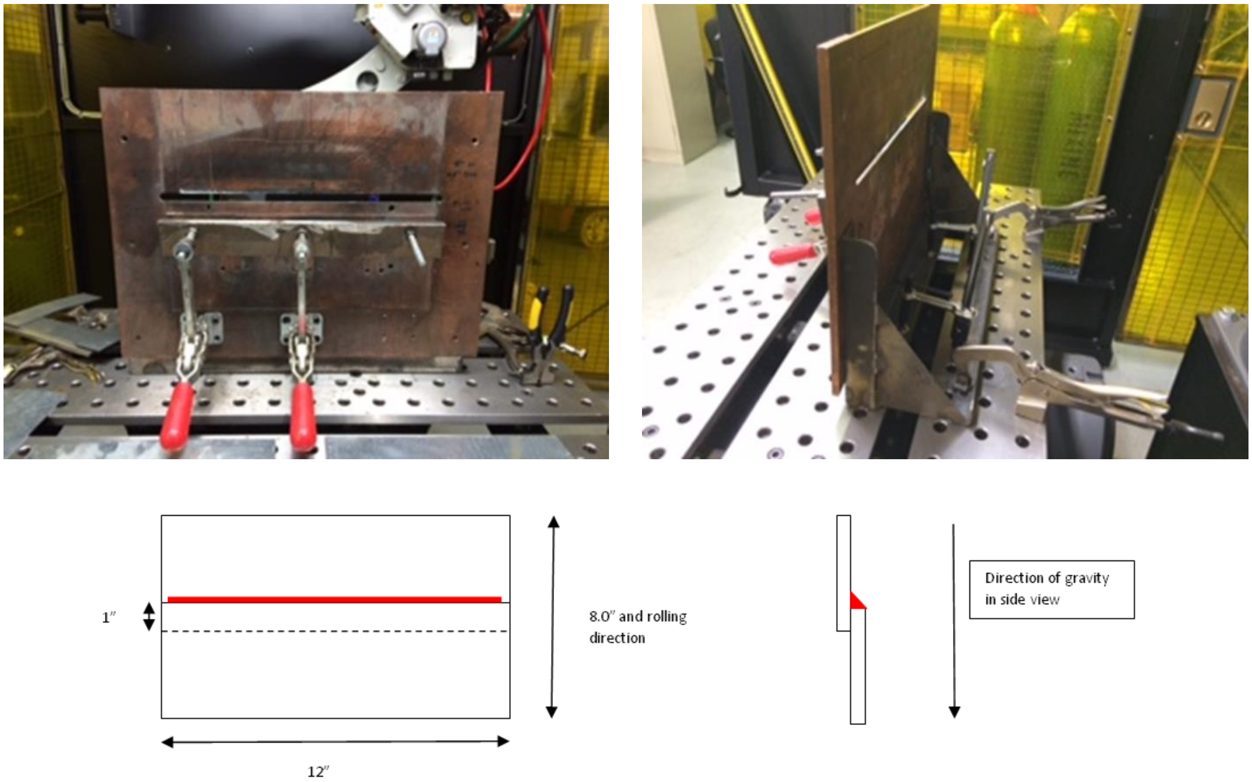

Figure 4. **Welding fixture and plate set-up.**

Tower InternationalTest Results

Porosity

The key finding in the Tower International study was that the percentage porosity was strongly dependent on the wire type. The FabCOR F6 wire performed the best, followed by the self-shielded FCAW wire. The solid wires had the poorest performance. The results of the porosity study as a function of wire type are shown graphically in Figure 5 (S = ER70S-6, D= ER80S-D2, F = E71T-14, and M = FabCOR F6) and are summarized in Table 2.

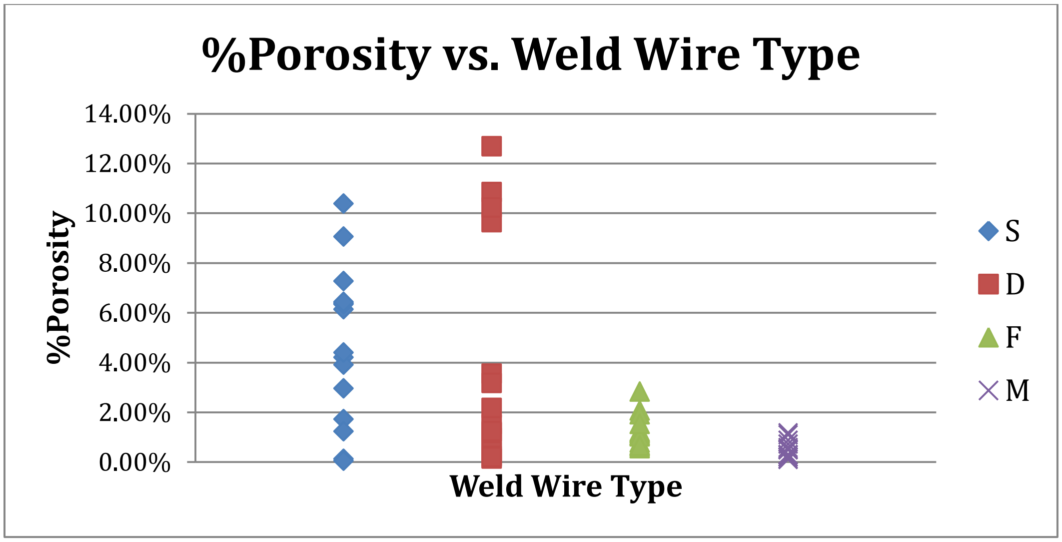

Figure 5. **Percent porosity as a function of wire type (S = ER70S-6, D= ER80S-D2, F = E71T-14, and M = FabCOR F6).**

Table 2. Summary of porosity results.

Wire Type	Mean	Median	Std. Dev	CoV	Max	Min	Range
S ER70S-6	4.71%	4.40%	0.0312	0.662	10.38%	0.05%	10.34%
D ER80S-D2	3.88%	1.51%	0.0451	1.161	12.69%	0.13%	12.56%
F E71T-14	1.22%	1.08%	0.0063	0.518	2.83%	0.55%	2.28%
M E70C-GS	0.49%	0.48%	0.0035	0.705	1.16%	0.10%	1.06%

There was a wide range in the amount of porosity in the welds made using solid wire. While some of the welds made using solid wire had minimal porosity, there were many that contained greater than 5%, and some that had 10% or more. The weld with the lowest amount of porosity overall was weld S-2 produced using ER70S-6, while the one with the greatest percentage was weld D-3 made with ER80S-D2. The welds are shown in Figure 6 and Figure 7. Note that Tower International produced both of these welds at a travel speed of 89 cm/min [35 inches/minute (ipm)]. As can be seen in Figure 5 and Table 2, the variability in the amount of porosity in the welds produced with the cored wires (flux- and metal-cored wires) was much less than for those made using solid wire.

Figure 6. **Sample S-2, which was produced using ER70S-6 at 89 cm/min (35 ipm) and contained 0.05% porosity.**

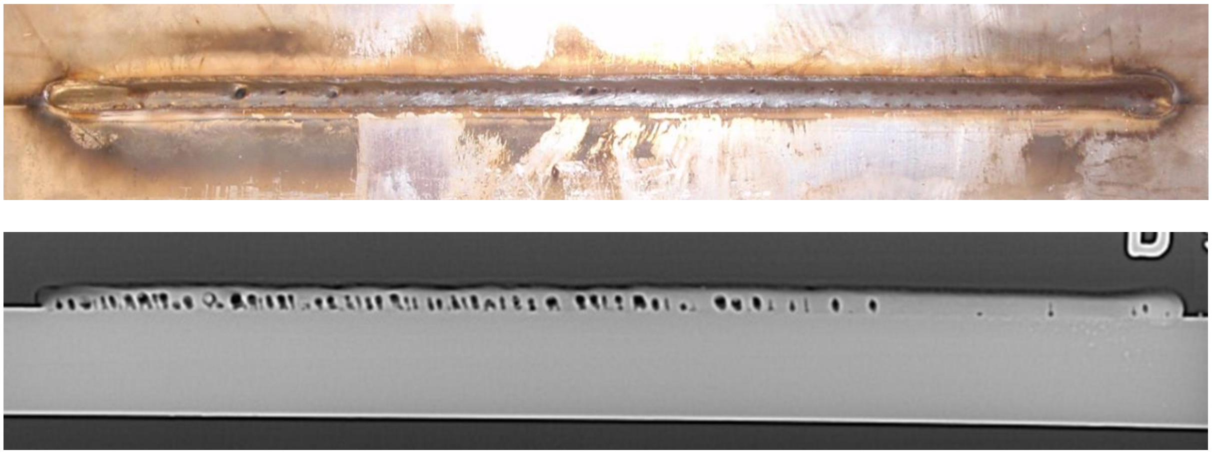

Figure 7. **Sample D-3, which was produced using ER80S-D2 at 89 cm/min (35 ipm) and contained 12.69% porosity.**

The amounts of porosity in the welds produced with the two solid wires were not significantly different from one another, but were significantly higher than the amounts of porosity in the welds produced with the flux- and metal-cored wires. It was also noted that the surface quality of the weld was not necessarily indicative of the amount of internal porosity.

It was found that, in general, there was not a strong correlation between the amount of porosity and travel speed for any of the wire types (taken as a group, the Spearman rho correlation coefficient is 0.009). The solid wires had the greatest degree of variation in the amount of internal porosity. The ER80S-D2 welds made at 89 cm/min (35 ipm) had more porosity than welds made at lower or higher speeds, whereas the ER70S-6 welds made at 89 cm/min (35 ipm) had less porosity than corresponding welds made at 64 and 114 cm/min (25 and 45 ipm, respectively). For the E71T-14 welds, the ones made at 114 cm/min (45 ipm) had the most porosity. There was effectively no difference among the FabCOR

F6 welds as a function of travel speed. At all travel speeds, the FabCOR F6 welds had the lowest amount of porosity followed by those produced with E71T-14 wire.

Tensile Test Results

Tower International performed transverse tensile testing on three welds from each wire type/travel speed, for a total of 36 tensile tests. The welds chosen for tensile testing were randomly selected. The welds were made perpendicular to the rolling direction and as a result, the transverse tensile samples were pulled parallel to the rolling direction. Engineers also tested an unwelded coupon, which had a peak force of 2873 kg (6333 lbs).

All of the broken tensile samples were examined visually to determine if the fracture surface contained porosity. Samples that had lower levels of porosity typically failed in the HAZ). The samples with more porosity (typically greater than about 6%) failed in the weld metal at the location of the porosity. Figure 8 shows an example of a fracture in a weld that contained porosity, produced using ER70S-6 at 64 cm/min (25 ipm). The weld itself and the radiograph are shown in Figure 9. A typical HAZ failure is shown in Figure 10.

Figure 8. **Typical tensile failure in sample containing porosity. Example shown is Sample S6 [ER70S-6, 64 cm/sec (25 ipm), 7.27% overall porosity].**

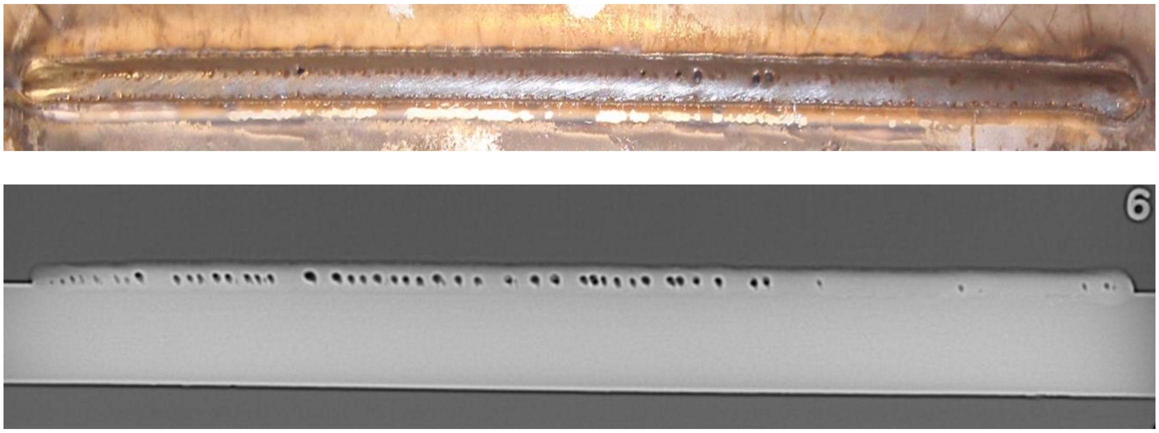

Figure 9. Sample S6, prior to tensile testing.

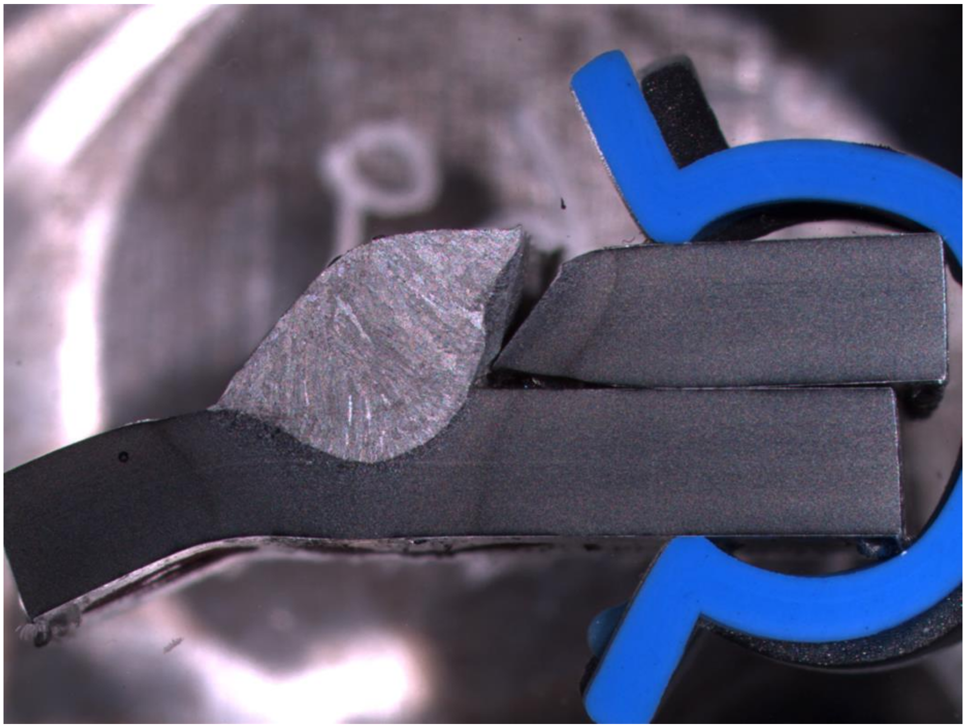

Figure 10. Example of fracture that occurred in HAZ adjacent to weld (Sample M6 - typical of all failures that were not a result of internal porosity).

As expected, the greater the amount of porosity that was in a sample, the lower the peak force at failure. Figure 11 shows peak force as a function of the amount of porosity in the weld. Note that the percent porosity is measured over the entire weld, not just the area where the tensile samples are taken. Because the porosity is not uniform over the length of the weld, a weld with relatively high levels of porosity may perform better than expected if the porosity is clustered in a location outside of the tensile sample.

It was noted that the samples welded using the E71T-14 at 45 ipm (114 cm/min) all had failures due to porosity, even though the overall amount of porosity in those samples was low (0.65 – 2.83%). A closer examination of the radiographs revealed that the porosity in those samples tended to be very fine and was typically dispersed along the entire length of the weld (see Figure 12). The welds made using the E71T-14 at lower travel speeds failed in the HAZ, similar to the other welds that did not fail due to porosity.

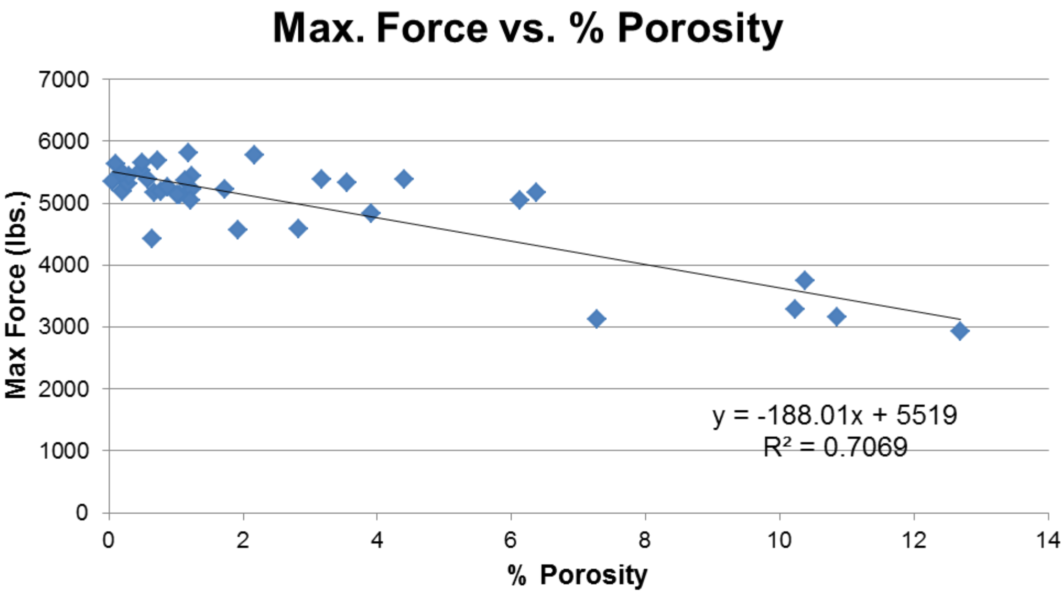

Figure 11. **Peak force versus percent porosity.**

Figure 12. **Sample F-12, produced using E71T-14 (1.92% porosity).**

The mean peak force for welds that did not contain porosity was significantly higher than for those that exhibited porosity at the failure location. This can be seen graphically in Figure 13. The data is summarized in Table 3.

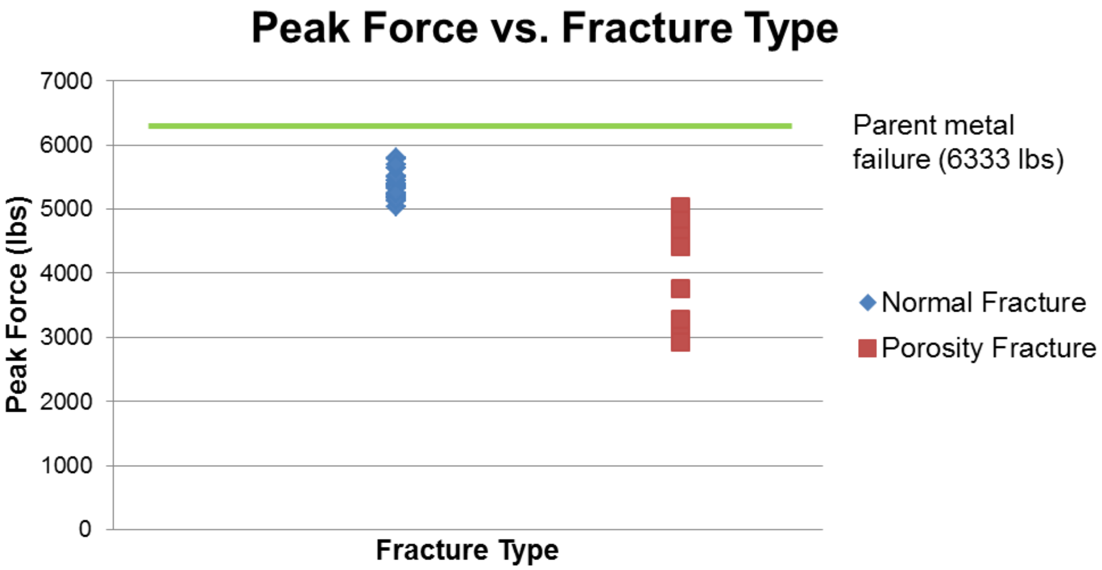

Figure 13. Peak force as a function of fracture type.

Table 3. Summary of peak force data.

	Mean Peak Force kg (lbs)	Median Peak Force kg (lbs)	Std Dev	CoV	Max Kg (lbs)	Min kg (lbs)	Range kg (lbs)	Mean % of Parent Metal Peak Force
Normal Fracture	2439 (5376)	2434 (5365)	94 (207)	0.039	2634 (5808)	2287 (5041)	348 (767)	85%
Porosity Visible	1801 (3970)	1854 (4087)	363 (802)	0.202	2288 (5045)	1329 (2929)	960 (2116)	63%

It was found that the peak force did not increase as the strength of the weld metal increased. All of the non-porosity welds failed in the HAZ. The softening that occurs in the HAZ is dependent on the amount of heat that is put into the weld, so welding parameters have a greater effect on joint strength than the wire type, provided that the weld overmatches the base material.

Summary of Tower International Test Results

Of the wires tested, the metal-cored FabCOR F6 metal-cored wire performed the best, both in terms of porosity and weld strength. At all travel speeds the cored wires (F6 and E71T-14) performed better than the solid wires with respect to porosity, and welds that exhibited higher levels of porosity generally had lower joint strength. For welds that did not fail due to porosity, the strength of the HAZ determined the joint strength. Finally, surface quality was not necessarily indicative of the level of internal porosity that was in the weld.

All-Weld-Metal Mechanical Property Testing

Even though Hobart Filler Metals designed FabCOR F6 wire specifically for single pass welding, it has been tested in a multiple-pass weldment. The results of the mechanical property and chemical analysis testing are shown below.

Table 4. Multi-pass FabCOR F6 weld metal properties with 75% Ar/25% CO_2 and 90% Ar/10% CO_2 shielding.

Weld	Shielding Gas	UTS MPa (ksi)	YS MPa (ksi)	% Elong.	CVN @ -4°F J (ft-lbs) (Average of 5)	CVN @ -40°F J (ft-lbs) (Average of 5)
F6	75% Ar/ 25% CO_2	735 (106.4)	652 (94.5)	20.2	60 (44)	42 (31)
F6	90% Ar/ 10% CO_2	734 (106.5)	665 (96.5)	22.8	61 (45)	49 (36)
ER70S-6 (typical)	90% Ar/ 10% CO2	565 (82)	455 (66)	27		57 (42)

Table 5. All-weld-metal chemical analysis results for FabCOR F6 and ER70S-6.

	C	Mn	Si	P	S	Cu
F6 - 75% Ar/25% CO_2	0.11	1.62	0.75	0.007	0.014	0.06
F6 - 90% Ar/10% CO_2	0.13	1.65	0.92	0.008	0.020	0.07
ER70S-6 Deposit Typical (90% Ar/10% CO_2)	0.08	1.22	0.73	0.013	0.012	0.11

Note that the strength of the welds made using the FabCOR F6 wire is significantly higher than what is typical for an ER70S-6 solid wire. The carbon and manganese levels in the deposit are also considerably higher than the ER70S-6 deposit. This is because FabCOR F6 is designed for single-pass welding. Products that are designed for single-pass welding typically have higher levels of carbon and other alloying elements than those designed for multiple-pass welding. In order to meet the mechanical property requirements it is necessary to start at a higher alloy level to overcome the potential loss of alloy that results from dilution.

Dilution is the mixing of the weld metal and the base metal. As a result of dilution, the weld deposit chemistry will be somewhere between that of the welding consumable and that of the base material. If dilution is very high the deposit chemistry will be closer to that of the base material, whereas if it is very low, it will be closer to that of the welding consumable.

Dilution with the base material is high in single-pass welds, and as a result, the weld metal chemistry may be vastly different from that of a multiple-pass weld made with the same product. Note that a product designed for multiple-pass welding and utilized in a single-pass application may create a weld with significantly lower joint strength than expected, especially if the base material is relatively low in carbon or other alloying elements.

Bend Testing

A series of customer weld samples were evaluated in a 180-degree bend test using a 19 mm (0.75-inch) mandrel. Photos of the bend-test specimens are shown in Figure 14 and Figure 15. Figure 14 shows welds that were made using ER70S-3 solid wire, while Figure 15 shows welds that were made using FabCOR F6. Note how pores have "opened up" in the welds made using the ER70S-3, whereas there is no evidence of porosity in the welds made using the F6.

Figure 14. Bend test samples produced at customer location using ER70S-3. Note that porosity that was present in the weld has opened up during bend testing.

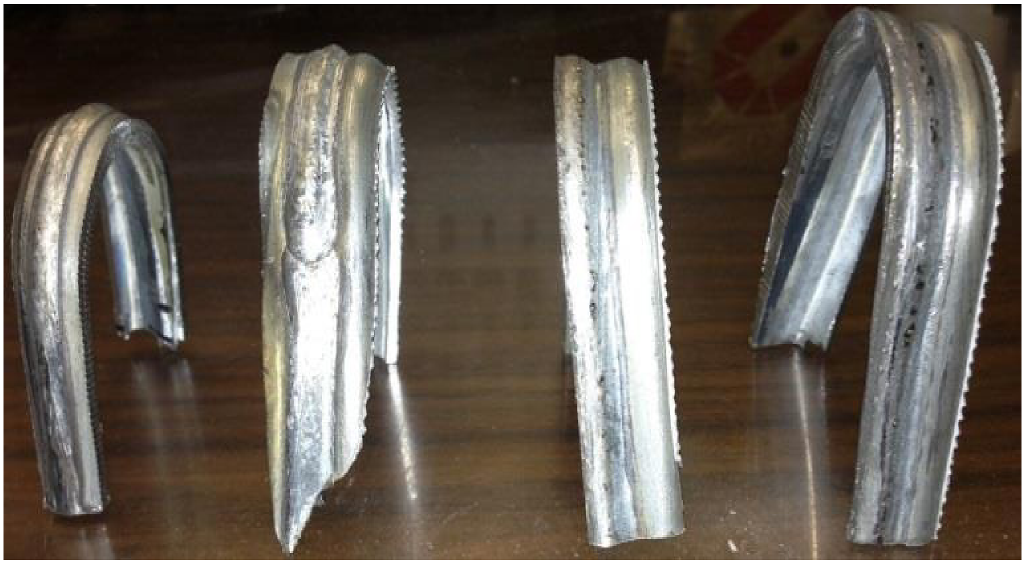

Figure 15. Bend test samples produced at customer location using FabCOR F6. Note that there is no evidence of porosity.

Summary

Welding on galvanized steel can be extremely challenging, especially when the base material thickness is 3 mm or less. Thinner base materials have a tendency to burn through if the welds are not made at sufficiently fast travel speeds. However welding at high speeds can result in porosity because the weld may solidify before the zinc vapors have an opportunity to escape from the molten metal. The key to producing sound welds under these circumstances is to produce the welds using negative polarity and just enough fluxing ingredients to counteract the effects of the zinc vapors. DCEN focuses the heat of the arc at the electrode rather than on the base plate. The metal-cored electrode must be properly formulated so that the DCEN welding arc is stable, producing little or no spatter and a rounded, smooth bead shape. This was accomplished in the FabCOR F6 product with a combination of fluxing ingredients, along with a small quantity of slagging ingredients that focus the arc and interact with the zinc to take the vapors out of solution before they cause porosity. Unlike some products that require specialized equipment or adapters, FabCOR F6 can be used with standard pulse-capable equipment, with no specialized hardware.

Extensive testing has shown that the new formulation significantly reduces the amount of porosity and burn-through, which results in fewer rejections and significantly less rework. Results of comparisons to other products that are used to weld galvanized steel, such as ER70S-6, show that the amount of internal porosity is significantly lower in welds made using FabCOR F6 over a full range of travel speeds. The net result is better, more consistent mechanical properties and a decreased likelihood of failures due to tensile loading and forming.

References

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[1] Clasius, R., 2014. 80 Day Cyclic Corrosion Test Results ArcelorMittal Report #: RAC2014-006.
[2] Galiher D. et al., 2014. Solutions for Coated Steels. FabTech 2014.
[3] Narayanan, B. et al. 2014. Solutions for Welding Zinc Coated Steels. AWS Sheet Metal Welding Conference, 2014.