#24-052
2024 AFS Proceedings ©American Foundry Society

Development of Improved Repair Welding Alloy and Process for Al-Cu Sand Castings

David J Weiss
Eck Industries, Inc. (Retired), Manitowoc, Wisconsin, USA

Gerald A Gegel
Material & Process Consultancy, Morton, Illinois, USA

ABSTRACT

This project addresses important considerations in the welding of 200 series alloys, specifically castings produced from A206 alloy. This alloy is difficult to weld unless key process parameters are controlled. As the volume of the welded area increases, the difficulty is compounded. We show that control of temperature of the casting during welding is the most important process parameter for low defect welding with acceptable mechanical properties, assuming that basic good welding practices are followed. The weld filler rod is also an important consideration, with the most successful welds produced using 2319 alloy.

Keywords: welding, 200 series alloys, incipient melting

INTRODUCTION

Current practices to weld 206 alloy castings, particularly for repair of through wall defects or defect depths of greater than 0.25" result in unsatisfactory welds. Both 206 and 2319 weld rods are typically used for repair welding of 206 castings. The composition specifications for A206 and 2319 weld wire are listed in Tables 1 and 2 respectively.

Table 1. A206.0 Weld Wire Composition Specification (AMS4244C)

Element	min	max
Silicon	--	0.05
Iron	--	0.10
Copper	4.2	5.0
Manganese	0.20	0.50
Magnesium	0.15	0.35
Nickel	--	0.05
Zinc	--	0.10
Titanium	0.15	0.30
Tin	--	0.05
Other Elements, each	--	0.05
Other Elements, total	--	0.15
Aluminum	remainder	

Table 2. 2319 Weld Wire Composition Specification (AWS A5.10)

Element	min	max
Silicon	--	0.20
Iron	--	0.30
Copper	5.8	6.8
Manganese	0.20	0.40
Magnesium	--	0.02
Zinc	--	0.10
Vanadium	0.05	0.15
Titanium	0.10	0.20
Zirconium	0.10	0.25
Beryllium	--	0.0003
Other Elements, each	--	0.05
Other Elements, total	--	0.15
Aluminum	remainder	

A recent project[1] to determine the effect of weld repair on the static & dynamic properties of A206 sand castings did not successfully produce welds of the desired quality. At the time we speculated that the problem may have been related to weld alloy chemistry or process parameters for the welding such as workplace pre-heat, surface preparations or other unknown factors. The two alloys typically used by foundries and allowed by military specifications (A206 and 2319) either produce inconsistent weld quality (A206) or low ultimate tensile strength (2319). Figure 1 is a radiograph of the weld repair area made with A206 weld wire showing defects in the weld area. Figure 2 is a micrograph of the weld repair area made with 2319 wire and shows an inhomogeneous grain structure in the weld area.

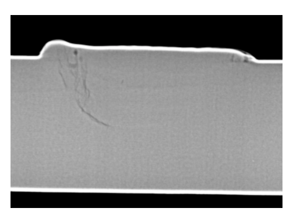

Figure 1. Radiograph cross section of plate containing a weld repair made with A206 weld wire.

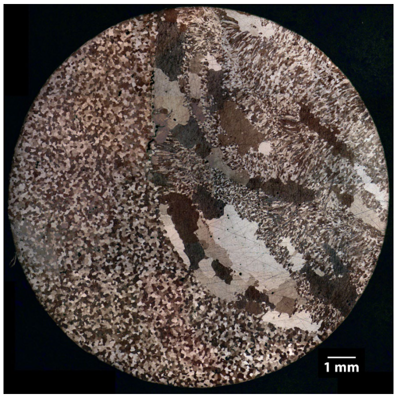

Figure 2. Cross section of a tensile bar containing weld repair made with 2319 weld wire.

Table 3 summarizes the tensile results from three baseline A206 cast plates and weld repair samples made with A206 and 2319 weld wire. All samples were heat treated to the T4 condition after welding. The weld repair area accounted for ~40% of the tensile bar cross-sectional area. There is a more significant decrease in the strength and elongation for the 2319 weld repair samples.

Table 3. T4 Tensile Properties for Baseline A206 and Weld Repair Samples Made with A206 and 2319 Weld Wire (Data from Ref. 1 with ± standard error)

ID	*UTS (ksi)*	*YS (ksi)*	*Elong. %*
No Weld	58.3 +/-1.3	37.6 +/-1.0	13.5 +/-2.1
A206 Weld	55.3 +/- 1.6	36.0 +/-0.5	12.5 +/-2.1
2319 Weld	44.4 +/-3.1	34.4 +/-0.9	5.8 +/-1.2

Analysis of the weld structure at the University of Alabama-Birmingham using A206 weld rod showed significant $CuAl_2$ segregation at the fusion line (Figure 3) of the weld plus indications of eutectic melting (Figure 4) in the weld structure. In this alloy, eutectic melting can occur when not enough of the $CuAl_2$ is dissolved before the alloy reaches the final solution temperature of 986F (530C).

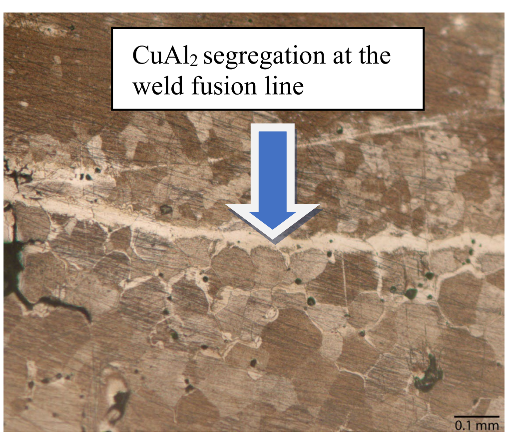

Figure 3. Copper segregation in an A206 casting welded with A206 weld rod.

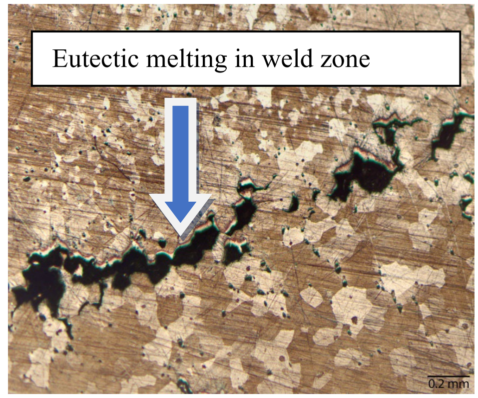

Figure 4. Eutectic melting in A206 casting welded with A206 weld rod.

PROJECT OBJECTIVES

To mitigate the effects of weld wire chemistry and other variables on weld repair quality, a project was initiated to optimize a weld alloy chemistry and the welding parameters necessary for the successful weld repair of A206 sand castings. The key objectives are summarized as follows:

- Develop new weld wire alloy.
- Develop improved repair welding practices.
- Establish effect of welding parameters on weld quality.
- Determine the effects of homogenizing post-weld heat treats.
- Determine effect of weld repair on tensile properties of A206 sand castings .

APPROACHES AND PROCEDURES

A cast A-206 plate was used with approximate dimensions of 6" x 12" with artificial defects machined in for weld repair is shown in Figure 5. Our preliminary work had shown that a T4 heat treatment before heat treatment resulted in lower levels of Cu segregation and a reduction in size (Figure 6) and was used as the default pre-weld heat treatment. It is worth noting that while the size of the weld defect is fairly large, plates welded in A356 and E357 were able to meet the mechanical properties of the parent metal and an x-ray soundness level of Grade B per AMS-2175.[2]

Initial weld settings were as follows:

- Frequency: 120 Hz
- AC current: 225 amps
- Polarity Setting: 75% negative / 25% positive
- Balance Control: 70 – 75%
- Ceriated tungsten electrode; 3/32" diameter
- 90He/10Ar gas flow at 24 CFH or 100% Ar

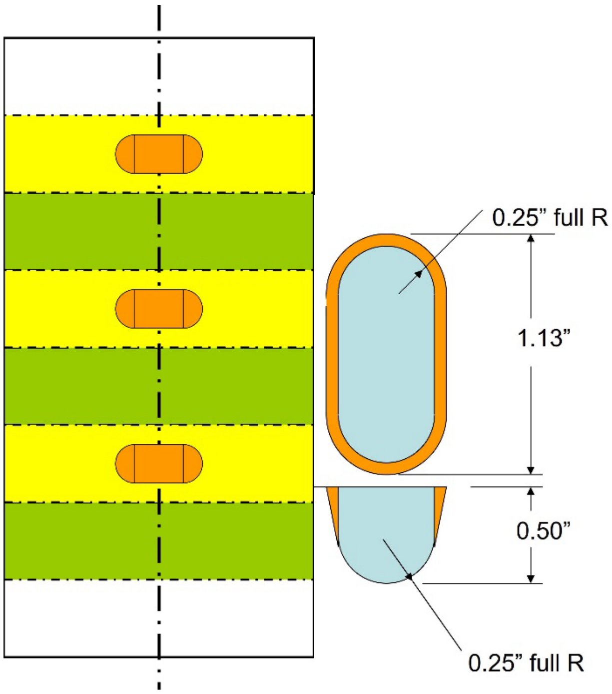

Figure 5. Welding test plate and geometry of machined defects.

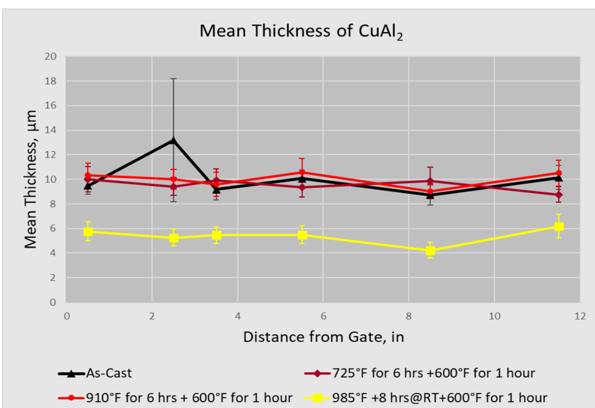

Figure 6. Mean thickness and segregation of $CuAl_2$ in test plates.

ROLE OF PRE-HEAT AND POST-HEAT ON WELD QUALITY

Conversation with those in industry that weld 200 series casting alloys and 2000 series wrought alloys yielded different recommendations from 250F (121C) preheat temperatures on the low end to 850F (454C) on the high end. The consensus was an intermediate temperature between the two, to balance welder comfort and effectiveness. The literature is ambiguous on this, suggesting that a lot of heat is needed to puddle correctly but too much will cause cracking, oxide inclusions and porosity.[3] Preheating will prevent cold cracking and reduce residual stress in the weld.

Preheating also lowers the cooling rate after welding. This is usually desirable in aluminum to reduce the weld-affected zone. In aluminum welds the heat affected zone is always the weakest area of the weld. Figure 7 shows the tensile strength of the base aluminum away from the weld. Note that the strength drops approaching the heat affected zone and then comes back up when in the pure, unaffected base material.

In some cases, post-heating, by returning the casting to an oven or a heater at or below the solution temperature of the alloy may reduce residual stress and the probability of cracking. In addition to the problems of managing the transition to a furnace, there is little evidence that this is helpful in a practical sense. There was no advantage in doing this in any of the trials. Hot cracking in A206 alloys occurs very close to the solidus of the material, and the very narrow temperature range makes it extraordinarily difficult to manage the temperature effectively.

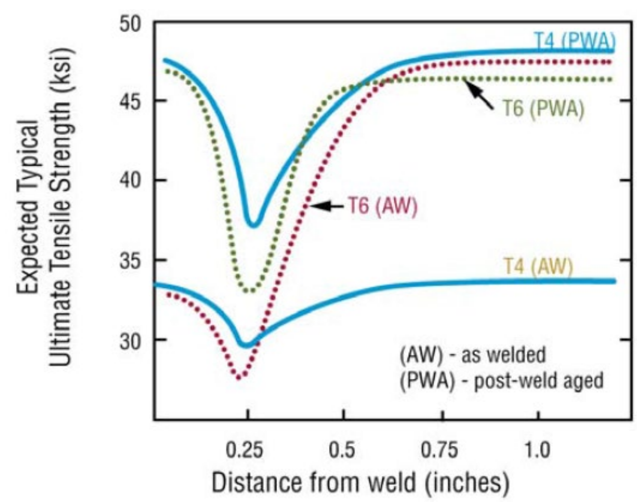

Figure 7. Impact of heat affected zone in aluminum-typical.[4]

Results of the welded defect based on pre-heat temperature of the plates are shown in Table 4.

ROLL OF CASTING COOLING RATE ON WELD SUCCESS

Anecdotal evidence suggested that thin section castings and chilled areas of castings respond better to welding with less defects than heavier sectioned castings. This appears not to be related to intrinsic levels of porosity but the cooling rate of the casting. Figure 8 shows the casting pre-weld. The lighter circle in the center of the image coincides with the riser used to feed the castings. Figure 9 shows significant defects post-weld under and at the edge of the riser, even though the casting was sound, while in the area with a higher cooling rate, the weld was free of defects. This welding was done with A206 welding rod.

Table 4. Mechanical Properties Using Different Chemistry Weld Rods and Temperatures

Preheat Temp		**250F**			**500F**	
Weld Wire	**Tensile**	**Yield**	**%E**	**Tensile**	**Yield**	**%E**
A206 30 ppm B	40,900	35,900	3.0	46,900	34,700	5.3
A206 3% Mg	44,800	33,800	5.0	43,500	36,700	2.4
2319	50,600	35,100	7.0	48,700	34,700	5.5
No Weld	56,100	35,300	11.0	55,300	36,600	10.7
B206 3% Mg	30,900	26,900	1.5	32,700	32,700	1.1
A206 Nano	37,900	32,000	3.5	29,900	28,300	1.8

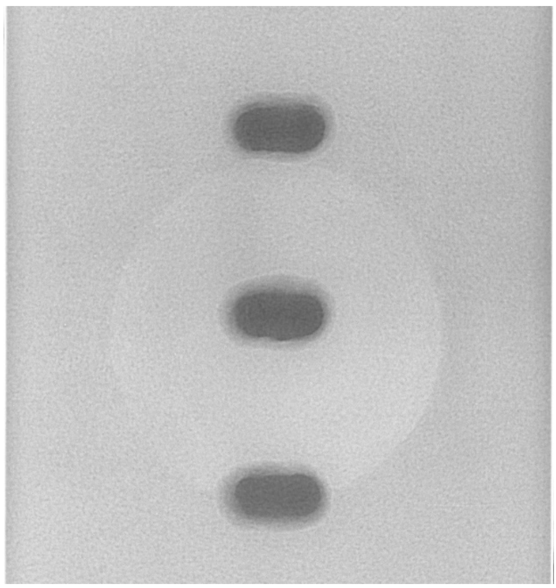

Figure 8. Casting prior to welding.

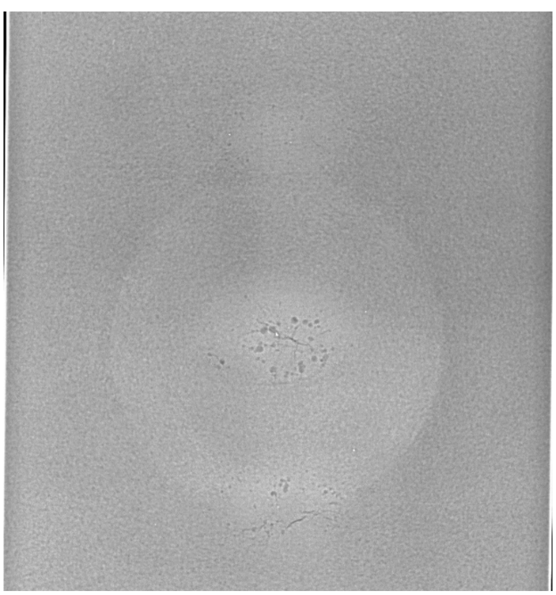

Figure 9. Casting post-weld.

ROLL OF WELD WIRE CHEMISTRY

This program investigated many weld wire chemistries. The chemistry choices were based on approved alloy chemistries for welding of A206 castings (A206 and 2319) and experimental chemistries that were suggested based on fundamental analysis and anecdotal accounts from the industry. The designation of the weld rods is shown in Table 5. The difference between A206 and B206 is the amount of titanium (Ti) in the alloy. A206 requires Ti of between 0.15 and 0.25%, B206 restricts Ti to a maximum of 0.05%. In some of the alloys magnesium (Mg) was added to decrease the liquidus in the weld pool. The table shows Mg added beyond the standard 0.15-0.35% specified for the alloy. In addition, some trials were done with 2024 weld rods containing 1% TiC nano-reinforcements and A206 with scandium (Sc) and 1% Al_2O_3 additions. These additions are reported to improve the cracking tendency during aluminum welding.[5,6]

Table 5. Trial Weld Wire Designations

Alloy	**ppm B**	**Mg (wt%)**
B206	0	0
B206	30	0
B206	0	3
B206	30	3
A206	30	0
A206	0	3
A206	30	3
2319		
2024-Nano		
A206-0.2 Sc		
A206-Nano		

Broken test bars of the alloys were investigated near the fracture zone. Figure 10 shows the sectioning protocol for these samples. The results are shown in Figures 11 to 19. All these alloys except for B206 with 3% added Mg showed some cracking at or near the weld zones, with varying severity levels. The 3% added Mg alloy showed severe shrinkage in the weld consistently. None of the 2319 welds, the A206 with B additions, the A206 or the A206 with alumina additions, showed cracking within the weld but all showed some porosity. The A206-B welds had the least porosity of the samples produced. Table 6 shows the summary results of the microstructural analysis.

Table 6. Weld Crack Analysis

ID	Interface Cracking	Weld Cracking
2319	Yes	No
2319	Yes	No
2319	Yes	No
B206 + 3% Mg	No	Yes
A206 + 30 ppm B	Yes	No
A206	Yes	No
A206-Nano	Yes	No
2024-Nano	Yes	Yes
B206	Yes	Yes
A206-0.2 Sc	Yes	Yes

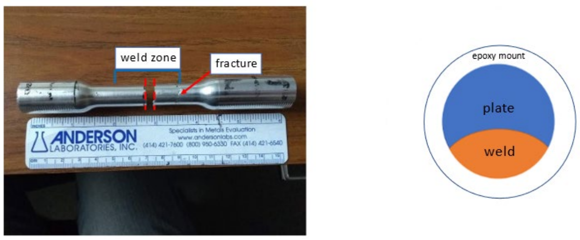

Figure 10. Test bar transverse image locations.

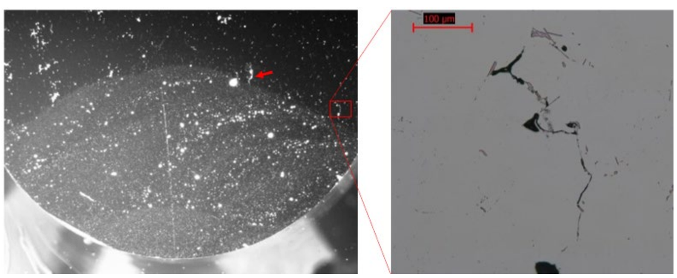

Figure 11. 2319 cracking/melting near the weld interface.

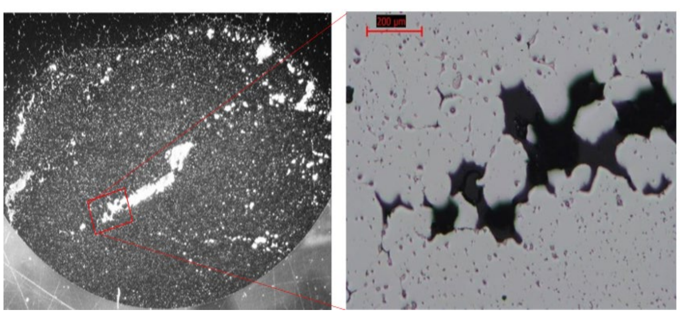

Figure 12. B206 with 3% Mg added showing shrinkage.

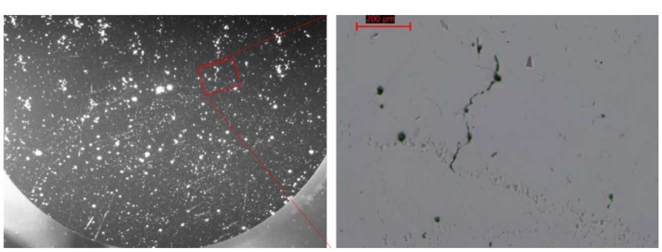

Figure 13. A206 cracking/melting near the weld interface.

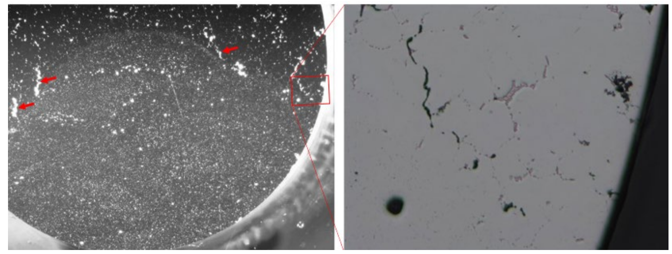

Figure 14. A206 + 30 ppm B showing cracking/melting near the weld interface.

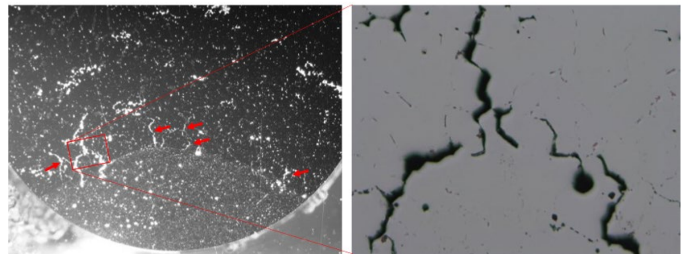

Figure 15. A206-nano showing cracking near the weld interface.

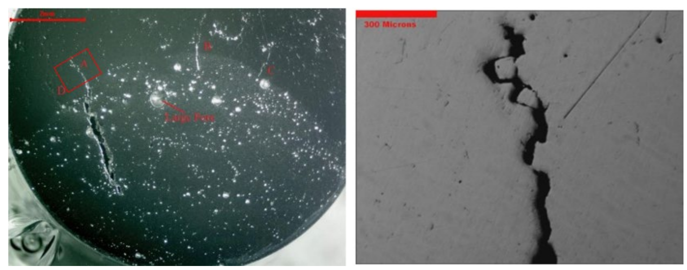

Figure 16. 2024-nano showing cracking at the interface and through the weld.

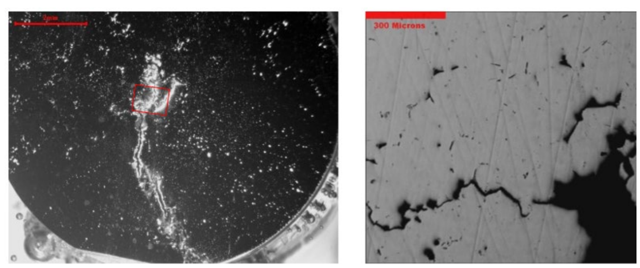

Figure 17. B206 with cracking at the interface and through the weld.

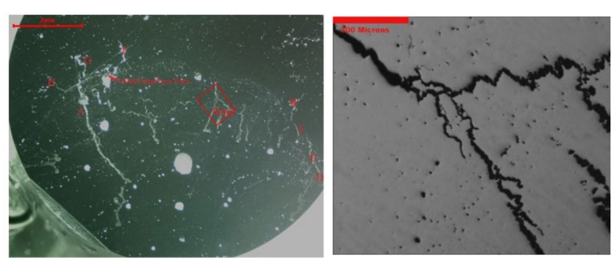

Figure 18. A206-0.2 Sc showing entensive cracking through and around the weld.

In spite of the microstructural defects evident in Figures 16,17 and 18, the x-rays of the plates were compliant with an ASTM Grade B requirement as shown in Figure 19. This suggests that x-ray should not be the only tool used to assess compliance in welded castings. The mechanical properties more accurately reflect the level of microstructural defects as shown in Table 7.

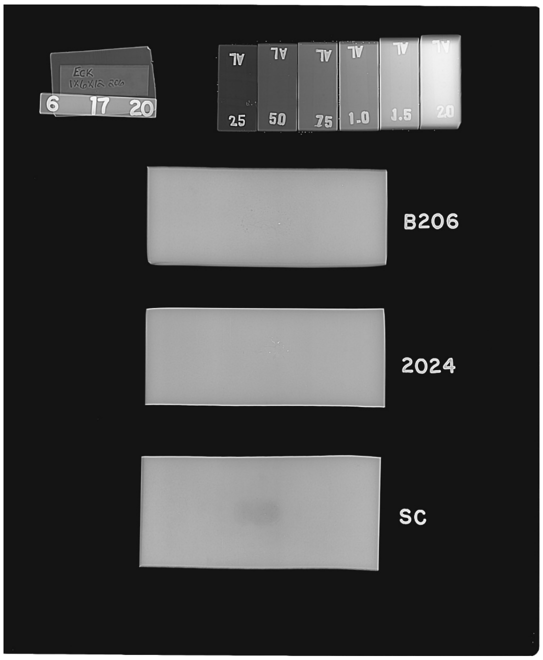

Figure 19. Weld cross-sections from unconventionalweld fillers.

Table 7. Mechanical Properties of Weld in Figure 19

Alloy	**Tensile**	**Yield**	**Elongation**
2024-Nano	43.4 +/-5.1	35.0 +/-0.5	2.5-6.85%
B206	31.3	26.7	2.8%
A206-.2Sc	23.2	19.7	3.1%
2319	45.5 +/-2.3	34.9 +/-1.2	4.0-4.1%
A206 Base	55.2	35.5	12.0%

It should be noted that while the 2024-nano passed x-ray and the 2319 did not, the mechanical properties were nearly the same. The comparison x-rays are shown in Figure 20.

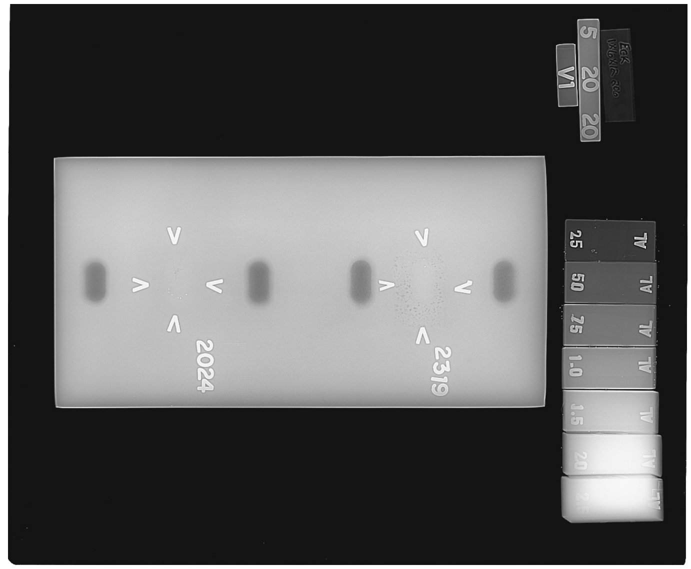

Figure 20. The 2024 and 2319 welds were compared via x-ray.

WELD INTERPASS CONTROL

"Interpass temperature" refers to the temperature of the material in the weld area immediately before the second and each subsequent pass of a multiple pass weld. In normal shop practice, minor welds, normally defined as welds of less than 20% of the wall thickness, requiring just a few passes, do not exhibit the same problems with cracking and porosity as deep welds do. The results from Table 5 are inconclusive but suggest that a lower preheat temperature yields better properties than higher, perhaps because it yields a lower interpass temperature. The minimum interpass temperature must be sufficient to prevent cracking, while the maximum interpass temperature must be controlled to provide adequate mechanical properties.

In the case of A206 base alloy interpass temperatures above 1008 F (542C) will create incipient melting as shown in Figure 4. This can be monitored and controlled by using two temperature indicating crayons. A surface applied temperature indicating crayon (often referred to by the trade name Tempilstik) melts when the material to which it is applied reaches the crayon's melting temperature. One temperature indicating crayon is typically used to measure both the minimum specified preheat temperature and the minimum specified interpass temperature, while the second is a higher temperature crayon used to measure the maximum specified interpass temperature. It can be difficult to control this interpass temperature in practice, since it may be necessary to interrupt the weld to maintain a lower temperature. To counter these problems, a fan was utilized on the underside of the plate to control the interpass temperature to under 550F (288C) utilizing a starting preheat temperature of 250F (121C). Using 2319 rod we were able to consistently produce weld meeting x-ray requirements of at least a grade C with mechanical properties exceeding AMS 4236 requirements for other than designated areas. Data from 5 tensile samples is 54.4+/-4.1 tensile, 33.4 +/-0.9 yield and 10% +/- 2% elongation. It is not known if the temperature is optimized to yield the best mechanical properties, but it is a good starting point when welding heavy sections. It is suggested that the temperature range be as narrow as possible but more sophisticated temperature controls will be required along with experimentation to determine the best range for any given welding situation.

OTHER CONSIDERATIONS

With a few exceptions, the majority of the weld porosity [as distinguished from cracks or lack of fusion] in these trials was found in the upper surface of the weld. In welding, as in casting, this is the last area to solidify, and gases would tend to go to that area. This "porosity affected zone" could be extended by welding above the surface and removing the affected area by grinding or machining. This could be useful if the controlling defect is porosity but not if it is some sort of incipient melting or weld cracking. (Figures 21 and 22).

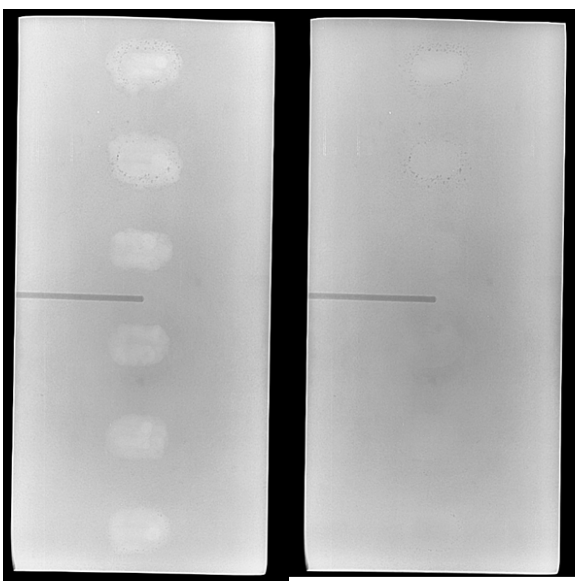

Figure 21. Left image, before stock removal, right image after 1 mm stock removed

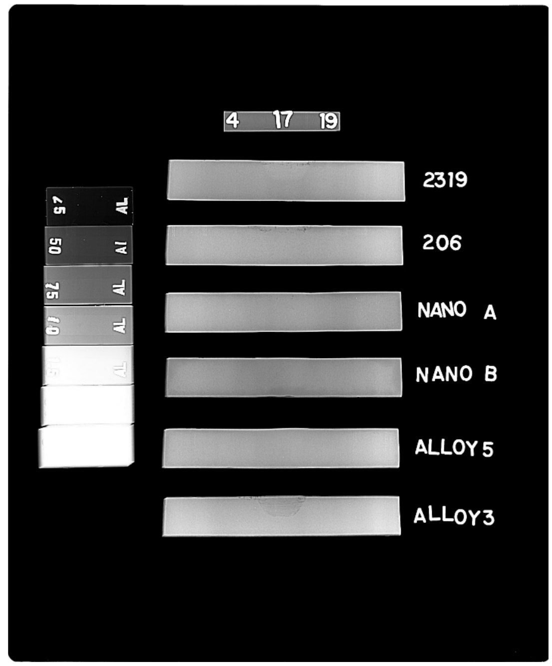

Figure 22. Porosity defects on the surface of the weld area. Cross section of plates from Figure 21, welded at 350F (177C) with argon shielding gas.

CONCLUSIONS

1. The use of 206 welding rod yields better properties when welded correctly, but it has a narrower process window to produce sound welds than the alternative 2319 alloy.
2. 2319 welding rod is easier to use than 206 welding rod. It has a higher Cu content than 206 which reduces its liquidus making it easier to puddle in the weld. However, the higher Cu content also reduces its incipient melting temperature, making weld interfaces more prone to defects if overheated.
3. Alternate welding rods used in this study did not show useful advantages over 206 or 2319 and in many cases led to greater amounts of defects and lower mechanical properties.
4. The most important factors in welding 200 series alloys, particularly for large defects is the control of preheat and the interpass temperature during welding. This must be controlled to a greater extent than in aluminum-silicon alloys.
5. Preheat temperatures of around 250F (121C) and interpass temperatures of no more than 550F (288C) will produce acceptable welds using 2319 filler rod.

6. This study looked at a difficult welding situation of 50% of the cross-sectional area, with the test bars comprising about 50% of filler rod material. Exact adherence to pre-heat and interpass temperatures is required to be successful under these demanding conditions. Some customers restrict welding to less than 20% of the cross-sectional area or a maximum weld depth of 0.25”. This is much easier under welding conditions that are more variable.

ACKNOWLEDGEMENTS

The authors thank the American Foundry Society and its Aluminum & Light Metals Technical Division for support and funding under Project #17-18#07.

REFERENCES

1. Gegel, G.A. and Weiss, D., “Effect of Weld Repair on Static & Dynamic Tensile Properties of A206 Sand Castings,” Presentation 17-092, *2017 AFS Proceedings of the 121st Metalcasting Congress*, Milwaukee Wisconsin (2017).
2. Gegel, G.A, Hoefert, D., Hirvela, J., Oehrlein, R. “Effect of Weld Repair on Static and Dynamic Tensile Properties of E357-T6 Sand Castings” *International Journal of Metalcasting*, Vol 7, Issue 4, pp. 43-48 (April 2013).
3. Cutts, Gina, “Controlling Heat Is Key in Welding Aluminum,” *The Welder*, p. 42 (July-August 2021).
4. The Importance of the Heat Affected Zone (HAZ) | WELDING ANSWERS, (Link last accessed 04-04-2024.)
5. Sokoluk, M., Yuan, J., Pan, S., Li, X. “Nanoparticles Enabled Mechanism for Hot Cracking Elimination in Aluminum Alloys,” *Metallurgical and Materials Transactions A*, 52, 3083-3096 (2021).
6. Ryazantsev, V., Filatov, Y., Ignat’ev, Y., “Selection of Filler Wire for Arc Welding Aluminum Alloys of the Al-Mg and Al-Cu Systems,” *Welding International*, 17:10, 821-824 (2003).