Special Alloys and Overmatching Welding Products Solve FGD Corrosion Problems

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ABSTRACT

Wet lime and limestone flue gas desulfurization (FGD) scrubbers are in widespread use worldwide to reduce sulfur dioxide emissions from coal-fired electric power generating facilities. The environments found in many parts of these systems are very corrosive, containing mixed (generally reducing) acids, oxidizing salts, and significant levels of halides at elevated temperatures. To resist these aggressive conditions, highly alloyed, nickel-base materials are widely used. Nickel-chromium-molybdenum alloys have been shown to be particularly effective in resisting FGD corrosion. Recent field experience and laboratory tests have demonstrated that advanced corrosion-resistant alloys offer excellent resistance to even the most corrosive FGD environments. In the past, autogeneous and matching weld metals have sometimes exhibited preferential corrosion due to elemental segregation in the cast weld structure. However, by the use of over-matching composition welding products, weld metals can be deposited which exhibit corrosion resistance equivalent to or better than wrought alloy products. The use of overmatching welding products is particularly important when alloy clad steel plate products are being fabricated.

INTRODUCTION

Continuous plant operation means that there is an increasing need to avoid downtime and repair of equipment. The more reliable plant designs place demands on materials to be both ‘fit for purpose’ and capable of withstanding ever more severe operating conditions. Variations in operating conditions such as chloride concentration, temperature and pH can be critical. Gas quenching zones and areas of condensation can be especially corrosive. Increasingly the material selected must resist corrosion in environments which are beyond the capability of INCONEL® alloy C-276 (UNS N10276) parent metal and welding consumables. The selection of the correct parent metal and welding consumable is vital to achieve the right balance between capital and operating expenditures. INCONEL® alloy 686 (UNS N06686) parent material and INCO-WELD® Filler Metal

686CPT (AWS A5.14 ERNiCrMo-14) and Welding Electrode 686CPT® (AWS A5.11 ENiCrMo-14) welding consumables are increasingly the material of choice for critical process plant environments. The corrosion resistance of nickel alloys in FGD plant equipment will, of course, vary with the environment, alloy composition and form of corrosion. The most corrosion resistant nickel alloys typically contain about 15 to 23% chromium plus molybdenum and sometimes tungsten additions. Localized corrosion (pitting and crevice attack) resistance increases with the total Cr + Mo + W content. The standard Pitting Resistance Equivalent Number (PREN) equation used for stainless steels cannot be used for the more highly alloyed nickel base alloys.

Alloy 686, with the highest commercially available total alloy content has been found to have superior localized corrosion resistance as a base metal and as a welding product. This is illustrated by the crevice corrosion test results in Figure 1. When pitting of welds is a potential problem alloy filler metal 686 can be used as an overmatching filler metal on many nickel alloys to prevent preferential weld metal attack. This welding product is more resistant to pitting attack than matching composition filler metals of alloys C-276, C-22 (UNS N06022), C-2000 (UNS N06200)and 59 (UNS N06059). When weld overlaying on steel, iron dillution significantly reduces the corrosion resistance of the weld deposit. Experimental results show that as the nominal iron content of the filler metal increases, so does the iron dilution in the weld deposit. A low iron, highly alloyed filler metal such as filler metal 686CPT overlay can produce corrosion resistance in one layer superior to three layers of filler metal C-276.

The same elemental alloying principles apply to autogenous welding during welded tubing manufacture. As a result welded tubes produced from highly alloyed alloy 686 are more resistant to pitting than alloys C-276 and 59 tubes. Cold work followed by solution annealing increases the corrosion resistance of tubes made from all these alloys.

Though resistance to general corrosion varies widely with the environment, it is well known that alloying with a combination of chromium for oxidizing acids and molybdenum for reducing acids will provide the best overall corrosion resistance. A comparison of isocorrosion charts shows overall high alloy content helpful in sulfuric acid, while the highest molybdenum alloys are most resistant in hydrochloric acid. When oxidizers are present in hydrochloric acid a combination of chromium and molybdenum are beneficial.

EXPERIMENTAL PROCEDURES

Welding of test samples in this study was conducted by Gas Metal-Arc Welding (GMAW) by either spray or pulsed transfer mode and by Gas Tungsten-Arc Welding (GTAW). Commercial base metals and filler metals were used in all instances. Welded specimens were tested in the as-welded condition and surface finish, unless otherwise noted. Typical welding parameters are given in Table 1 and 2. Some variations to these parameters were made as necessary to conform with specific manufacturer's recommendations.

Corrosion testing was carried out in the specific environment listed for each set of test results. Intergranular corrosion tests were conducted in ASTM G-28, Practice A (600 ml 50% H_2SO_4 + 25 g $Fe_2(SO4)_3.H_2O$) and ASTM G-28, Practice B (23% H_2SO_4 + 1.2% HCl + 1% $FeCl_3$ + 1% $CuCl_2$) at boiling temperatures for 24 hours. Pitting and crevice corrosion tests were conducted in a severe acidic, oxidizing chloride solution (11.9% H_2SO_4 + 1.3% HCl + 1% $FeCl_3$ + 1% $CuCl_2$) at the temperatures and times indicated. This solution has been found to closely simulate an extremely corrosive environment found in a coal fired power plant flue gas duct[1]. Acid and salt concentrations are based on weight percent.

In evaluation of welds made on solid alloy sheet [approximately 0.062" (1.6 mm) thickness] or plate [approximately 0.250" (6.4 mm) thickness], the maximum depth of attack in the base metal or weld metal was reported. Pit and crevice depths were measured with a point depth gauge. When results are compared visually, the specimen surface with the greatest attack was photographed.

RESULTS AND DISCUSSION

Alloy Design

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Substantial alloying additions of nickel, chromium, molybdenum and other elements are needed for many applications where a high level of corrosion resistance is required. Chromium provides resistance to oxidizing environments while molybdenum improves resistance to reducing environments. A combination of both chromium and molybdenum increases resistance to localized corrosion (pitting and crevice corrosion). Additions of tungsten may also further increase resistance to localized corrosion. Though nickel provides resistance to caustic and mild reducing environments, its main benefit in alloys containing high levels of chromium and molybdenum is to maintain a stable austenitic single phase structure. This is important in obtaining optimum corrosion resistance in an alloy capable of being economically produced and fabricated.

Several high nickel alloys containing various levels of alloying elements are listed in Table 3. Overall, the general corrosion resistance of the high nickel alloys listed is in the same range but the localized corrosion resistance varies predictably with increasing Cr + Mo + W content. A pitting resistance equivalent number (PREN) can be calculated, using the alloy chemical composition, to estimate relative pitting resistance of alloys. The PREN calculations for each alloy are shown in Table 3. Actual crevice corrosion test results for the various alloys in a very aggressive oxidizing chloride solution are compared in Figure 1. Resistance of the alloys to crevice corrosion is determined by maximum measured depth of attack at increasing test temperatures. Both alloy C-4 and C-276 are attacked at 103ºC but the alloy C-276 shows much lower depth of attack. The main compositional difference in the two alloys is the presence of about 4% tungsten in the C-276, see Table 3. This beneficial effect of tungsten has been noted previously[2] . At 125ºC alloys C-276, N06022, N06200 and 622 experience significant attack. Increasing relative resistance is observed in the order listed. Alloys 59 and 686 are not attacked at 125ºC but significant attack of the 59 occurs at 135ºC and 140ºC, while the alloy 686 is only slightly attacked. The main difference between the two alloys is the presence of 3.9% tungsten in the alloy 686. Thus the same beneficial effect of tungsten is found in 686 as was found in C-276 when C-276 was compared to C-4 at a lower temperature.

Resistance to crevice corrosion increases steadily with increasing Cr + Mo + W content, which is generally reflected by the PREN. Alloy C-2000, which has less crevice corrosion resistance than the PREN number would predict, is an exception to this alloying effect. This is apparently due to the detrimental effect of 1.6% copper in the alloy. Copper has previously been shown to adversely affect pitting resistance of austenitic stainless steels[3] and also high nickel alloys[4]. This detrimental effect of copper is the basis for the – 0.5Cu factor in the equation shown in Table 3.

Effect of Welding on Corrosion Resistance

A weld is a small casting. In the as welded condition it has a coarse grain dendritic structure with microsegregation within the weld. Molybdenum and other elements are enriched in the interdendritic solute during weld solidification. This condition is severe in alloy 625 welds due to the niobium content and has been widely studied and reported in the literature [5,6,13]. Segregation of molybdenum in an alloy C-276 weld is demonstrated by the scanning electron microscope (SEM) photo in Figure 2. Also the SEM produced molybdenum line scan of Figure 3 verifies fluctuation in molybdenum content across the dendrites. This microsegregation and its effect on weld metal corrosion resistance was addressed by Garner[7] some time ago. The end result is lower corrosion resistance, especially to localized corrosion, of the weld metal than the base metal. This occurs even though the bulk composition of both are the same.

Welded Tubing

The effect of segregation is demonstrated by the welded tube tests shown in Table 4. At 103ºC the as welded alloy 59 weld is severely attacked but solution annealed welds and cold drawn + annealed welds are resistant. At 138ºC the annealed welds are attacked, while the cold worked and annealed welds are not. Finally, at 150ºC both the cold worked and annealed welds and the base metal are equally attacked. The alloy 686 welded tubing shows the same relative behavior, though the minimum temperature to produce attack in the different conditions is higher for this material. Diffusion of segregated elements during post weld annealing improves corrosion resistance to some extent. In addition, cold working plus annealing breaks up the dendritic structure and produces an equiaxed grain structure with minimal segregation. In this case corrosion resistance similar to the base metal is achieved.

The corrosion resistance of welded tubing can be improved substantially by weld bead refining. Bead refining employs cold work and annealing of the weld to bring about recrystallization and diffusion of segregated elements. Cold work is accomplished by either planishing (rolling forge), or by a static loading mechanism during tubing production and is followed by a solution anneal.

Overmatching Filler Metal

The detrimental effect of segregation occurs during any fusion welding process. Either autogenous welds or welds made with "matching composition" filler metal will have less corrosion resistance than the base metal. In most applications it is not practical to post weld anneal or cold work and anneal welded structures. In this case the best way to produce a weld with corrosion resistance equal to or better than the base metal is to use an "over matching" filler metal. This concept has been used for some time with austenitic and duplex stainless steels to prevent weld attack [8,9,13]. Even though the weld metal may retain its inherent segregated characteristics, a higher alloy content than the base metal will outweigh these adverse effects.

The results of pitting tests in the same aggressive oxidizing chloride environment of Figure 1 are shown for welded specimens in Figure 4. Welds made on alloys 622, C-276 and N06022 base metals using matching composition filler metals were found to pit severely. Over matching alloy filler metal 686 welds on the same base metals, however, were resistant to attack. The same beneficial effect of the overmatching filler metal is shown for alloys N06200 and 59 base metals welded with filler metal filler metal 686 in Figure 5. Visual results in Figures 4 and 5 agree well with depth of attack measurements given in Tables 5 and 6.

Optimum pitting resistance, of course, would be realized by use of both alloy 686 base metal and filler metal 686. The filler metal 686 welding product has the same composition as the base metal.

Iron Dilution of Weld Metals

During overlay welding on steel and welding of alloy clad steel plate iron dilution of the alloy weld metal is of concern. Iron dilution can significantly reduce the corrosion resistance of welds made with low iron alloys like alloy C-276 [10]. In addition to effectively reducing the concentration of chromium, molybdenum and tungsten in the weld, iron dilution may promote the formation of detrimental second phases such as mu phase.

The iron content of multiple pass weld overlays made by various nickel alloy filler metals on carbon steel are shown in Figure 6. The total iron content is a function of initial filler metal iron content plus the amount of iron diluted from the steel substrate. The iron content of the first weld metal layer is of course much higher than subsequent layers, as would be expected. An unexpected effect, however, is that the initial iron content of the filler metal appears to influence the amount of iron dilution from the steel substrate. The lower iron filler metals like filler metal 686 and alloy 622 pick up much less iron in the first pass than the higher iron alloys N06022 and alloy C-276. The low initial iron content plus minimal iron dilution from the steel substrate results in a very low iron content weld overlay in the filler metal 686. Note that these welds were made using pure helium shielding gas with the pulsed – GMAW process.

Pitting Resistance of Weld Overlays on Steel

Actual corrosion test results clearly demonstrate the beneficial effect of low iron content in weld overlays on steel. Critical pitting temperatures (the minimum temperature at which pitting is produced) for each of three weld layers on steel and four different filler metals are shown in Table 7. Critical pitting temperatures were determined for duplicate specimens with one, two and three weld passes. For each of the four filler metals employed, the critical pitting temperature increases (indicating increased corrosion resistance) as additional weld layers are applied. This is the result of decreasing iron content with each successive layer. The relative performance of the alloys N06022, C-276 and 622 and filler metal 686 follow the well established order of corrosion resistance shown in Figure 1.

It is important to note that due to inherently superior corrosion resistance and lower weld deposit iron content, one layer of filler metal 686 offers better corrosion resistance than 3 layers of alloy C-276 filler metal (see Table 5). From a cost perspective, this means that substantial savings could be realized by use of the filler metal 686.

Welding Clad Plate

Iron dilution from the steel substrate during the welding of nickel alloy clad steel plate will also affect the weld metal corrosion resistance. Proper welding technique is necessary to avoid excessive iron dilution from the steel in the clad layer weld bead. Typical weld procedures are shown in Figure 7. If these procedures are followed the clad surface weld will be as corrosion resistant as a matching composition weld in solid plate[11].

However there is sometimes concern that the procedures will not be followed exactly and also, even matching composition welds in solid plate are less corrosion resistant than the base metal. For this reason an alloy sheet capping (or batten) strip is sometimes used to cover the clad steel weld joint, as shown in Figure 8. This is of course an added expense. The use of an overmatching filler metal is an alternative to this expensive weld capping procedure. As demonstrated in Figures 4 and 5, filler metal 686 is an effective overmatching filler metal. Also, possible iron dilution from the steel substrate will be minimized by use of this welding product, see Figure 6.

Welding of Sheet Lining or “Wallpaper”

In this type of application, thin alloy sheet is attached to an existing steel vessel or duct[12]. Overlapping seam welds in this type of construction are not subject to iron dilution if welded properly, but an overmatching filler metal is required if weld metal corrosion resistance is to be as good as or better than the base metal. Iron dilution can occur in the arc spot or “plug” welds used to attach the alloy sheet to the steel backing. In this case the iron contaminated weld may be covered with a second alloy weld pass to minimize iron dilution, or a thin alloy cap or batten strip can be applied with circumferential seal welds. Again, an overmatching low iron filler metal would be preferable.

General Corrosion

Pitting and crevice corrosion are usually more destructive forms of weld metal attack than general corrosion. Though the weld metal corrosion rate may be somewhat higher than base metal rate, general corrosion is predictable and can be accounted for by a corrosion allowance in the original design. In typical aggressive oxidizing acid environments like concentrated sulfuric acid and reducing environments like hydrochloric acid the nickel alloys considered herein have roughly similar corrosion resistance. Isocorrosion curves for various alloys in sulfuric and hydrochloric acids are shown in Figures 9 and 10. In sulfuric acid the 0.5 mm/y lines show an advantage for the alloy 686, while in hydrochloric acid the alloys 686 and C-276 are similar. A review of published data shows that the relative corrosion resistance of alloys C-276, 622, 686, N06022, 59 and N06200 may vary with acid temperature and concentration. Also acid mixtures of different concentrations may lead to further variations in relative corrosion resistance.

It is important to note that in a reducing environment like pure hydrochloric acid Ni-Mo alloys such as alloy B-2 have superior corrosion resistance. If even small amounts of an oxidizer are present, however, chromium bearing nickel alloys will have corrosion resistance superior to the alloy B-2. This is illustrated by isocorrosion curves in Figures 11 and 12. Substitution of alloy 686 for the B-2 can result in significant cost savings.

Thermal Stability of Welds

In highly oxidizing environments intergranular corrosion of sensitized weld or base metals may result. In some instances heat from the welding process can cause intergranular sensitization of the base metal or weld deposit. In Ni-Cr-Mo or Ni-Cr-Mo-W alloys precipitation of mu phase is the usual cause of this intergranular sensitization. ASTM G-28, Practice A and G-28, Practice B are two common intergranular corrosion tests. Results for various sheet and plate base metal/weld metal combinations made by two different welding process are shown in Table 8. In ASTM G-28, A only alloy C-276 exhibited evidence of heat affected zone (HAZ) attack in these as-welded specimens. The overall higher corrosion rate for alloy C-276 in this test was typical, and is due to the alloy’s relatively low chromium content. In the ASTM G-28, B test severe intergranular weld attack occurred in some cases for alloys N06022, C-276 and 622 when welded with matching filler metal. This attack was reduced when the overmatching welding product was used. Though weld metals of the less resistant alloys may be susceptible to attack in the severe G-28, B test, intergranular corrosion of the base metal HAZ only occurred in alloy C-276. It should be noted that even this attack was slight.

These alloys are used for aqueous corrosion resistance and are seldom subjected to temperatures above about 500ºC (932ºF). No detrimental secondary phase precipitation will occur in the weld metal or base metal of any of the alloys being considered when exposed in this temperature range during normal equipment life cycles.

Mechanical Properties of Welded Material

Typical room temperature yield strength, tensile strength and elongation results for various weld metal / base metal combinations are shown in Table 9. The strength of welded samples is in the same general range as for unwelded material and the ductility is also very good. The compatibility of the overmatching filler metal 686 with various alloys is further demonstrated by the excellent mechanical properties of welded joints.

Plant Performance

Plant designers have become increasingly aware of the outstanding corrosion resistance of alloy 686 in a range of aggressive corrosive environments where it is critical to avoid repair of equipment because of operating efficiency or hazardous service issues. The alloy was selected for the closed loop heat transfer system at the VEAG power station at Boxberg in Germany. The system is required to perform in an environment with chlorides, fly ash and sulfuric acid which tests revealed was too aggressive for lower alloyed C-276 and N06022 compositions.

Plant operators are also increasingly using filler metal 686 for a wide range of construction, operation and maintenance requirements. Applications include joining duplex, super duplex and super austenitic stainless steels, overmatching alloys C-276, 622, 59 and N06200, joining clad plate and overlaying lower alloy compositions. Significant improvements in performance and cost savings can be secured by using this higher alloyed filler metal in the appropriate environments.

Representative alloy 686 and filler metal 686 applications

- Filler metal 686 is used by FMC to weld overlay carbon steel sour gas wellhead equipment in the North Sea.

- Filler metal 686 was found to resist attack in a bypass flue gas environment at Seminole Electric in Palatka, Florida, USA where both C-276 base metal and weld metal were failing. This lead to further use of both alloy 686 plate and filler metal 686. The condensate causing severe attack of alloy C-276 in this power plant was very similar to the oxidizing chloride test solution used in pitting and crevice corrosion tests reported in this paper.

- Filler metal 686 was used to weld an alloy 59 vessel used to handle various hydrocarbons, sulfuric acid, ammonium fluoride and proprietary catalysts at an Alabama, USA chemical plant operated by a major chemical company.

- Alloy 686 welded tubing produced by Schoeller Werk GmgH & Co. is being used in a closed-loop flue gas heat transfer system at the VEAG power station at Boxberg, Germany.

- Alloy C-276 sheet flue gas system lining or “wall papering” at power utilities for Opatovice and Melnik in the Czech Republic are welded with filler metal 686.

- Alloy 686 plate welded with filler metal 686 is used in flue gas desulfurization systems at Lakeland, Florida, USA and heat exchanger systems at Pocerady in the Czech Republic.

- Alloy C-276 clad steel has been welded with filler metal 686 at Salt River Project, Navaho Station in Page, Arizona, USA and at the Israel Electric Company Rutenberg Station in Israel.

CONCLUSIONS

1. The inherent lower corrosion resistance Ni-Cr-Mo or Ni-Cr-Mo-W alloy weld metal, as compared to the matching composition base metal, can be compensated for by use of an overmatching filler metal such as filler metal 686.

2. During nickel alloy weld overlaying of carbon steel, the initial iron content of the nickel alloy filler metal influences the degree of weld metal iron dilution from the steel substrate.

3. The combined effects of low iron content and inherent superior localized corrosion resistance of filler metal 686 allows the following advantages:

- Single layers of this product provide better localized corrosion resistance than three layers of alloy C-276.
- Use of this product for joining nickel alloy clad steel plate can alleviate concern of weld metal iron dilution and make use of cap or batten strips over weld joints unnecessary.

4. The general corrosion resistance of filler metal 686 is equivalent to other highly alloyed nickel alloys in oxidizing and reducing environments. A small amount of oxidizer in reducing environments make chromium bearing Ni-Cr-Mo-W compositions superior to Ni-Mo compositions.

5. The above corrosion and welding advantages represent significant fabrication cost savings as well as reliability improvements.

REFERENCES

1. Wess, T.J., et. al., Paper No. 414, CORROSION 94, Baltimore, Maryland, USA, February 29 – March 4, 1994
2. Streicher, M. A., Corrosion, Vol. 32, No. 3, March, 1976.
3. Dindas, H.J., et. al., Paper 122, CORROSION 81,
4. Unpublished data, Inco Alloys International, Inc. Laboratory Report, C-403R of August 7, 1986
5. Cieslak, M. J., The Welding and Solidification Metallurgy of Alloy 625, WELDING JOURNAL 70: 49s - 56s, 1991.
6. DuPont, J.N., Robino, C.V., and Marder, A.R., Solidification and Weldability of Nb Bearing Superalloys, WELDING JOURNAL 77: 417s – 431s, 1998.
7. Garner, A, Pulp and Paper, Canada, December 1981, 82, 12, p 414
8. Enos, E.G. et. al., Corrosion, Vol. 52, No. 11,
9. Kearns, J.R., POWER Magazine, August 1991
10. Wu, J.B.C., et. al., Paper No. 302, CORROSION 85, Boston, Massachusetts, USA, March 25-29, 1985.
11. Orie, K E, et al, Paper 422, CORROSION 93, New Orleans, LA, March 6 – 12, 1993
12. NACE Standard Recommended Practice RP0202-92, Item No. 53088, NACE International, P.O. Box 218340, Houston, Texas, 77218-8340, USA
13. Kiser, S.D., et al, WELDING JOURNAL 69, November, 1990, p 30-35

Table 1
Typical Welding Parameters
Gas Metal-Arc Welding (GMAW)

Transfer Type	Electrode Diameter (mm)	Wire Feed Speed (mm/s)	Welding Voltage (V)	Welding Current (A)
Spray	0.9	190-250	26-32	180-245
Spray	1.2	100-150	26-32	225-300
Spray	1.6	50-90	27-33	250-345
Pulsed	0.9	115-170	19-22	90-140
Pulsed	1.2	40-95	21-26	125-185
Pulsed	1.6	30-55	23-28	160-240

Argon or argon/helium mixtures with a flow rate of 1.0-1.4m^3/h

Table 2
Typical Welding Parameters
Gas Tungsten-Arc Welding (GTAW)

Wire Diameter (mm)	Welding Current (A)	Gas Cup Size (mm)	Tungsten Diameter (mm)
1.6	90-160	9.5-15.9	1.6-2.4
2.4	100-190	9.5-15.9	1.6-2.4
3.2	110-210	12.7-15.9	2.4-3.2

Argon or argon/helium mixtures with a flow rate of 0.4 -1.4m^3/h.

Table 3
Typical Compositions of Nickel Base Alloys Examined

UNS No.	Fe	Ni	Cr	Mo	W	Cu	Total Cr + Mo + W	PREN*
N06455	2	66	16.0	16.0	--	--	32.0	40.0
N10276	5	57	15.5	16.0	3.9	--	35.4	45.4
N06022	4	57	21.4	13.4	3.1	--	37.9	46.2
N06022	2.5	59	20.5	14.2	3.2	--	37.9	46.6
N06200	1	57	23.0	16.0	--	1.6	39.0	46.2
N06059	1	59	23.0	16.0	--	--	39.0	47.0
N06686	<1	57	20.5	16.0	3.9	--	40.4	50.4

*Pitting Resistance Equivalent Number (PREN) = % Cr + 1.5(%Mo + %W) – 0.5Cu

Table 4
Effect of Processing on Pitting Resistance of Welded Tube
Produced with Continuous Autogenous Weld
11.9% H_2SO_4 + 1.3% HCl + 1% $FeCl_3$ + 1% $CuCl_2$

Tube Alloy	Tube Condition	Exposure Conditions		
		103°C for 168 h	138°C for 24 h	150°C for 24 h
686	As-welded	No pitting	--	--
686	Weld + anneal	No pitting	One pit in weld	--
686	Draw + anneal	No pitting	No pitting	3 pits*
59	As-welded	Severe weld attack	--	--
59	Weld + anneal	No pitting	Severe weld attack	--
59	Draw + anneal	No pitting	No pitting	Severe attack*

*Attack in weld metal and base metal

Table 5
Pitting Test Results for GTAW Welded Specimens
11.9% H2SO4 + 1.3% HCl + 1% FeCl3 + 1% CuCl2
Boiling at 103°C for 72 Hours

Base Metal Alloy	Filler Metal	Maximum Pit Depth (mm)	Overall Corrosion Rate (mm/y)	Comments
N06200	FM N06200	2.6	11.3	Severe attack of weld metal
N06200	FM N06200	2.3	9.8	Severe attack of weld metal
N06200	FM N06200	2.4	10.6	Severe attack of weld metal
N06200	FM 686	0	0.1	No attack
N06200	FM686	0	0.1	No attack
N06200	FM 686	0	0.1	No attack
59	FM 59	0.4	0.2	Light attack of weld metal
59	FM 59	1.6	6.7	Severe attack of weld metal
59	FM 59	1.9	10.6	Severe attack of weld metal
59	FM 686	0	0.1	No attack
59	FM 686	0	0.1	No attack
59	FM 686	0	0.1	No attack

Alloy N06200 base metal was 3.2 mm thick sheet
Alloy 59 base metal was 5 mm thick plate

Table 6

Pitting Test Results for GTAW and GMAW-P Welded Specimens

11.9% H_2SO_4 + 1.3% HCl + 1% $FeCl_3$ + 1% $CuCl_2$

Boiling at 103ºC for 72 Hour

Base Metal Alloy	Weld Filler Metal	Maximum Pitting Depth of Attack, mm Average Results for Duplicate Specimens			
		GTAW Process		GMAW-P Process	
		Base Metal	Weld Metal	Base Metal	Weld Metal
C-276[1]	FM C-276	0	6.2	0	3.4
C-276[1]	FM 686	0	0	0	0
N06022[1]	FM N06022	0.7	5.7	1.6	3.0
N06022[1]	FM 686	0.9	4.7	0.2	0
622[1]	FM 622	0	4.8	0.1	7.7
622[1]	FM 686	0	0	0	0
N06200[2]	FM N06200	0	2.4	--	--
N06200[2]	FM 686	0	0	--	--
59[1]	FM 59	0	1.3	--	--
59[1]	FM 686	0	0	--	--
686[1]	FM 686	0	0	0	0

1 - 5 to 6 mm thickness, 2 - 3 mm thickness

Table 7

Critical Pitting Temperatures for Nickel Alloy Overlays on Carbon Steel

One, Two and Three Weld Layers Tested

11.9% H_2SO_4 + 1.3% HCl + 1% $FeCl_3$ + 1% $CuCl_2$

Boiling (103ºC) for 24 Hours

Filler Metal	1st Weld Layer		2nd Weld Layer		3rd Weld Layer	
	Specimen #1	Specimen #2	Specimen #1	Specimen #2	Specimen #1	Specimen #2
FM C-276	75	75	95	95	95	95
FM N06022	75	70	100	100	100	100
FM 622	75	85	70	>100	>100	>100
FM 686	>100	>100	>100	>100	>100	>100

Before testing the steel substrate was removed and the weld overlay interface was protected from the environment. The overlay surface was ground smooth with 120 grit aluminum oxide grinding paper.

Table 8
Intergranular Corrosion Test Results for Welded Sheet and Plate
Different Base Metal / Weld Metal combinations by GTAW and GMAW-P Processes
Corrosion Rates in mm/y

Base Metal	Filler Metal	Sheet 1.6 – 3.2 mm				Plate ≈6.4 mm			
		GTAW Process		GMAW-P Process		GTAW Process		GMAW-P Process	
		G-28, A	G-28, B	G-28, A	G-28, B	G-28,A	G-28,B	G-28,A	G-28,B
C-276	FM C-276	5.8**	1.8	7.8**	9.2*	8.4**	1.4	12.3**	45.0*
C-276	FM 686	6.1**	2.0	7.0**	1.6	7.9**	1.9	10.7**	4.1
N06022	FM N06022	1.2	0.4	1.1	10.5*	1.1	20.2*	1.2	35.3*
N06022	FM 686	1.2	0.2	1.3	0.6	1.2	0.4	1.8	0.4
622	FM 622	2.0	0.7	1.9	0.7	1.4	0.4	3.3	5.2*
622	FM 686	2.0	0.7	2.0	0.7	1.8	0.4	3.6	2.0
N06200	FM N06200	1.0	26.2*	--	--	--	--	--	--
N06200	FM 686	1.1	0.2	--	--	--	--	--	--
59	FM 59	0.99	0.46	--	--	0.9	1.2*	--	--
59	FM 686	1.14	0.38	1.42	0.33	1.0	0.2	--	--
686	FM 686	3.0	1.4	3.1	1.2	2.3	0.6	2.5	0.5

*Accelerated weld attack **Slight heat affected zone attack

Table 9
Room Temperature Tensile Test Results for Welded Plate (≈ 6.4 mm)
Weld in Transverse Direction, Results in Mpa

Base Metal	Filler Metal	GTAW Process			GMAW-P Process		
		0.2% Yield Strength	Tensile Strength	% Elongation	0.2% Yield Strength	Tensile Strength	% Elongation
C-276	FM C-276	402	780	58.0	412	781	45.0
C-276	FM 686	388	768	48.0	400	789	42.0
N06022	FM N06022	363	745	52.5	386	770	50.0
N06022	FM 686	399	817	48.5	385	766	52.0
622	FM 622	417	743	67.0	354	735	54.5
622	FM 686	380	739	54.0	372	734	51.0
686	FM 686	387	738	54.5	385	736	50.0

Figure Captions

Figure 1 Relative Resistance of Nickel Base Alloys to Crevice Corrosion as a Function of Temperature Environment: 11.9% H_2SO_4 + 1.3% HCl + 1% $FeCl_3$ + 1% $CuCl_2$, 24 hour exposure.

Figure 2 Fusion zone of a manual GMA weld made in 0.062” (1.6mm) alloy C-276 sheet using Filler Metal C-276. SEM-SEI . 2000X, Etchant: 49% Phosphoric, 50% H_2O, 1% chromic acid, electrolytic

Figure 3 Molybdenum line scaf of dentrites in a manual GMAW weld in alloy C-276

Figure 4 Pitting Resistance of Various Base Metal – Weld Metal combinations,Test Environment: 11.9% H_2SO_4 + 1.3% HCl + 1% $FeCl_3$ + 1% $CuCl_2$, Boiling (103ºC) for 72 Hours

Figure 5 A Comparison of the Pitting Resistance of Welds Made in Alloys N06200 and 59 Base Metals with Matching Composition Filler Metals and with Alloy 686 Filler Metal, Test Environment: 11.9% H_2SO_4 + 1.3% HCl + 1% $FeCl_3$ + 1% $CuCl_2$, Boiling (103ºC) for 72 Hours

Figure 5a
Alloy N06200 Base Metal, 0.125” (3.2mm) sheet welded with N06200 Filler Metal (on right) and welded with 686 Filler Metal (on left)

Figure 5b
Alloy 59 Base Metal, 0.200” (5.1mm) sheet welded with 59 Filler Metal (on right) and welded with 686 Filler Metal (on left)

Figure 6 Iron contents measured in various weld overlays on steel - 1st, 2nd, and 3rd layers. Effect of the initial filler metal iron content on final weld metal iron content is shown. Iron dilution decreases as filler metal iron content decreases.

Figure 7 Welding Procefures Used to Fabricate Nickel Alloy Clad Steel Plate

Figure 8 Example of a Nickel Alloy Clad Steel Plate with a Cap or Batton Strip to Protect the Weld

Figure 9 Comparative Behavior of Several Nickel Base Alloys in Sulfuric Acid. The isocorrosion Lines Indicate a Corrosion Rate of 0.5 mm/y

Figure 10 Comparative Behavior of Several Nickel Base Alloys in Hydrochloric Acid. The isocorrosion Lines Indicate a Corrosion Rate of 0.5 mm/y

Figure 11 Isocorrosion Chart for Alloy B-2 in Hydrochloric Acid + 500 ppm Fe^{+++}

Figure 12 Isocorrosion Chart for Alloy 686 in Hydrochloric Acid + 500 ppm Fe^{+++}