The Effect of Iron Dilution on Cu-Ni Weld Deposits Used in Seawater

Iron dilution levels and filler metal compositions were evaluated for welding CA706 clad steel intended for seawater applications

BY R. K. WILSON, T. J. KELLY AND S. D. KISER

ABSTRACT. CA706 clad steel has for many years been welded for marine applications, but the acceptable iron dilution limits for seawater service have not been established. The results of this work demonstrate that CA706 clad steel can be welded for seawater service with up to 10% iron dilution, using either 70-30 copper-nickel or 70-30 nickel-copper filler metal. Additionally, these results show that 90-10 copper-nickel filler metal is unacceptable for welding CA706 clad steel for seawater service, regardless of the amount of iron dilution which occurs in the weld.

Introduction

As resources on land have become scarce, civilization has begun to turn to the oceans of the earth for energy, fresh water, and minerals. In dealing with seawater, normal structural materials have proven to be poor choices due to corrosion and biofouling. Copper-nickel alloys have excellent resistance to seawater corrosion and biofouling, but they are expensive and have lower strength-to-weight ratios than structural steels. Due to the cost of the Cu-Ni alloys, as well as to their lack of adequate strength for some applications, it is common to consider using Cu-Ni alloys as cladding on structural steels.

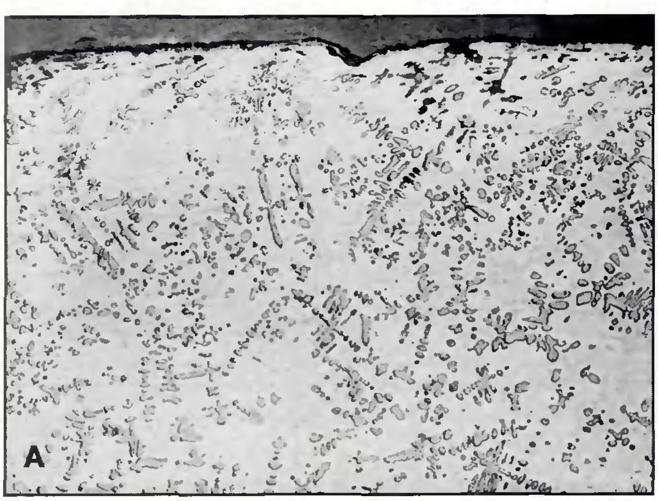
The use of Cu-Ni alloys for cladding of steel structures in seawater service presents several questions, such as what thickness of Cu-Ni to use, how to join the cladding to steel, how to compute the strength of the structure, and what (if any) additional corrosion protection is needed. The work described in this paper was mainly concerned with iron dilution, but the data can also be useful in determining cladding thickness and the proper joining process.

Most of the technical publications (Refs. 1-10) available on the welding of clad steel cite levels of iron dilution which vary with the filler metal, but only two papers (Refs. 1 and 7) cite the effects of welding process and cladding thickness on the resulting dilution. It is obvious that, for a given filler metal, the maximum dilution permissible must be factored into the selection of the correct cladding thickness, since, if a given combination of welding process and cladding thickness would produce excessive weldment iron dilution, then either the welding process (or procedure) or the cladding thickness must be changed. The most economical shipbuilding system for Cu-Ni clad hulls would require integration of these factors.

Copper-nickel clad structures (generally using CA706 alloy, 90-10 Cu-Ni) are currently being welded with either cop-

KEY WORDS
CA706 Clad Steel
Seawater Service
70 Copper-30 Nickel
90 Copper-10 Nickel
Iron Dilution Limits
Cladding Thickness
Cu-Ni Weldments
Corrosion Resistance
Galvanic Couple Test
Corrosion Testing

R. K. WILSON is Group Leader—Metallography, Inco Alloys International, Inc., Huntington, W. Va. T. J. KELLY is with General Electric Co., Cincinnati, Ohio. S. D. KISER is with IAII Welding Products Co., Newton, N.C.



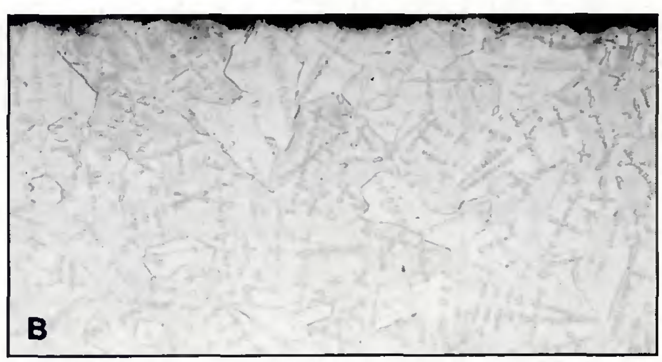


Fig. 1—Comparison of the cast pin microstructure to that of the weldment microstructure. A—The microstructure of a CA706 weldment with 11.7% Fe dilution; B—the microstructure of a cast pin of 90-10 Cu-Ni electrode deposit composition with 8.8% Fe dilution

per-nickel (90-10 or 70-30) or nickel-copper (70-30) electrodes or filler metals. Due to the wide range of composition in the electrodes, there is also a wide range of permissible iron dilution in the resulting weld deposits, but the effects of iron dilution have not yet been fully documented. The lack of data on the effect of iron dilution on the seawater performance of Cu-Ni weldments is a problem since 1) organizations in several countries will soon establish standards for the welding of clad offshore structures and desalination plants, and 2) if Cu-Ni cladding of ships develops into a commercial practice, it will also require standards for permissible iron dilution in weld deposits.

There are several ways in which iron content can render a Cu-Ni weldment unsuitable for service: 1) excessive iron can affect the physical integrity, or soundness, of the weld metal; 2) iron can adversely affect mechanical properties of the joint; and 3) it can lower the corrosion resistance of the weldment. In this paper, two levels of iron dilution in Cu-Ni weldments are determined. The first, higher dilution level established is the level required to fail a visual inspection; the second, and lower, iron level established in this work is the level at which the weldment corrosion resistance becomes inadequate.

Both bulk chemical analysis and microprobe data were used to measure iron dilution. The corrosion rate data for the iron-diluted weldments are presented based on measurements made using simulated weld deposits galvanically coupled to CA706 and compared to actual weldments exposed in seawater.

Experimental Procedure

The iron dilution levels required to produce visibly defective welds were established by welding with 90-10 Cu-Ni and 70-30 Cu-Ni electrodes into weld grooves that had been machined into CA706 (90-10 Cu-Ni) clad steel plates. The cladding thickness was 2.5 mm (0.10 in.) and the steel plate was 25.4 mm (1.0 in.) thick. Various amounts of heat input were used to establish different levels of iron dilution in the weld. When a weld was made that was visibly defective due to cracking or porosity, then its bulk composition was analyzed by removing the top third of the weld deposit for chemical analysis to determine the level of iron dilution which caused the surface discontinuity. Once a level of iron dilution that caused the discontinuities was established, then this level was used as a maximum iron dilution.

In the case of the 70Ni-30Cu electrode, it was necessary to set an arbitrary iron dilution limit. Because the nickel-rich side of the system has a much greater iron solubility than does the copper-rich side of the system, visible weld discontinuities would not be expected until the weld metal iron content was much too high to produce a weldment resistant to seawater corrosion.

Since the corrosion testing was to be done by immersion in seawater, the actual corrosion test coupons could not be made from CA706 clad steel, because the steel would be too difficult to isolate from the seawater; and if not totally isolated, the steel would galvanically protect the entire Cu-Ni weldment. Therefore, the test specimens had to be made of solid CA706 with a simulated iron-diluted weld either attached to or made across the specimen. This was accomplished in two ways: 1) one set of specimens was made from pieces of CA706 in which iron rods were placed at the bottom of machined grooves, and 2) welds were then made over the iron rods to achieve the proper iron dilution. The other set of specimens consisted of blanks of CA706 coupled to pins of artificial weld metal. The artificial weld metal was made by extracting rods of molten metal from heats of Cu-Ni containing predetermined levels of iron. In both cases, the ratio of the surface areas of the CA706 baseplate to the weld bead was kept at 25:1 to allow a direct comparison of galvanic data and actual weld exposure data. Examination of the cast pin microstructure and the actual weldment microstructure shown in Fig. 1 indicates that the segregation pattern in the pin was similar to that of the weld.

The two types of seawater corrosion test specimens described above are shown in Figs. 2 and 3. Fresh seawater was used in 400-L (106-gal) tanks replenished at a rate of 2 L/min (0.5 gal/min); all tests lasted at least 60 days and were done at two different temperatures—17.5°C (63.5°F) and 27.2°C (81.0°F). Both corrosion potential and weight loss were measured as functions of time.

Fig. 2—Example of galvanically coupled simulated weld pin and CA706 plate

Fig. 3—Example of iron-diluted weld bead specimens used for seawater exposure testing

Bulk chemical analysis samples removed from the upper one-third of the weld were used to determine the levels of iron dilution in the weld bead, while microprobe measurements were used to determine the amounts of iron segregation in the weldments. Metallographic examinations of the weldments were performed to document the effects of segregation on the weld microstructure.

A separate set of weldments was made and tested to determine the effects on tensile and bend properties of Cu levels that were acceptable from a corrosion standpoint. While gross degradation of properties was not expected, there was concern that bend ductility in particular would be reduced by iron dilution.

Results

Welding

Representative samples of the actual welds made into CA706 clad steel plate are shown in Figs. 4 and 5. The weld in Fig. 4 was made with 70Cu-30Ni (MONEL[1] Welding Electrode 187), while the weld in Fig. 5 was made with 90Cu-10Ni (UTP[2] 389 welding electrode). In Fig. 4, one of the weldments has a number of

1. Trademark of the Inco family of companies.

2. Trademark of UTP Welding Materials, Inc.

Fig. 4 — Weldments made with 70Cu-30Ni electrode on CA706 clad steel (8052 and 8053 containing 20.3 and 7.5% iron, respectively). Note that weld number 8052 is cracked in several locations

Table 1—Percent Iron Dilution in Cu-Ni Weldments Made in Grooves Machined into CA706 Clad Steel[a]

Electrode Nominal Composition	% Fe	Condition of Weld
90Cu-10Ni	1.8	Good
90Cu-10Ni	5.6	Passable[b]
90Cu-10Ni	10.4	Defective[c]
70Cu-30Ni	1.0	Good
70Cu-30Ni	10.4	Good
70Cu-30Ni	17.5	Cracked

(a) The iron content was measured from chips taken from the top one-third of the weld bead. This data was used to establish iron dilution levels for visible defects.
(b) Poor surface appearance, some porosity. No gross defects, no cracking visible.
(c) Extremely poor surface appearance, including extensive porosity, possible cracking. Uneven weld bead surface is equivalent to significant undercut.

transverse cracks, while in Fig. 5, the weldment is very porous. The iron contents of these two weldments were used as the levels of iron dilution that would produce defective welds — Table 1. Visible defects were found in the weldments at 10% iron dilution for the 90-10 weld deposit and at 17.5% iron dilution for the 70-30 Cu-Ni weld deposit. Though these were the upper limits of iron dilution desired for testing, the actual corrosion test specimens were slightly different in iron content, having 11.7% iron in the 90-10 Cu-Ni specimen and 14.1% iron in the 70-30 specimen.

Since weldments of the CA706 with 70Ni-30Cu weld metal were not used to establish a maximum iron dilution level, the maximum was arbitrarily set at a target value of 16%. The actual weldments made for corrosion testing, however, contained a maximum of only 11.8% iron.

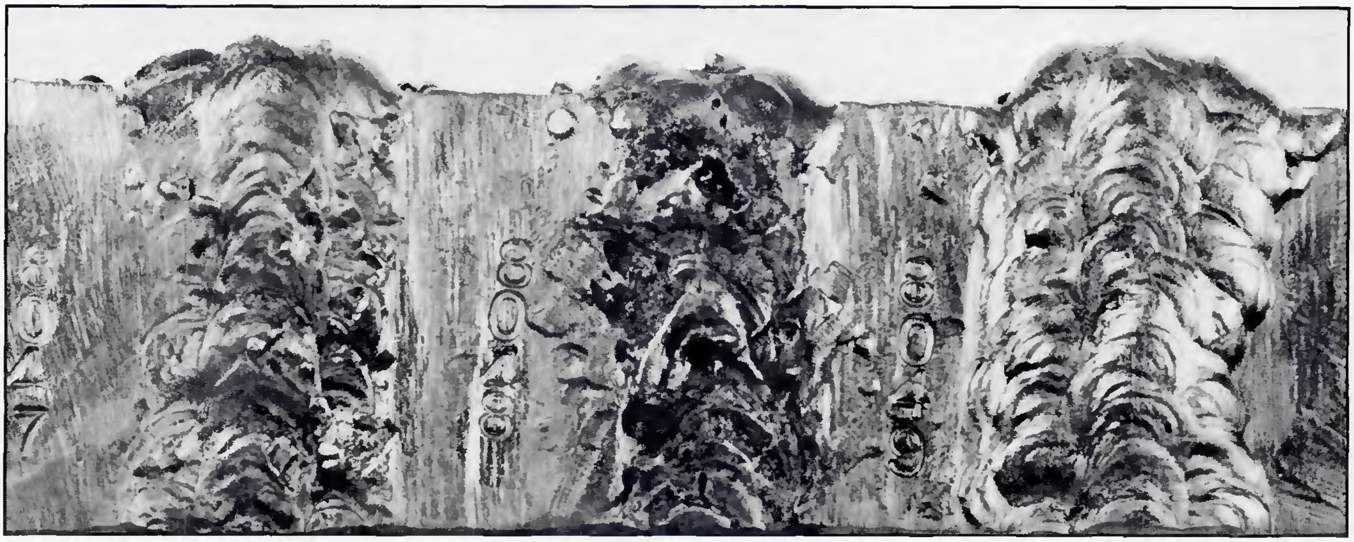


Fig. 5 — Surface appearance of three welds made with 90Cu-10Ni welding electrode on CA706 clad steel: W8047 contained 5.6% Fe, W8048 contained 10.4% Fe, and W8049 contained 1.8% Fe. W8048 was determined to be unacceptable based on visual inspection, and was used as the maximum allowable Fe dilution for this electrode

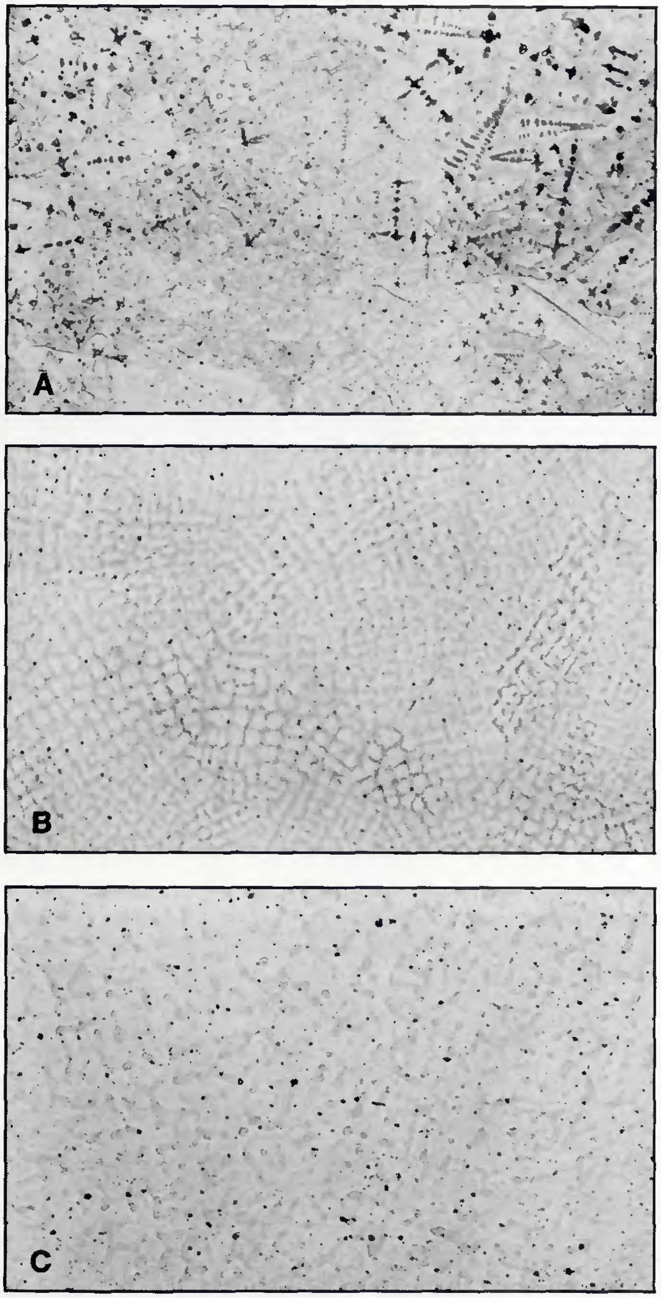


Fig. 6 — Microstructures of the weldments containing one-half the maximum amount of iron used for seawater exposure testing. A — The 90Cu-10Ni deposit with 5.1% Fe; B — the 70Cu-30Ni deposit with 7.5% Fe; C — the 70Ni-30Cu deposit with 9.2% Fe

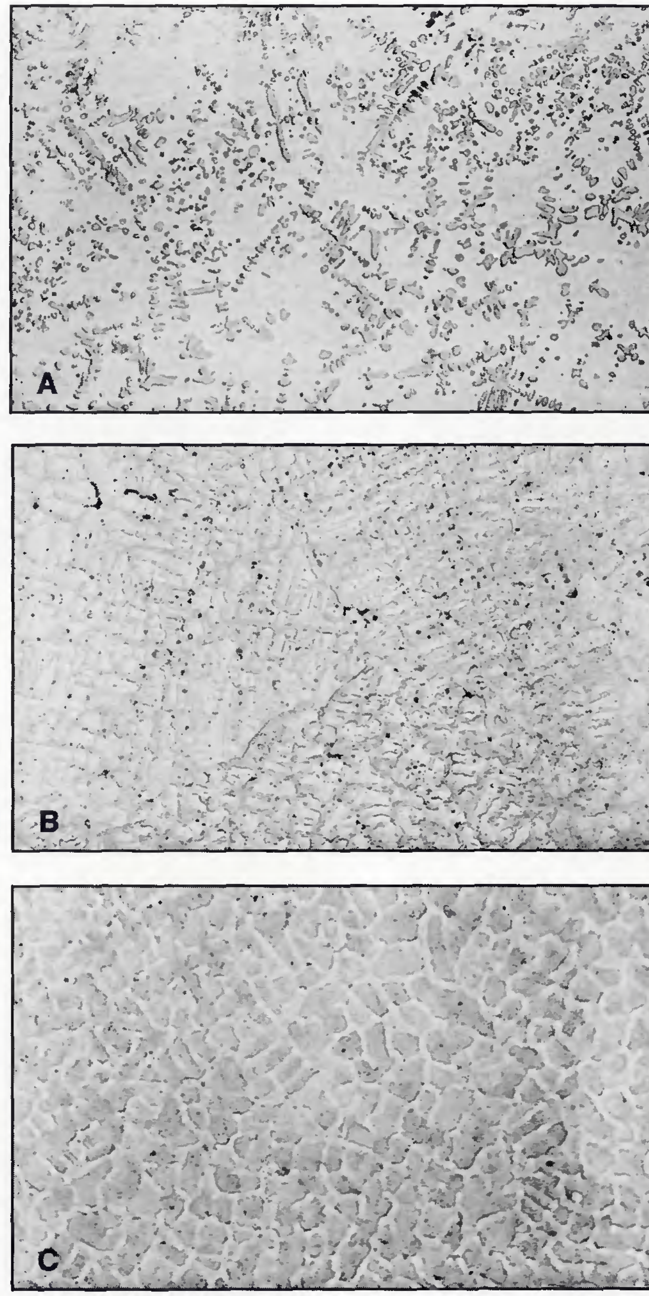


Fig. 7 — The microstructures of the weldments containing the maximum amount of iron dilution used for seawater exposure testing. A — The 90Cu-10Ni deposit with 11.7% Fe; B — the 70Cu-30Ni deposit with 14.1% Fe; C — The 70Ni-30Cu deposit with 11.8% Fe

Metallographic Examination

Figures 6 and 7 show the effects of iron dilution on the microstructures of the weldments. In Fig. 6, the microstructures of weld metals at the half-maximum iron dilution level are compared for each welding electrode, while in Fig. 7, the effect of the maximum iron dilution is demonstrated. Both the 70Cu-30Ni and 70Ni-30 Cu welding electrodes produced deposits which are single phase at the half-maximum and maximum iron content, while the 90Cu-10Ni electrode produced a two-phase microstructure at both the maximum and half-maximum iron dilution levels.

Table 2 presents the results of the microprobe analysis done on the material shown in Figs. 6 and 7. In all cases, there was a marked degree of segregation, even in the welds which retained a single-phase structure. Similar results were found by Van Dyck (Ref. 9) and Rockel (Ref. 10). The bulk iron content in one of the 70Ni-30Cu deposits was 11.8%, but the iron level found in the microprobe analysis varies from a minimum of 5.4% to a maximum of 13.8%. Similarly, in one of the 70Cu-30Ni deposits, the bulk iron level was 14.1%, but the minimum was 5.0% and the maximum was 18.2%. The greatest segregation was found in the 90Cu-10Ni deposit with an 11.7% bulk iron dilution, which segregated to a minimum of 2.9% and a maximum of 64.0%, as would be expected since it was a two-phase structure.

Corrosion Testing

The actual weldments were tested by immersion in quiet seawater at 1-m (3.3-ft) depth for up to 525 days, during which time the temperature varied from 5°C

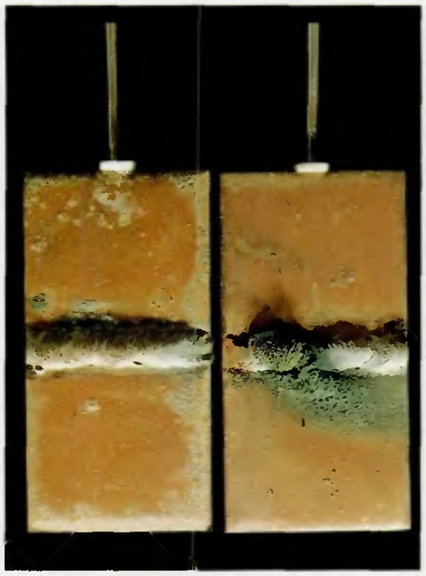


Fig. 8—CA706 welded with Ni-Cu alloy with 11.8% iron dilution after 60-day exposure in quiet seawater

Fig. 9—CA706 welded with 70-30 Cu-Ni with 14.1% iron dilution after 60-day exposure in quiet seawater

Fig. 10—CA706 welded with 90-10 Cu-Ni with 11.7% iron dilution after 60-day exposure in quiet seawater

(41°F) to 30°C (86°F). Results of these tests appear in Figs. 8 through 10. Note that there is minimal evidence of iron oxide (rust) on the 70-30 Cu-Ni and 70-30 Ni-Cu weld deposits (Figs. 8 and 9), while the 90-10 Cu-Ni deposit shows a heavy red deposit on the weld bead—Fig. 10. In most cases, the corrosion product showing on the higher Ni deposits can be traced either to welding craters which were not backfilled or to a slight amount of undercutting. In any case, the higher Ni weldments contained as much or more iron with considerably less rusting evident, and the rusting that is evident can be attributed to the way in which the specimens were made.

The cast pins that were made to simulate the compositions and structures of weld deposits containing various amounts of iron were placed in quiet

Fig. 11—90-10 Cu-Ni simulated weld deposit pins after 60-day exposure in quiet seawater (left to right: 1.7% Fe, 3.5% Fe and 6.9% Fe)

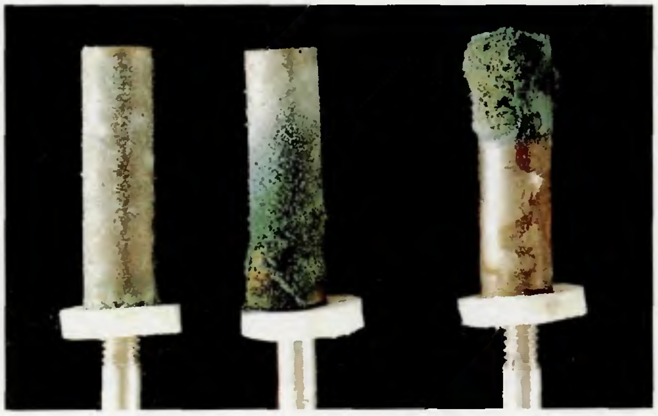
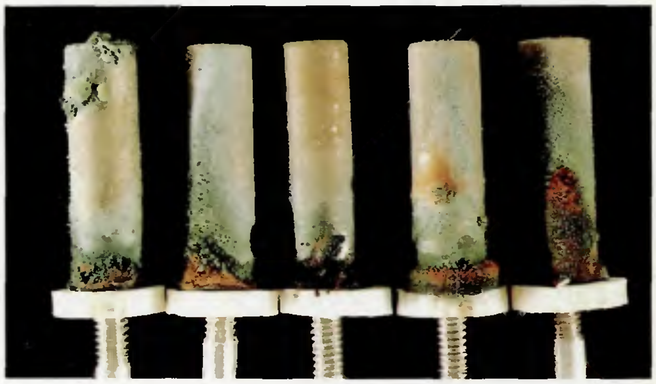


Fig. 12—70-30 Cu-Ni simulated weld deposit pins after 60-day exposure in quiet seawater (left to right: 0.8% Fe, 5.5% Fe and 9.6% Fe)

Fig. 13—Ni-Cu alloy simulated weld deposit pins after 60-day exposure in quiet seawater (left to right: 2.5% Fe, 7.1% Fe, 11.3% Fe, 25.6% Fe and 19.7% Fe)



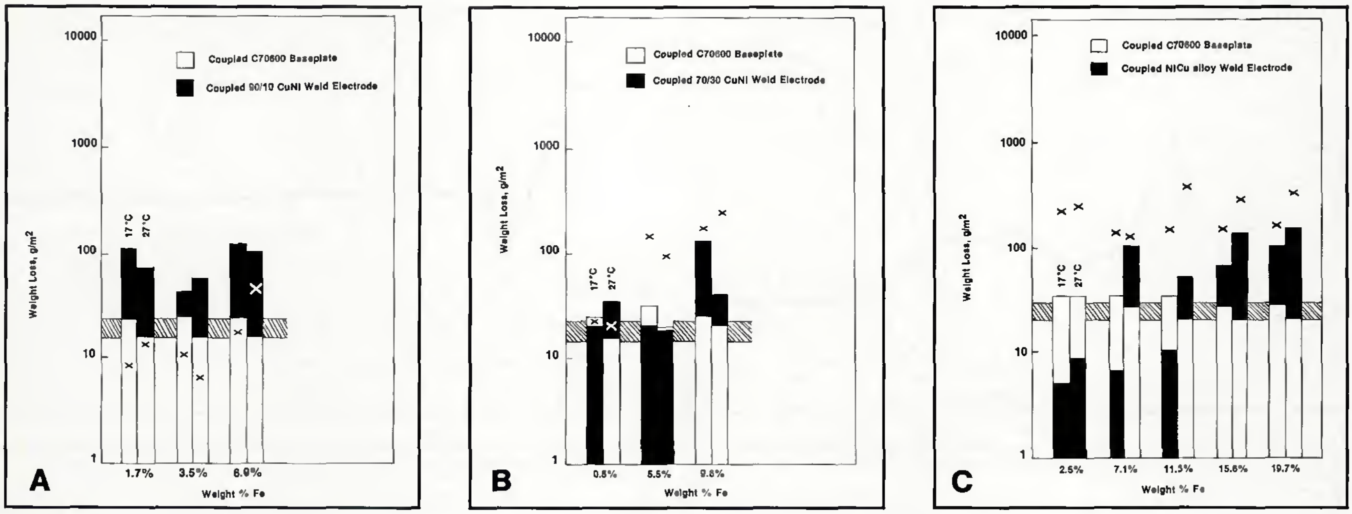


Fig. 14 — Effect of galvanic coupling on weight loss of CA706 baseplate and 90-10 Cu-Ni weld electrodes with various iron levels. Data shown are from tests in seawater at 17°C (first bar of each pair) and 27°C (second bar of each pair). Comparative weight loss of uncoupled control specimens of CA706 baseplate is shown by the crosshatched area. Comparative weight losses of uncoupled control specimens of 90-10 Cu-Ni weld electrodes are shown by the individual crosses. A — 90Cu-10Ni electrode; B — 70Cu-30Ni electrode; C — 70Ni-30Cu electrode

seawater for 60 days, and weight loss measurements were made. Figures 11 through 13 contain typical pin test results. All of these pins corroded (at differing rates, as shown in Figs. 14A–C) in quiet seawater.

A representative sample of a coupled corrosion pin and CA706 baseplate is shown in Fig. 2. This test specimen was used to develop corrosion potential data in quiet seawater. The data was plotted as corrosion potential and current vs. time, with negative current indicating galvanically accelerated corrosion of the weld metal specimen, and positive current indicating preferential corrosion of the baseplate. A sample of these corrosion potential plots is shown in Fig. 15.

The average currents measured during the last 10 days of the 60-day tests of galvanic couples are given in Table 3. Five of the six current readings for 90Cu-10Ni weld metal in 17°C (63°F) seawater were negative, indicating that the weld metal was corroding preferentially. All other current readings at this point in the testing were positive (except one reading of 0). Positive current readings indicate galvanic protection of the weld metal by the base metal.

Weldment Mechanical Tests

Laboratory shielded metal arc electrodes of 70Ni-30Cu and 70Cu-30Ni were formulated, containing sufficient Fe powder to produce 5% and 10% Fe weld metals. These were used to weld butt joints in 0.75-in. (19-mm) thick 90-10 Cu-Ni plate. Longitudinal and cross-weld tensile tests, and face and side bend tests were performed to evaluate the effects of iron.

This method produced a uniform iron concentration throughout the weld metal, but it also resulted in more porosity than would likely result from iron dilution. The porosity increased the severity of the bend tests by providing numerous flaws that could enlarge during testing.

The bend test results presented in Table 4 indicate that iron levels up to 10%

Table 2—Iron Content of Maximum and Half-Maximum Dilution Levels in Welds of 90-10, 70-30 and 30-70 Cu-Ni on CA706 Base Metal, as Determined by Microprobe Analysis and Wet Chemical Analysis

Electrode Type Cu-Ni	CA706 Position of Microprobe Distribution(a) 1	2	3	Bulk Iron Content(b) of Weld
30-70	3.6-4.4	6.3-7.9	4.6-6.2	9.2
30-70	8.8-11.2	5.4-13.8	7.2-8.2	11.8
70-30	5.7-7.6	2.5-2.5	7.0-8.4	7.5
70-30	6.7-12.3	5.0-12.9	7.0-18.2	14.1
90-10	4.3-13.1	3.5-3.9	3.7-20.2	5.1
90-10	9.8-64.0	2.9-57.3	4.8-51.8	11.7

(a) These are the high and low readings from five separate counts at each position. Positions 1, 2 and 3 were ~50 microns from the weld surface.
(b) Samples for analysis were taken from the top third of the weld bead.

Table 3—Average Galvanic Currents Measured During Final 10 Days of 60-Day Seawater Tests

Simulated Weld Metal Portion of Galvanic Couple(b)	Average Current(a), uA 17°C(c) Seawater	27°C Seawater
90-10 Cu-Ni with		
1.7% Fe	−6.5, −29	0.1, 0
3.5% Fe	3.3, −0.4	2.3, 0.9
6.9% Fe	−15, −33	4.4, 3.0
70-30 Cu-Ni with		
0.8% Fe	1.6, 5.4	0.4, 3.1
5.5% Fe	51, 47	31, 52
9.6% Fe	14, 11	43, 57
70-30 Ni-Cu with		
2.5% Fe	59, 57	92, 106
7.1% Fe	62, 61	37, 69
11.3% Fe	45, 46	34, 54
15.6% Fe	19, 12	44, 25
19.7% Fe	20, 17	25, 32

(a) Negative current indicates that the weld metal is corroding preferentially with respect to the base metal.
(b) Base metal in all cases is 90-10 Cu-Ni.
(c) Readings separated by commas are results of duplicate tests.

Table 4—Bend Test Results for Iron-Containing Cu-Ni and Ni-Cu Weldments

Weld Metal	% Fe	Approximate Number of Pores Observed As-Welded: Dye Penetrant	Radiograph	Number of Cracks Detected by Visual Inspection of Tested Specimens: Face Bends(a)	Side Bends(b)
70Cu-30Ni	5	5	50	8,0	0,0,0,0,0
70Cu-30Ni	10	35	300	6,1	0,3,2,4,3
70Ni-30Cu	5	0	11	0,0	1,1,0,0,3
70Ni-30Cu	10	0	12	0,2	2,0,1,2,1

(a) All cracks ¹⁄₆₄ in. long or smaller.
(b) All cracks ¹⁄₃₂ in. long or smaller.

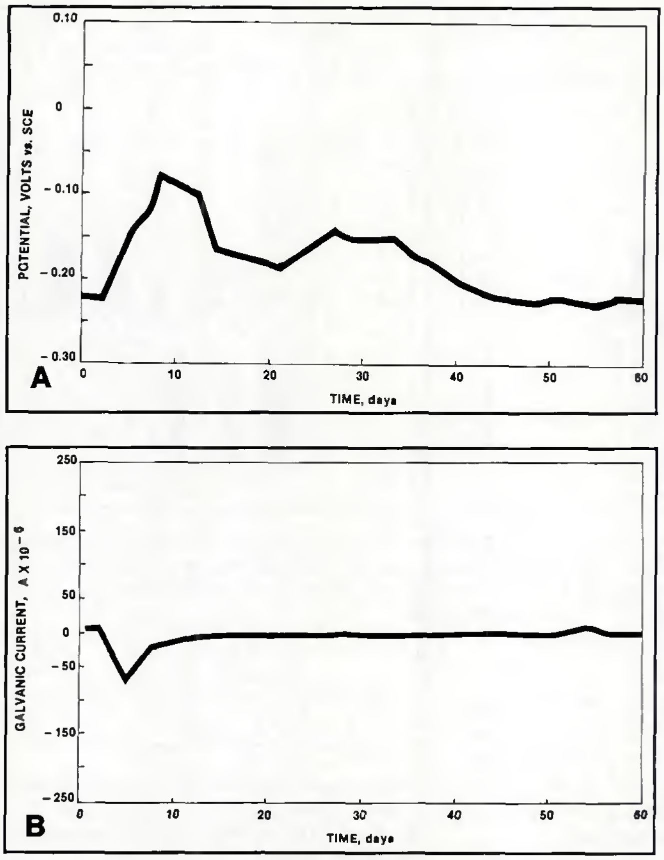


Fig. 15—Example of polarization plots for galvanically coupled specimens. A—Corrosion potential vs. time; B—current vs. time. This test, for CA706 (90-10 Cu-Ni) coupled to a simulated 90Cu-10Ni weld metal containing 3.5% Fe, was conducted in 27°C (81°F) seawater

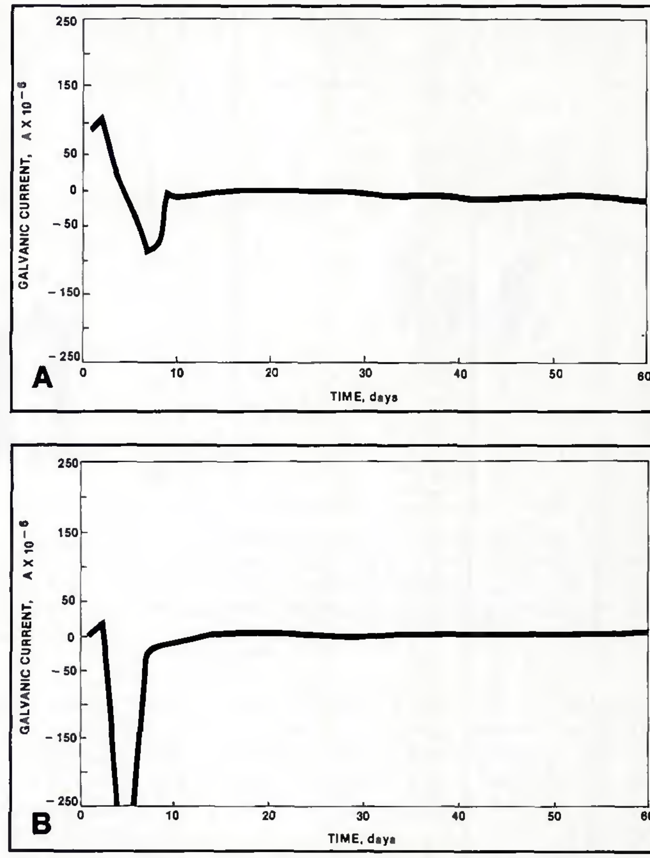


Fig. 16—Effect of temperature on galvanic current measured in 90-10 Cu-Ni weld metal samples with 6.9% Fe. A—Tested at 17°C (63°F); B—tested at 27°C (81°F)

are not significantly detrimental. Despite the porosity, all bend tests were satisfactory.

Tensile test results were similar, with duplicate cross-weld tensile tests of each weld metal and iron level all failing in the base metal well away from the heat-affected zone. This is to be expected since both weld metals, even without the additional solid solution strengthening effect of Fe, are stronger than annealed 90-10 Cu-Ni.

All weld metal tensile properties show both the strengthening effect of Fe and the detrimental effect of porosity on tensile ductility (Table 5). Despite the porosity, the ductility of the high-iron Cu-Ni and Ni-Cu weld metals is acceptable.

Discussion

The results of the corrosion tests are summarized in Fig. 14, in which weight losses are plotted against iron dilution for 60-day quiet seawater immersion tests. On the graphs, the X's represent the 60-day weight losses of the uncoupled corrosion pins, while the black bars represent the 60-day weight losses of the corrosion pins galvanically coupled to the baseplate, and the open bars represent the 60-day weight loss of the baseplate galvanically coupled to the corrosion pins. The crosshatched areas represent the uncoupled 60-day weight loss of the CA706 baseplate.

The data from the 90Cu-10Ni simulated weld deposit is summarized in Fig. 14A. It is clear from the graph that the 90-10 Cu-Ni weld deposit corroded preferentially to the baseplate at every iron dilution level tested, and this is corroborated by the potential and current vs. time plots (Figs. 15–17) made for these couples. Additionally, the weldments that were exposed in seawater also showed marked amounts of corrosion product after 525 days' exposure. This can be contrasted to the results of the 70Cu-30Ni simulated weld deposit in Fig. 14B, which shows no preferential attack of the weld bead up to approximately 10% iron dilution. This result was corroborated by the corrosion potential measurements during the 60-day test period and by the weldments exposed to seawater for 525 days. Similar results were attained for 70Ni-30Cu simulated weld deposits (Fig. 14C), which show no preferential attack of the weld deposit with up to 10% iron dilution at 17.5°C (63.5°F), but some attack at 27.2°C (81.0°F). All of the corrosion data were verified by the corrosion potential plots.

The current readings from the last 10 days of the 60-day galvanic couple tests also point out some significant trends. First, it is surprising that the 90-10 Cu-Ni weld metal corroded preferentially at 17°C, but not at 27°C, between 50 and 60 days. Since total weight losses were approximately equivalent, it is possible that the difference in current reflects a

Table 5—All-Weld Metal Tensile Properties

Weld Metal	% Fe	Yield Strength, psi	Tensile Strength, psi	Elongation, (%)	Reduction in Area (%)
70Cu-30Ni	4.9	35,400	59,100	40.0	64.5
70Cu-30Ni	10.0	44,000	68,300	31.0	43.2
70Ni-30Cu	4.7	40,200	72,900	43.0	61.6
70Ni-30Cu	10.0	40,600	75,900	46.0	54.9

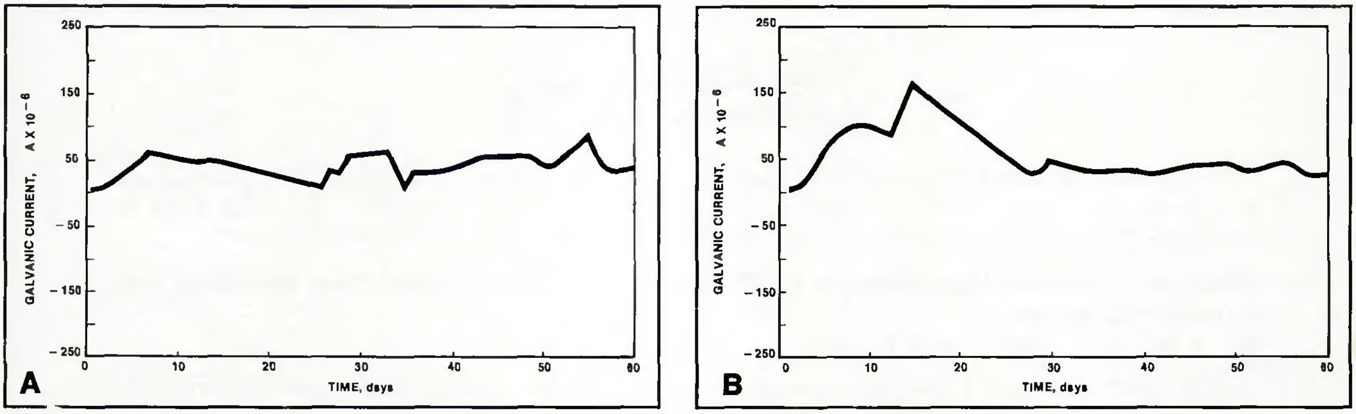


Fig. 17 — Galvanic current vs. time for: A — 70Cu-30Ni, and B — 70Ni-30Cu weld metals containing substantial iron dilution. Positive galvanic current shows that the weld is protected; contrast with current plots for 90Cu-10Ni weld metals in Figs. 15B and 16A and B. The 70Cu-30Ni weld metal in A contained 9.6% Fe, while the 70Ni-30Cu weld metal in B contained 11.3% Fe

change in the kinetics of corrosion attack. Figure 16 shows that the 90-10 Cu-Ni sample containing 6.9% Fe underwent a period of initial attack at much higher current levels than did the sample exposed to seawater at 17°C.

The second observation from the galvanic couple measurements is that the 90-10 Cu-Ni weld metal corrodes preferentially to the base metal at 1.7% Fe, which represents the upper limit of iron content for the base metal. This suggests that even when solid 90-10 Cu-Ni is being welded, it is prudent to use a more highly alloyed (overmatching) welding product. The difference in electrochemical behavior can be understood by comparing the current vs. time plots in Figs. 15 and 16 with the two in Fig. 17. In the latter, galvanic current is positive during the entire test, indicating that the weld is galvanically protected from the outset.

Tensile and bend tests performed on uniformly diluted welds of 70Ni-30Cu and 70Cu-30Ni indicate no detrimental effects in welds containing up to 10% Fe. A weld in a clad structure that contains 10% iron at the surface, however, is likely to contain higher Fe in sections below the surface, due to gradient effects from the underlying steel. Therefore, these results should be applied with caution.

Conclusions

1. CA706 clad steel structures should be welded with overmatching weld metal compositions (higher Ni content) if they are to be used for seawater applications, even where no iron dilution is expected.

2. 70-30 Cu-Ni and 70-30 Ni-Cu welding electrodes can be used to weld CA706 clad steel structures for seawater applications, as long as the iron dilution in the weld deposit is kept below 10%.

References

1. Copper Development Association, Inc., Application Data Sheet, 1970. Welding copper-nickel clad steel.
2. International Nickel, 1968. *Welding Copper-Nickel Alloys.*
3. Kenyon, N., and Minard, L. C. November 1976. *Welding of Copper-Nickel Clad Steel.* INCRA Project 240.
4. McKeown, D. 1978. Copper alloys: a growing role in marine environment. *Welding and Metal Fabrication* (9):457–460.
5. Prager, M. *Developments in Welding Copper and Clad Steel.* CDA-ASM Conference on Copper, October 16–19, 1972, Cleveland, Ohio.
6. Prager, M., Keay, L. K., and Thiele, E. W., Jr. 1978. Joining copper and copper-nickel clad steels. *Welding Journal* 57(9):22–34.
7. Elson, C. C., Thornley, J. D. 1973. Cladding mild steel with copper-nickel sheet. *Metal Construction* (6):220–225.
8. Prager, M., and Thiele, E. W., Jr. 1979. Welding a copper-nickel clad ship — Copper Mariner II. *Welding Journal* 58(7):17–24.
9. Van Dyck, G. A. P., and Thornley, J. C. February 1976. Technical aspects of welding copper-nickel alloys. INCO Europe Publication No. 4420.
10. Rockel, M. B., and Rudolph, G. September 1981. Effect of iron pick up on corrosion resistance of welded CuNi10Fe steel compound in artificial seawater. *8th International Conference on Metallic Corrosion* 2:1298–1303, Mainz, West Germany.

WRC Bulletin 318
September 1986

The primary objective of this Bulletin, which contains two papers, is to present a comprehensive picture of the research work conducted to establish the current techniques and procedures for specifying the ferrite content of austenitic stainless steel weld metal and measuring its level.

Factors Influencing the Measurement of Ferrite Content in Austenitic Stainless Steel Weld Metal Using Magnetic Instruments

By E. W. Pickering, E. S. Robitz and D. M. Vandergriff

This report describes a program conducted under the auspices of the Welding Research Council (WRC) Subcommittee on Welding Stainless Steel to identify the optimum procedure for the preparation of austenitic stainless steel weld samples for Ferrite Number (FN) determination.

Measurement of Ferrite Content in Austenitic Stainless Steel Weld Metal Giving Internationally Reproducible Results

By E. Stalmasek

This report is a summary of the results of 14 years' work by the IIW Commission 2 in the field of ferrite content measurement, done prior to 1978.

The publication of these reports was sponsored by the Subcommittee on Welding Stainless Steel of the High Alloys Committee of the Welding Research Council. The price of WRC Bulletin 318 is $24.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.

WRC Bulletin 319
November 1986

Sensitization of Austenitic Stainless Steels: Effect of Welding Variables on HAZ Sensitization of AISI 304 and HAZ Behavior of BWR Alternative Alloys 316NG and 347

By C. D. Lundin, C. H. Lee, R. Menon and E. E. Stansbury

The research described in this report was undertaken to derive a better understanding of the HAZ sensitization response of 304, 304LN, 316NG and 347 austenitic stainless steels. The results are directly applicable to both the as-welded and long-time service behavior of these austenitic stainless steels.

Publication of this report was sponsored by the Subcommittee on Welding Stainless Steel of the High Alloys Committee of the Welding Research Council. The price of WRC Bulletin 319 is $24.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.

WRC Bulletin 320
December 1986

Welding Metallurgy and Weldability of High Strength Aluminum Alloys

By S. Kou

A literature survey was conducted to gather the information available on the welding metallurgy of high strength aluminum alloys, and its effect on their weldability. Both conventional high strength aluminum alloys and newer products, *e.g.*, powder metallurgy aluminum alloys, Al-Li alloys and Al-matrix composites, are included in this report.

Publication of this report was sponsored by the Aluminum Alloys Committee of the Welding Research Council. The price of WRC Bulletin 320 is $12.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.