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CORROSION TESTING TYPE HP 9-4-20 STEEL

A. G. Dobbins
J. W. Koger
T. M. Mustaleski, Jr

February 1979

**UNION
CARBIDE**

OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

*prepared for the U.S. DEPARTMENT OF ENERGY under
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ABSTRACT

Forged HP 9-4-20 steel exhibits a high yield strength [1240 MPa (180 ksi)], a high fracture toughness (K_{IC}) [120 MN/m^{3/2} (110 ksi $\sqrt{\text{in}}$)], and good weldability. The alloy was studied to determine some of its corrosion and stress-corrosion characteristics, especially after welding.

Potentiodynamic-polarization studies established that pitting of the steel was most severe when the chloride ion concentration was high and the pH of the solution was low. Higher potentials (approaching 1 V) caused increased corrosion rates also.

Pitting of the welded samples was not preferential to any part of the weld and was uniform on both the base metal and weld. Dead-weight stress-corrosion tests demonstrated that welding did not increase susceptibility of the alloy to stress corrosion. The specimens failed in a ductile manner from the increased tensile load as the cross-sectional area was reduced by dissolution of the metal in the corrosive solution.

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SUMMARY

Corrosion tests were performed on welded HP 9-4-20 steel, at the Oak Ridge Y-12 Plant^(a), using both the potentiodynamic-polarization and dead-weight tensile-stress methods, with the material in a corrosive solution. Susceptibility to stress-corrosion cracking did not occur when the material was welded. Pitting corrosion occurred uniformly on both the weld and base metal in the former test; in the latter test, ductile failure occurred in the base metal (rather than in the fusion or heat-affected zone) after the cross-sectional area was reduced by a solution-type attack in the gage length of the tensile specimen.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the Department of Energy.

INTRODUCTION

Interest in the use of new high-strength alloys has been increasing due to the improved strength-to-weight ratio which can be achieved without a sacrifice in material toughness. HP 9-4-20 alloy^(b) was developed for use in the quenched-and-tempered condition. Strength is provided primarily by interstitial carbon (0.20%, nominal), and the major alloying elements are nickel (9%) and cobalt (4%). The designed minimum properties for this alloy are a 1240-MPa (180-ksi) yield strength with a fracture toughness (K_{Ic}) of 120 MN/m^{3/2} (110 ksi $\sqrt{\text{in}}$) at room temperature. The stress-corrosion resistance of this alloy in sea water is considered good; and, consequently, it has been considered for use in deep-submergence vehicles.^{1,2}

HP 9-4-20 was developed for use in the as-welded or stress-relieved condition. Extensive work^{3,4} was done to produce a filler-wire composition which would provide adequate as-deposited properties. Gas tungsten-arc (GTA) welding with cold-wire-filler additions is the recommended method for joining this material to achieve the necessary weld quality and mechanical properties.⁵ Resistance of the welded joint, particularly the heat-affected zone (HAZ), to stress-corrosion cracking has caused some concern.^{5,6} These tests involved the use of precracked specimens to induce localized corrosion and to obtain valid K_{ISCC} values for the regions. Tests of the entire welded joint could provide insight into determining the susceptibility of actual assemblies to this type of attack. Therefore, a program was planned to assess the stress-corrosion susceptibility for welded and unwelded HP 9-4-20 steel. Typical welding defects were included in some test specimens to observe their effect on the corrosion resistance of the joints. Additionally, potentiodynamic-polarization tests were performed to compare the susceptibility of the weld, the HAZ, and the parent HP 9-4-20 alloy to pitting corrosion.

(b) Developed by Republic Steel.

STRESS-CORROSION TESTING OF WELDED HP 9-4-20 STEEL

MATERIAL BACKGROUND

Base Metal

The material for this study was from a single plate of HP 9-4-20 alloy. Table 1 lists the composition of the plate. This plate was produced from an air-melted heat which had been vacuum-arc remelted (air-VAR). To generate stock which was usable for this study, the plate was unidirectionally hot rolled to approximately 14 mm in thickness.

Table 1
COMPOSITIONS OF HP 9-4-20 BASE MATERIAL
AND WELDING WIRES
(All Values are in wt %)

Element	Base Material	Electron-Beam Weld Wire ⁽¹⁾	Gas Tungsten-Arc Weld Wire ⁽²⁾	
			Wire 1	Wire 2
C	0.200	0.15	0.160	0.15
Co	4.49	4.16	3.70	3.66
Cr	0.77	0.97	1.01	1.09
Cu	0.21	-	-	0.09
Fe	Balance	Balance	Balance	Balance
Mn	0.33	0.70	0.48	0.51
Mo	0.96	0.46	0.52	0.53
Ni	9.36	9.87	9.90	10.02
P	0.007	0.004	0.005	0.005
S	0.003	0.005	0.004	0.005
Si	0.14	0.32	0.20	0.21
V	0.1	0.07	0.09	0.09

(1) This wire was 0.89 mm in diameter.

(2) Wire 1 was tested by the potentiodynamic-polarization method and Wire 2 was tested by the dead-weight tensile-stress method. Both wires were 1.59 mm in diameter.

Potentiodynamic Polarization - The plate used for potentiodynamic-polarization weld specimens was cut into strips and hot pressed into U shapes (hollow half cylinders). The longitudinal edges of these blanks were machined, and the longitudinal edges of two of the U blanks were welded together to form a weld-ring blank. The weld-ring blanks were then heat treated according to the procedures outlined in Table 2. After heat treatment, the weld-ring blanks were machined to a 6.35-mm wall and a 114-mm OD at the weld joint, and the appropriate weld-groove features were machined into the cross sectional face of the rings, as noted in Figure 1.

Dead Weight - Welds for the dead-weight specimens were made on 355 x 76 x 7.62-mm-thick plates which were heat treated per the schedule given in Table 2. The joint preparation was machined along the 355 x 7.62-mm edges.

Table 2
HEAT-TREATMENT PROCEDURES THAT WERE USED
FOR HP 9-4-20 STEEL BLANKS

Treatment Step	Electron-Beam Specimen Blanks	Gas Tungsten-Arc Specimen Blanks
Normalize	900° C for 1 Hour; Water Quench	900° C for 1 Hour; Water Quench
Austenitize	815° C for 1 Hour; Water Quench	815° C for 1 Hour; Water Quench
Refrigerate	Not Done	-73° C for 2 Hours
Temper	550° C for 4 Hours; Water Quench	565° C for 4 Hours; Air Cool
Retemper	550° C for 4 Hours; Water Quench	Not Done

Welding Procedures

Potentiodynamic Polarization - Electron-beam welding (EBW) for the potentiometric-polarization specimens was done in a 6-kW (150-kV, 40-mA) welder equipped with the programmer and wire-feeding system described by Murphy and Turner.⁷ A total of eleven welding passes were made on the joint. Small passes were made so that the later passes could provide heat treatment of the earlier heat-affected zones. The weld groove was not filled completely in all areas by this procedure (as can be seen in View a of Figure 2), but was judged to be adequate for this test. The weld wire used was 0.89 mm in diameter, with the composition given in Table 1. The weld was made at a rate of 10.6 mm/sec, with wire feedrates of 12.7 mm/sec for the first two weld passes, 16.9 mm/sec for the next seven passes, and 21.1 mm/sec for the final two passes.

The GTA welds of the potentiodynamic-polarization specimens were made in four passes, using 1.59-mm-diameter wire of the composition given in Table 1 (GTA Wire 1). These four passes were made at 3.0 mm/sec with wire feedrates of 10.6 mm/sec for the first two passes and 12.7 mm/sec for the last two. This procedure just filled the weld groove, as can be seen in a typical cross section (View b, Figure 2).

Dead Weight - Plate for the dead-weight specimens was GTA welded at 3.0 mm/sec.

(a) Joint Preparation for the Gas Tungsten-Arc-Welded Samples.

(b) Joint Preparation for the Electron-Beam (cold-wire-fed)-Welded Samples.

Figure 1. JOINT PREPARATIONS USED ON HP 9-4-20 STEEL FOR THE POTENTIODYNAMIC-POLARIZATION AND DEAD-WEIGHT STRESS-CORROSION SPECIMENS. (Dimensions are in mm)

L417-6

(a) Electron-Beam, Cold-Wire-Fed Weld Used for the Potentiodynamic Polarization Tests. (10X)

N26-2A

(c) Typical Gas Tungsten-Arc Weld with "Temper Beads". (6X)

N26-1A

(b) Typical Gas Tungsten-Arc Weld without "Temper Beads". (6X)

Figure 2. CROSS SECTIONS OF WELDS IN TYPE HP 9-4-20 STEEL.

Due to the greater plate thickness (7.62 mm rather than the 6.35 mm for the potentiodynamic-polarization specimens), five weld passes were required to fill the weld groove. Three additional weld passes were used to temper the heat-affected zone near the surface. A view of a typical weld with these temper passes is included as View c of Figure 2. (Note: The weld shown in View c was made with 6.35-mm-thick material; and, thus, required only seven passes, but the structure is typical of the thicker plate.) The plate weld was made with 1.59-mm-diameter wire of the composition given in Table 1 (GTA Wire 2). The wire feedrate was 10.6 mm/sec for the first three passes and 12.7 mm/sec for the next four. No wire was used for the final tempering pass. After welding, the plate was radiographed. A lack-of-fusion defect of 3.8 mm in length at one sidewall and some scattered porosity of less than 0.9 mm in diameter were noted.

Corrosion Tests

Potentiodynamic Polarization - Potentiodynamic-polarization tests were run on small, square specimens cut from the weld rings of HP 9-4-20 alloy such that the welds were across the center of the specimen. The Petrolite Potentiodyne Analyser M-4100, used in these studies, controlled the potential between the corrosion sample (test electrode) and a standard electrode. As the potential, with respect for an Ag/AgCl standard electrode, swept between -1 and +1 volt at a preset rate of 2 volts per hour, the Potentiodyne measured the current required to maintain the prescribed voltage and plotted that current against the potential of the test electrode. The counter electrode was a platinum sheet that supplied the current to the cell; the cell environment was an aqueous solution of corrosive ions. All tests were run at room temperature (about 25° C).

Dead Weight - Dead-weight stress-corrosion tests were run on flat tensile specimens machined from a welded plate so that the weld was at the middle of the gage-length section and perpendicular to its longitudinal axis. The specimens were placed under a static load with an electrolyte surrounding the gage length of the specimen. The test apparatus applied the load to the specimen from lead bricks hung on a cantilever beam. A calibrated, movable weight on the cantilever beam was used for additional control of the dead-weight load. The time to failure was plotted against the applied load to give a comparison of the welded to unwelded material as well as to samples having a defective weld. All tests were run at room temperature which varied from 20 to 25° C.

RESULTS

Potentiodynamic Polarization

Potentiodynamic-polarization tests yielded the series of curves presented in Figure 3, in which the current density is plotted as a function of the applied potential. This rapid testing method was used with a number of buffered solutions (Table 3) that varied in chloride ion concentration and pH. Graph a (Figure 3) shows that, in the absence of chloride ions, only the most strongly acidic solution did not have a plateau indicative of a passive region in the anodic portion of the curve. When the chloride ion concentration was low, as in the

(a) Corrosion Curves for Solutions Containing No Chloride Ions at Various pH Values.

(b) Corrosion Curves for 0.01 Molar Sodium Chloride Solutions at Various pH Values.

(c) Corrosion Curves for 0.1 Molar Sodium Chloride Solutions at Various pH Values.

(d) Corrosion Curves for Solutions at a pH of 4 - 4.1 and at Various Chloride Ion Concentrations.

(e) Corrosion Curves for Solutions at a pH of 9 - 9.6 and at Various Chloride Ion Concentrations.

(f) Corrosion Curves for Solutions at a pH of 12.5 - 12.7 and at Various Chloride Ion Concentrations.

Figure 3. POTENTIODYNAMIC-POLARIZATION CURVES FOR HP 9-4-20 STEEL. (These Curves were Used to Evaluate the Effects of the Chloride Ion Content and the pH of the Solutions on the Corrosion Characteristics of the Material)

0.01 molar NaCl solution (Graph b), the passive anodic region disappeared for all but the most basic solution (highest pH). When the chloride ion content was 0.1 mole per liter, none of the curves showed passive anodic regions (Graph c).

Effects of the chloride ion content on the pitting behavior of HP 9-4-20 is illustrated clearly in Graphs d - f for pH values of 4 to 12.7. The "no-chloride" curves had a broad, passive region at all levels of acidity. In contrast, the 0.1 M solution was most aggressive, as indicated by the more negative "open circuit potential" (earlier onset of anodic behavior; that is, current goes to zero) and the greater current density for the solutions with the highest chloride ion content.

In summary, the attack that resulted from the potentiodynamic tests (Table 4) indicated that more pitting occurred at high chloride ion concentrations and low pH values. The curves in Figure 3 also indicated that the 0.1 molar NaCl solution with a pH value of 5 was the most corrosive.

Uniform pitting was observed on welded HP 9-4-20. View a in Figure 4 (photomicrograph of heavy-rolled material welded by the GTA process) showed that pits were distributed evenly; View b is of the electron-beam, cold-wire-fed weld and illustrates a similar attack. There was no preferential attack on the weld metal or the heat-affected zone. Uniform pitting was observed on welded HP 9-4-20 (Figure 4) with no weld-metal or heat-affected-zone attack. Metallographic sections through the pits characterized the subsurface enlargement of the pit (Figure 5).

Dead-Weight Stress Corrosion

Time to failure in the most corrosive solution (a 0.1 M NaCl solution, buffered to a pH of 5) as a function of the stress level was used to compare the susceptibility to stress-corrosion cracking of the base material with the welded material. In these tests, the longer times to failure were at the lower stress levels, with a regular progression to shorter times at higher stress levels for both the base material and the welded test specimens. There

Table 3
CHLORIDE ION CONCENTRATIONS AND pH VALUES
FOR THE BUFFERED CORROSION SOLUTIONS USED
IN THE POTENTIODYNAMIC-POLARIZATION TESTS

Chloride Ion Concentration	pH Values						
	1.7	4.1	5.4	7.1	9-9.6	10	12.5-12.7
None	X	X		X	X	X	X
50 ppm		X					
0.01 <u>M</u>		X	X		X		X
0.1 <u>M</u>		X		X	X	X	X

Table 4
PITTING CONDITIONS OBSERVED
ON CORROSION SAMPLES

pH	Chloride Ion Concentration (<u>M</u>)	Sample Surface Area (cm ²)	Pitting Condition
4.1	0.1	3.65	Bad
4	0.01	3.57	Some
4	50 ppm	4.15	Few, Small
4.1	0	2.94	Pitted
5.4	0.01	2.57	Some
7.1	0	4.05	None
9	0.1	5.30	Bad
9.1	0.01	2.99	Rough
9.5	0.1	4.03	Some
9.6	0	3.52	None
10	0.1	3.69	Some
10.1	0	3.52	None
12.5	0.1	4.43	None
12.5	0.01	3.17	None
12.7	0	4.43	Very Slight

M-135-1b

(a) Face of a Heavy-Walled Gas Tungsten-Arc Weld.

M-135-2b

(b) Face of an Electron-Beam, Wire-Fed Weld.

Figure 4. PHOTOMACROGRAPHS THAT SHOW THE FACES OF WELDS AFTER THE POTENTIODYNAMIC-POLARIZATION TESTS. (Note that the Pits are Randomly Spread on both the Base Metal and the Weld; 10X)

L-105-1d

Figure 5. DETAILED CROSS-SECTION VIEW OF A SINGLE CORROSION PIT. (Etched with Nital; Bright Field Illumination; 500X)

were no failures from stress-corrosion cracking. Longer times at the same stress level were recorded for the unbuffered 3.5% NaCl exposures at a pH of 7, emphasizing the accelerating effect of a lower pH on the attack rate. Specimens tested in 3.5% NaCl, to simulate more closely the salt-water tests of Republic Steel,^{8,9} give inconsistent data for the base material, but the data for the welded pieces were in agreement with their results. (These data are listed in Tables 5 and 6 and are shown in graphic form in Figure 6.) The number of dead-weight tests was insufficient to establish statistically that the welded and unwelded HP 9-4-20 specimens were of the same population, but the curves showed a close similarity in the time to failure.

A metallographic examination of selected specimens was used to evaluate the type and degree of attack. In Figure 7, a comparison of the failures in 0.1 molar NaCl (pH of 5) and 3.5% NaCl showed that more pitting and a more irregular interface was formed by the oxide in the 3.5% NaCl solution. The gas-pocket type of weld defects that were present in one set of specimens illustrated clearly the resistance of the welded area to preferential attack of stress-corrosion cracking (Figure 8). Only the presence of a flaw at the very edge of the weld caused failure through the weld and defect; and, even then, ductile-necking failure occurred.

Material bulk properties are often affected by the directional variations in the microstructure or inclusion orientation that remains from forming the metal. To

Table 5
TIMES TO FAILURE FOR UNWELDED, SMOOTH
HP 9-4-20 SPECIMENS EXPOSED
TO VARIOUS SOLUTIONS

Stress Load (MPa) (ksi)	Time to Failure (hr)			
	0.1 M NaCl pH of 5	3.5% NaCl pH of 7	0.1 M NaCl pH of 12.5	0.01 M NaCl pH of 12.5
1458 211.5	2.3		6192	
1421 206.1	6.2			
1402 203.3	7.4	982		8595 (test terminated)
1384 200.8	361.5			
1330 192.9	450.0			
1295 187.9		770		
1105 160.4	1495.3			
958 139.0	2928.5			
789 114.3	3822.0			

Table 6
TIMES TO FAILURE FOR WELDED, SMOOTH
HP 9-4-20 SPECIMENS EXPOSED TO
0.1 M AND 3.5% NaCl SOLUTIONS

Stress Load (MPa) (ksi)	Time to Failure (hr)		Failure Location
	0.1 M NaCl pH of 4.5	3.5% NaCl pH of 7	
1275	334	839	Base Metal
1273	908		Base Metal
1200	768		Base Metal
1180 166.7	697		Base Metal
1178	750		Base Metal
1088		2332	Base Metal
970 140.7	2447		Weld Defect
965		3506	Base Metal
958 138.9	2363		Base Metal

characterize the microstructure of the material tested in these studies, a three-dimensional montage was prepared (Figure 9). It shows a relatively uniform tempered martensite structure having isotropic properties. The long dimension of the figure is the long dimension of the machined test specimen. A longitudinal section of a

welded specimen (Figure 10, View a) illustrates the typical failure in the base metal. The material showed some effects of work in the banded structure near the failure (Figure 10, View b) while a fine-grained, slightly banded region formed near the weld (Figure 10, Views

Figure 6. TIMES TO FAILURE FOR VARIOUS
HP 9-4-20 SPECIMENS.

M269-1a

(a) Specimen Shows Smooth Reduction in Area. (35X)

M269-2a

(b) Specimen Shows Pitting at the Edges and Little Reduction in Area. (35X)

M269-1c

(c) Specimen Shows Dissolution. (1000X)

M269-2c

(d) Specimen Shows Aggressive Pitting. (1000X)

Figure 7. METALLOGRAPHIC EXAMINATION OF SELECTED SPECIMENS THAT ILLUSTRATE THE TYPE AND DEGREE OF CORROSION ATTACK.
(Views a and c—Specimens were Exposed to 0.1 M NaCl at a pH of 5; Views b and d—Specimens were Exposed to 3.5% NaCl at a pH of 6.6)

N161-1

(a) Ductile Failure in the Base Metal;
Pits in the Weld.

N161-3

(b) Large Defect in the Weld, but Failure in the
Base Metal.

N161-2

(c) Failure in the Weld through a Large Defect
(left side), but after Dissolution.

Figure 8. GAS-POCKET TYPE OF WELD DEFECT IN WELDED HP 9-4-20 STEEL. (10X)

c and d). A rather coarse martensitic needle structure formed immediately adjacent to the weld (Views c and e). The weld metal retained the dendritic cast structure (View f); however, failure typically was a stress failure after general-solution-type corrosion reduced the cross section of the test piece away from the weld.

Figure 9. MONTAGE, SHOWING A THREE-DIMENSIONAL VIEW OF THE MICROSTRUCTURE OF AN HP 9-4-20 DEAD-WEIGHT TENSILE-STRESS-CORROSION SPECIMEN. (Exhibits Uniform Tempered Martensite Structure; Bright Field Illumination; Nital Etch; 500X)

Figure 10. TYPICAL GAS TUNGSTEN-ARC WELD OF HP 9-4-20 STEEL. (Etch of 20% Nital)

CONCLUSIONS

Some conclusions that were reached as a result of this study are:

1. Potentiodynamic-polarization curves indicated that the HP 9-4-20 alloy was corroded by solutions of low pH or high chloride ion concentration. With increasing chloride ion concentrations there was no passive anodic region, and metal dissolution was continuous.
2. Potentiodynamic-polarization tests of HP 9-4-20 steel, welded by both the electron-beam cold-wire and gas tungsten-arc processes, showed that the base metal, the heat-affected zone, and the weld metal were pitted at the same rate.
3. Dead-weight stress-corrosion test specimens failed from a reduction in area by dissolution-type corrosion in acidic chloride-containing solutions. These failures had ductile fractures predominantly in the base metal, and no stress-corrosion cracks were produced.

REFERENCES

1. Woodland, B. T.; "Deep-Submergence Metal Structures", *Machine Design*, **40**, (2), pp 159 - 164; January 1968.
2. Crooker, T. W. and Lange, C. A.; *Corrosion-Fatigue Crack Propagation Studies of Some New High Strength Structural Steels*, NRL Report 6870; April 1969.
3. Ries, G. D. and Poole, S. W.; "Welding of Quenched and Tempered 9 Ni-4 Co Steels", *Welding Journal*, **45**, (10), pp 465-S - 476-S; October 1966.
4. Savas, J., Becker, P. C., and Matas, S. J.; "Development of a 180 ksi Yield Strength Stress-Relievable 9 Ni-4 Co Filler Metal Composition", *Welding Journal*, **48**, (11), pp 479-S - 492-S; November 1969.
5. Ault, R. T.; *HP 9-4-20 Steel Data*, TR 12018-132; Republic Steel Corporation, Cleveland, Ohio; March 1968.
6. Munford, J.; *Environmentally Assisted Crack Growth in High Strength Steels*, SAND 74-0270; Sandia Laboratories, Albuquerque, New Mexico; January 1975.
7. Murphy, J. L. and Turner, P. W.; "Wire Feeder and Positioner for Narrow Groove Electron Beam Welding", *Welding Journal*, **55**, (3); March 1976.
8. *Properties of HP 9-4-20 Steel*; Republic Steel Corporation Data Compilation; September 1972.
9. *Cobalt Monograph Series*; Centre D'Information Du Cobalt - Brussels 1974 (Cobalt Information Center of the Battelle Memorial Institute, Columbus, Ohio), p 48.

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