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ANALYSIS OF WELDMENT MECHANICAL PROPERTIES OF MODIFIED 9 Cr-1 Mo STEEL

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V. K. Sikka and P. Patriarca

ABSTRACT

The status of welding and weldability studies on modified 9 Cr-1 Mo steel is presented, and microhardness, tensile, creep, and Charpy impact properties of welds made by gas tungsten arc, shielded metal arc, and submerged arc processes are analyzed. Microhardness traverses of modified 9 Cr-1 Mo welds were examined after nominal and extended postweld heat treatments. Microhardness data on modified 9 Cr-1 Mo were also compared with similar results on standard 9 Cr-1 Mo, 2 1/4 Cr-1 Mo, and HT9. Tensile and creep data were primarily on weldment specimens in which the gage length contained the base metal, weld metal, and heat-affected zone. Charpy impact data were primarily on the weld metal, with notch parallel to the welding direction.

On the basis of the data presented, we concluded that standard 9 Cr-1 Mo wire and electrodes can be used to weld modified 9 Cr-1 Mo base metal if welds are given a nominal postweld heat treatment. If welds are to be normalized and tempered, we recommend the use of modified wire and electrodes having the base metal composition.

INTRODUCTION

A 9 Cr-1 Mo steel with elevated-temperature properties significantly improved over 2 1/4 Cr-1 Mo and standard 9 Cr-1 Mo steels has been developed jointly by ORNL and Combustion Engineering, Inc. (CE), Chattanooga. The composition specifications for this alloy are presented in Table 1. The alloy specifications for tubing and plate products have been published by the American Society for Testing and Materials (ASTM). The specifications for other product forms are in the last stages of approval by various committees of ASTM. The allowable stresses for the use of tubing to *ASME Boiler and Pressure Vessel Code,* Sect. I, rules have also been approved for this alloy. The approval for other products in Sect. VIII of

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Table 1. Chemical specifications for modified 9 Cr-1 Mo steel

Element	Specified content (wt %)
Carbon	0.08–0.12
Manganese	0.30–0.60
Phosphorus	0.020 Maximum
Sulfur	0.010 Maximum
Silicon	0.20–0.50
Chromium	8.00–9.50
Nickel	0.40 Maximum
Molybdenum	0.85–1.05
Aluminum	0.04 Maximum
Vanadium	0.18–0.25
Niobium	0.06–0.10
Nitrogen	0.03–0.07

the American Society of Mechanical Engineers (ASME) code is in progress. One of the areas of question during all stages of approval was the mechanical properties of weldments. This report presents the status of weldability and analysis of weldment data available for modified 9 Cr-1 Mo steel.

WELDABILITY OVERVIEW

The weldability and welding of modified 9 Cr-1 Mo steel have been pursued at

Oak Ridge National Laboratory
Combustion Engineering, Chattanooga
University of Tennessee
Struthers Wells
Leighton Industries, Inc.
Rockwell International
Climax Molybdenum Company of Michigan
Chicago Bridge and Iron
Babcock and Wilcox
Agecroft (United Kingdom)
Nooter Corporation

Weldability studies include determination of preweld and postweld heat treatment requirements, cold cracking response, hot cracking response, and reheat cracking response. The welding studies refer to development of various welding processes and actual welding of various products for either testing or actual plant installation.

The following are ORNL weldability and welding studies:

1. hot cracking susceptibility tests;[1]
2. Y-groove tests;
3. welding plates, tubes, and pipe of 6- to 51-mm thickness;
4. dissimilar-metal welds with (a) standard 9 Cr-1 Mo, (b) 2 1/4 Cr-1 Mo, and (c) stainless steels (types 304, 316, 321, and 347);
5. welding process sensitivity including (a) gas tungsten arc (GTA), (b) shielded metal arc (SMA), and (c) submerged arc (SA);
6. use of (a) standard 9 Cr-1 Mo, (b) modified 9 Cr-1 Mo, (c) 2 1/4 Cr-1 Mo, and (d) ERNiCr-3 (Inconel 82) as filler wires;
7. preheat effects, including (a) none, (b) 93°C (200°F), (c) 204°C (400°F), and (d) 316°C (600°F);
8. response of postweld heat treating (PWHT), including (a) none, (b) 677°C (1250°F), (c) 732°C (1350°F), (d) 760°C (1400°F), and (e) normalize and temper (1040°C followed by 760°C);
9. metallography, including macroetching and microetching; and
10. mechanical properties, including hardness, tensile, Charpy impact, and creep.

We prepared 105 welds at ORNL. Of the total, 60 were GTA, 30 were SMA, and 15 were SA. The material thickness ranged from 3 to 50 mm (1/8 to 2 in.), and the product forms used were tubes, plates, and pipe.

Over 100 tensile tests were conducted on weld and weldment specimens from room temperature to 677°C. Most of these tests were at room temperature and 593°C. Over 80 creep tests were conducted on weld and weldment specimens from 538 to 677°C. Eight of the tests were on all-weld-metal specimens; the remainder were on weldment specimens.

At least 30% of the welds were subjected to Charpy impact tests. Most of the tests were with the notch parallel to the rolling direction. A few heat-affected-zone (HAZ) impact tests were conducted at room temperature. Charpy impact tests were conducted in both the as-welded and PWHT conditions.

A limited number of tensile and creep tests were conducted on modified 9 Cr-1 Mo/ERNiCr-3/stainless steel weldment specimens. Tensile tests were at room temperature, 510, and 593°C. The creep tests were at 510, 593, and 649°C.

Weldability and welding studies at Combustion Engineering comprised the following.

1. Over one hundred tube welds of modified 9 Cr-1 Mo were made. The welds were made between the modified 9 Cr-1 Mo and (a) modified 9 Cr-1 Mo, (b) standard 9 Cr-1 Mo, (c) 2 1/4 Cr-1 Mo, and (d) stainless steels (types 321 and 347).

2. Stick electrodes for use in the SMA process were developed. The electrodes were developed with mild steel and standard 9 Cr-1 Mo core wire. Also, electrodes have been produced in large quantities.

3. Creep testing of full-section tubular specimens began. The welds in these tubes have been made by either the GTA or SMA process.

Weldability and welding studies at the University of Tennessee were as follows.

1. Cold cracking tests were conducted to (a) determine the preheat temperature for modified 9 Cr-1 Mo steel and (b) compare response of modified 9 Cr-1 Mo with that of other steels.

2. Reheat cracking tests were conducted on modified 9 Cr-1 Mo.

3. Continuous cooling transformation diagrams on modified 9 Cr-1 Mo steel under welding conditions were developed.

4. Microstructural examinations of welds made for various investigations were conducted.

Struthers Wells welded two 51-mm plates by the SA process and four 25-mm plates by the SMA process. Standard 9 Cr-1 Mo filler wire and Orlikon-76 flux were used for the SA welds. The SMA welds were made with standard 9 Cr-1 Mo electrodes. A preheat of 285°C was used during both welding procedures. Both the SA and SMA plates were PWHT 2 h at 732°C. One plate each made by the SA and SMA processes was used for conducting the ASME Code, Sect. IX, weld qualification tests. The qualification tests included tensile tests at room temperature, guided bend tests, Charpy impact tests, and hardness measurements. Both the SA and SMA welds passed all requirements of Sect. IX. The extra plates were shipped to ORNL, where they will be used for mechanical property characterization.

Leighton Industries prepared GTA welds in 76-mm-OD by 13-mm-wall (3 × 0.5 in.) tubes of modified 9 Cr-1 Mo steel. The welds were made with modified 9 Cr-1 Mo filler wire and ERNiCr-3 wire. These welds were not PWHT and are currently in long-term creep testing at ORNL. Leighton Industries also prepared several welds in 51-mm-OD (2-in.) tubes for installation in one of the American Electric Power's (AEP's) steam plants. These welds were between modified 9 Cr-1 Mo steel and modified 9 Cr-1 Mo or type 304H stainless steel. All these tubes have been operating in AEP's steam plant since April 1981.

Rockwell International prepared 14 in-bore tube-to-tube welds in 25-mm-OD (1-in.) tubing. Welds were examined in accordance with requirements of ASME Code, Sects. III and IX. Rockwell concluded that quality welds are readily made in modified 9 Cr-1 Mo steel by the autogeneous GTA welding process.

Climax Molybdenum Company of Michigan conducted Y-groove tests on modified 9 Cr-1 Mo steel and compared the results with those on HT9. Detailed microstructural analyses of weld metal, HAZ, and base metal of 2 1/4 Cr-1 Mo, standard 9 Cr-1 Mo, modified 9 Cr-1 Mo, and HT9 were also conducted. It was concluded that a region of slightly lower hardness in the HAZ than in base metal develops in all four alloys. Lower hardness was explained on the basis of carbide coarsening due to overtempering of a narrow base metal region.

Chicago Bridge and Iron Works (CB&I) prepared an SA weld in an ORNL-supplied 203-mm-thick plate of modified 9 Cr-1 Mo steel. A preheat of 200°C, standard 9 Cr-1 Mo filler, and OP-76 flux were used. A total of 145 passes were used, and the weld was PWHT at 732°C. This weld is currently in test at ORNL, Combustion Engineering, Georgia Institute of Technology, and Central Electricity Generating Board in the United Kingdom.

Babcock and Wilcox is making welds in 51-mm-OD tubing and is planning to subject these welds to various mechanical property tests.

Agecroft (United Kingdom) prepared welds between modified 9 Cr-1 Mo and 2 1/4 Cr-1 Mo tubes before installation of modified 9 Cr-1 Mo tubes at its steam plant. The welds were made with 2 1/4 Cr-1 Mo as the filler metal. They have been operating in the steam plant since April 1982.

Nooter Corporation is making SA welds in 25- and 51-mm-thick plates of modified 9 Cr-1 Mo steel. It is also making tube-to-tube welds in this alloy.

METALLOGRAPHY AND MICROHARDNESS

Typical microstructure produced during the welding of quenched or normalized and tempered chromium-molybdenum steels is shown in Fig. 1. Various regions shown in this figure are W, weld; TZ, transformed zone — this region is exposed to terperatures above AC_1 (about 840°C); and TMPZ, tempered zone — this region is exposed to temperatures close to AC_1 (higher than the tempering temperature).

Microhardness traverse across the SA by Struthers Wells is shown in Fig. 2. This weld used standard 9 Cr-1 Mo filler metal and was PWHT at 732°C for 2 h before shipping to ORNL. The weld was heat treated an additional 8, 18, 38, or 78 h to make total times of 10, 20, 40, and 80 h. Several observations can be made from Fig. 2.

1. After 2 h of PWHT, a base metal hardness of about 220 dph is observed, which is typical for this alloy. The tempered zone hardness is approximately 190 dph, 30 dph lower than that of the base metal. This is the region that was exposed to temperature below AC_1 but above the

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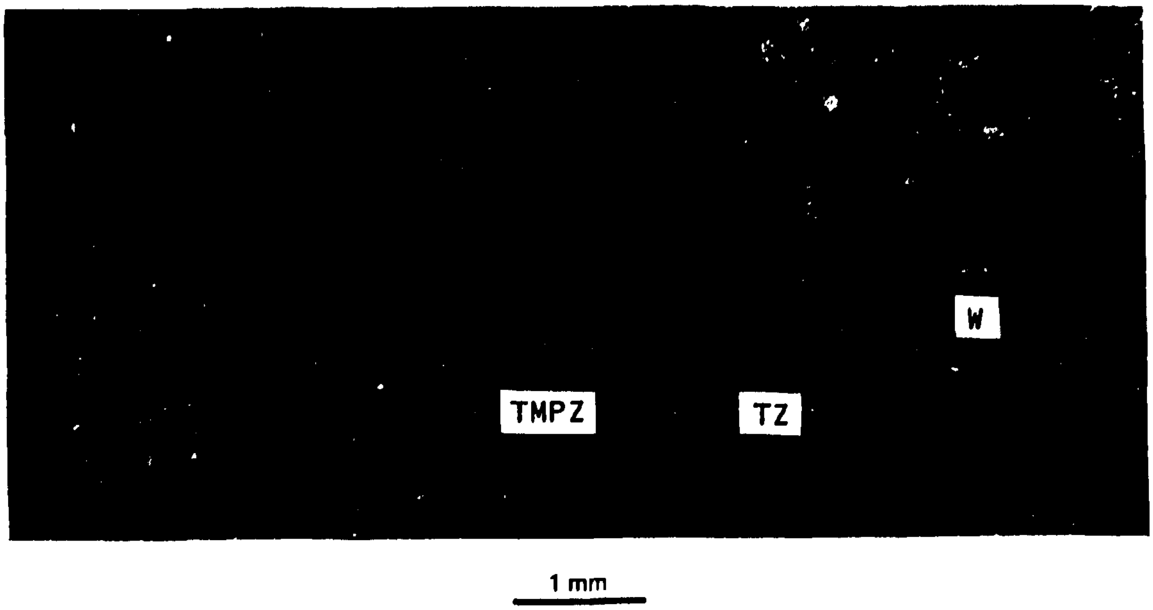

Fig. 1. Typical microstructure produced during welding of normalized and tempered chromium-molybdenum steels. Micrograph shows the weld (W) and two regions of the heat-affected zone: TZ, transformed zone, and TMPZ, tempered zone.

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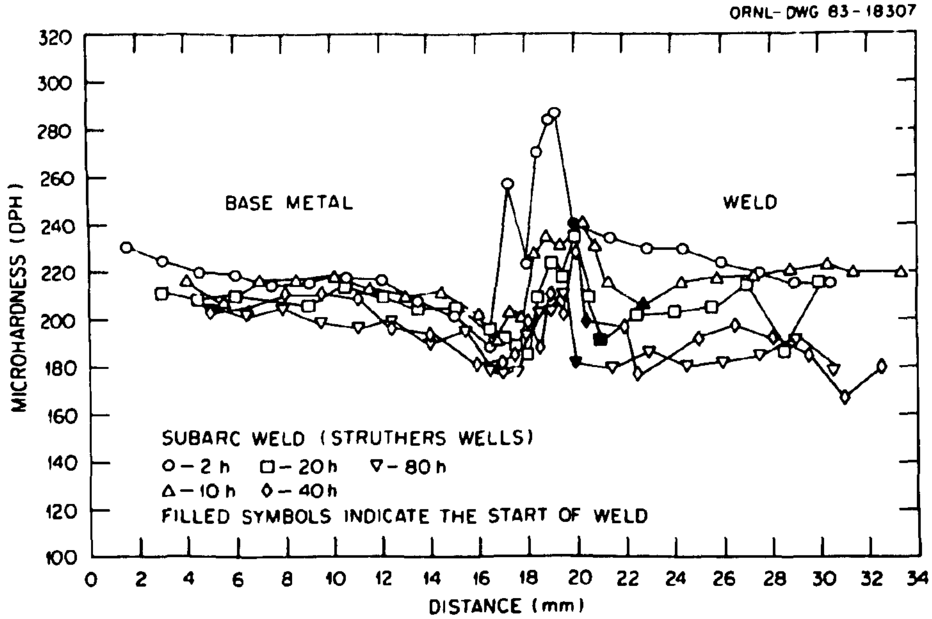

Fig. 2. Microhardness traverse across the submerged arc weld by Struthers Wells. The base plate was modified 9 Cr-1 Mo, and the filler wire was standard 9 Cr-1 Mo. The plate was postweld heat treated for 2, 10, 20, 40, and 80 h at 732°C.

tempering temperature. The transformed zone hardness is 250 to 260 dph. This is the region of the base metal that was austenitized during welding and transformed to martensite during air cooling to room temperature. The higher hardness of the transformed zone is a result of only a 732°C temper of martensite in this region compared with a 760°C temper in the base metal. The weld hardness for a 732°C PWHT is lower than that of the transformed zone because the weld is of standard composition (contains no V or Nb) and thus tempers more readily.

2. Increasing the PWHT from 2 to 80 h produces additional changes in the microhardness of various regions. The base metal, being very stable, shows only a small decrease in hardness. The tempered zone shows slightly more decrease with increasing PWHT. The transformed zone, which was partially tempered at 732°C, tempers further with time. Compared with various regions in the base metal, the weld region shows the most effect of additional PWHT time. This observation suggest that, where long PWHTs are necessary, one should use modified filler wire. This point will become clearer in the later sections.

Figures 3 through 5 show the microhardness traverses for welds in standard 9 Cr-1 Mo, 2 1/4 Cr-1 Mo, and HT9 (12 Cr-1 Mo VW alloy). These

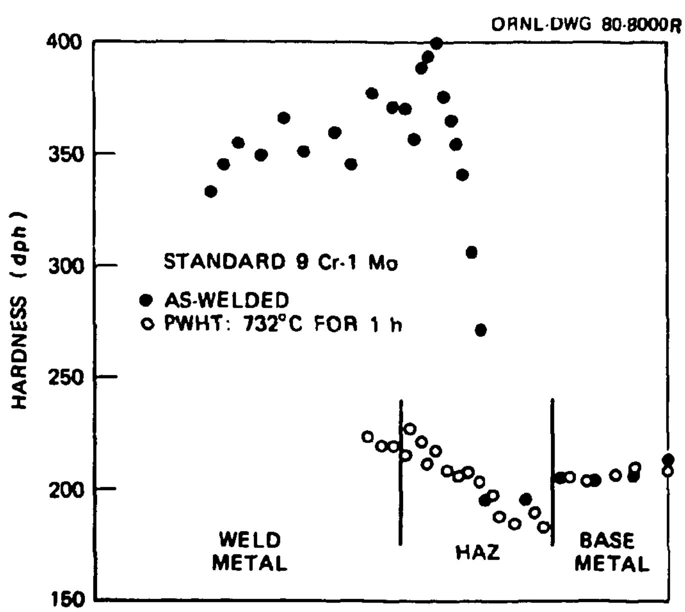

Fig. 3. Microhardness traverse across the gas tungsten arc weld in standard 9 Cr-1 Mo base plate. The filler wire was also standard 9 Cr-1 Mo. The weld was made at ORNL and was examined both as welded and after 1 h postweld heat treatment at 732°C.

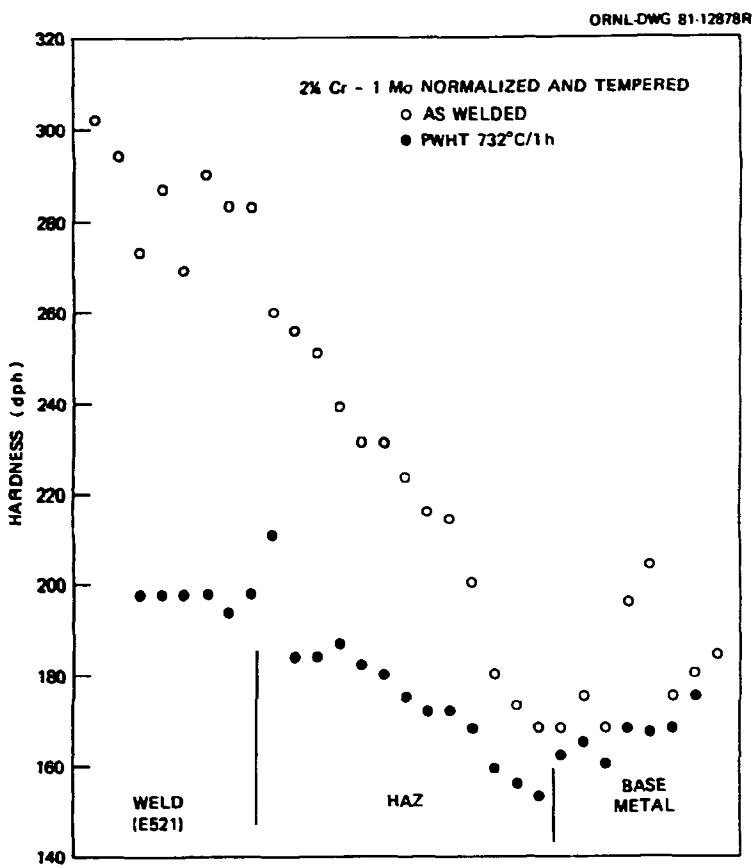

Fig. 4. Microhardness traverse across the gas tungsten arc weld in 2 1/4 Cr-1 Mo base plate. The filler wire was 2 1/4 Cr-1 Mo. The weld was made at ORNL and was examined both as welded and after a 1-h postweld heat treatment at 732°C.

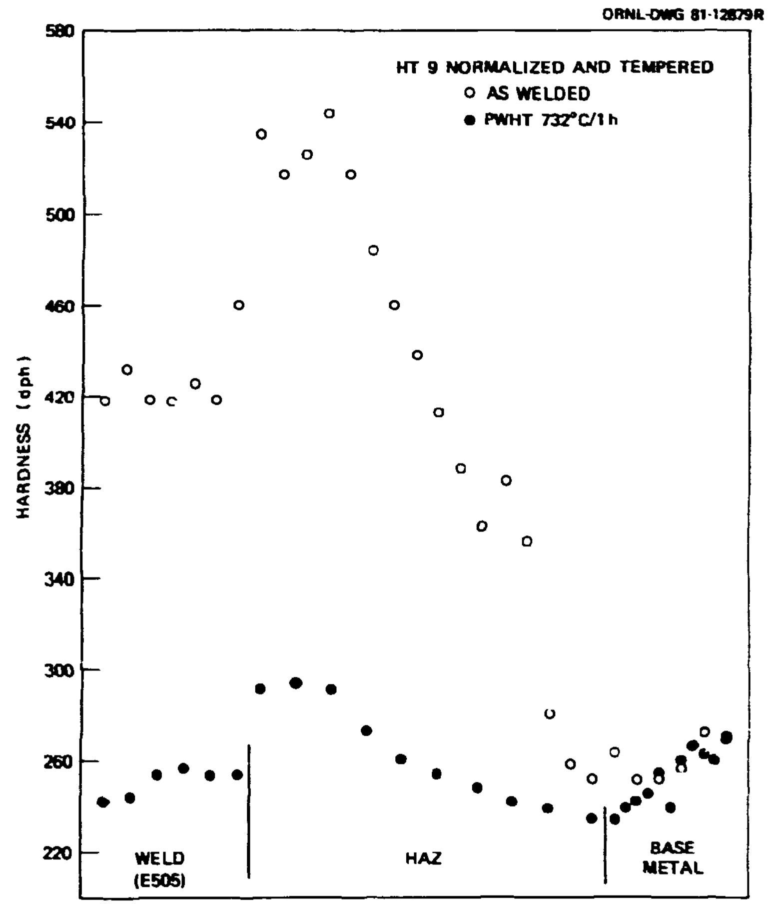

Fig. 5. Microhardness traverse across the gas tungsten arc weld in HT9 base plate. The filler wire was standard 9 Cr-1 Mo. The weld was made at ORNL and was examined both as welded and after a 1-h postweld heat treatment at 732°C.

figures show that all these alloys also contain a tempered zone as a result of welding. In fact, the difference in microhardness between the base metal and transformed zone is about the same for modified 9 Cr-1 Mo, standard 9 Cr-1 Mo, 2 1/4 Cr-1 Mo, and HT9.

Figure 6 compares the microhardness profile of a weld PWHT at 732°C and subsequently normalized at 1040°C and tempered at 760°C. The filler wire for this weld was of modified composition. The normalizing and tempering treatment completely eliminated all hardness variations observed in a weld subjected to only a PWHT. Figure 7 shows a profile similar to that in Fig. 6, except that the filler wire was standard 9 Cr-1 Mo. The normalizing and tempering treatment also eliminated the hardness variations observed between the base metal, tempered zone, and transformed zone. Note, however, that this treatment produces a much lower hardness for the weld region. The lower hardness for the weld region is expected because, as indicated earlier, the standard alloy tempers faster than

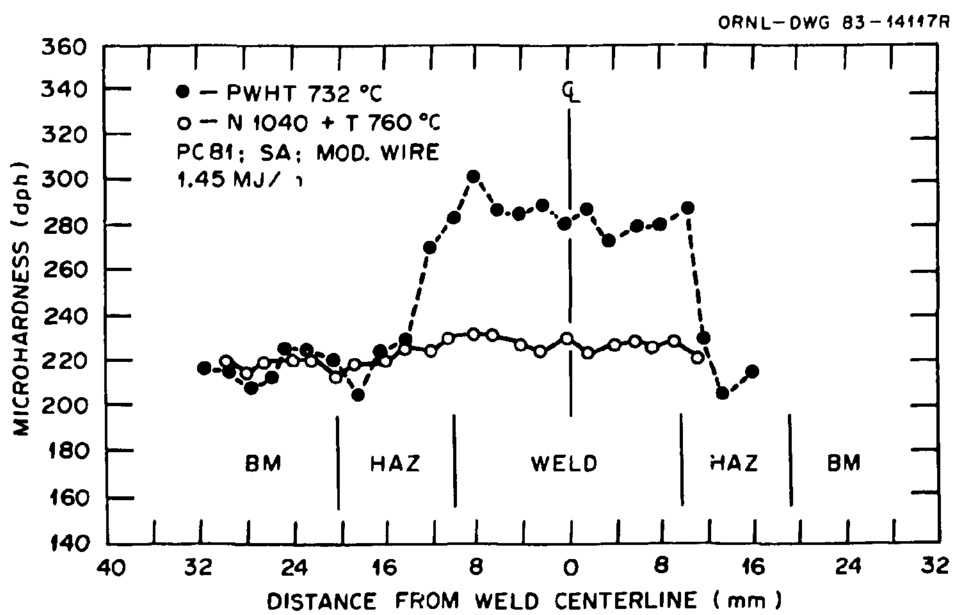

Fig. 6. Microhardness traverse across a submerged arc weld in modified 9 Cr-1 Mo plate. The filler wire was modified 9 Cr-1 Mo. The weld was made at ORNL and was examined after a 1-h postweld heat treatment at 732°C and after normalizing for 1 h at 1040°C and tempering for 1 h at 760°C.

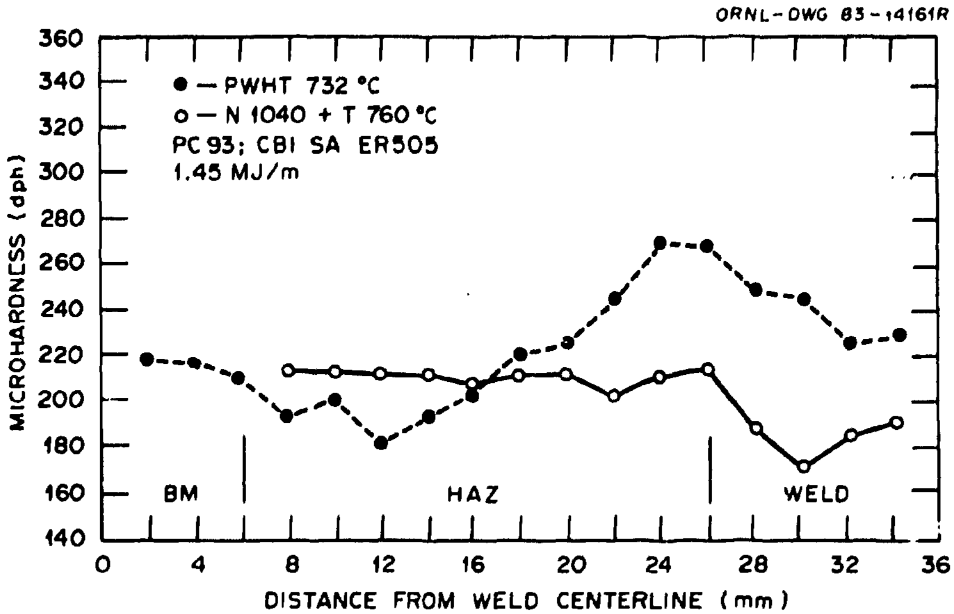

Fig. 7. Microhardness traverse across a submerged arc weld in modified 9 Cr-1 Mo plate. The filler wire was standard 9 Cr-1 Mo. The weld was made at Chicago Bridge and Iron and was examined after a 1-h postweld heat treatment at 732°C and after normalizing for 1 h at 1040°C and tempering for 1 h at 760°C.

does the modified 9 Cr-1 Mo composition. On the basis of Figs. 6 and 7, we recommend that, if a normalizing and tempering treatment is planned for a weld, the weld wire should be of the modified composition (same as the base metal).

MECHANICAL PROPERTY DATA ANALYSIS

TENSILE PROPERTIES

The qualification of 9 Cr-1 Mo welds to ASME rules requires that they meet the room-temperature minimum properties for the base metal. The base metal minimum values for yield and ultimate tensile strengths are 414 and 585 MPa. The minimum value of reduction of area is 55%. In an effort to determine if weldments will meet the minimum strength properties, we divided weldment properties by base metal minimum values and plotted the ratio as a function of test temperature (Fig. 8). The reduction of area values are plotted, not as ratios, in Fig. 9. These figures show the following.

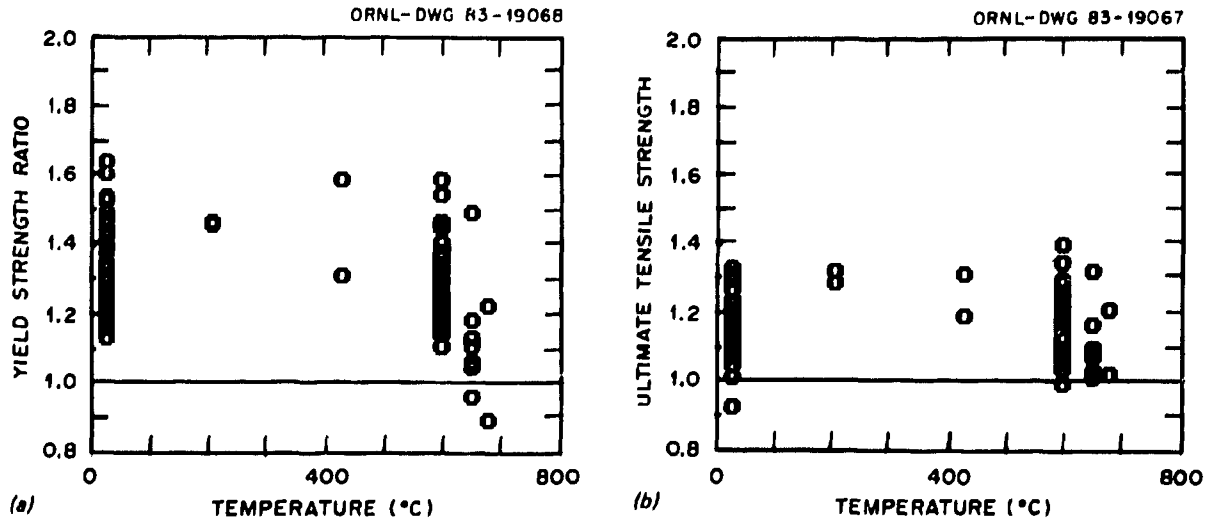

Fig. 8. Strength ratios (weldment to base metal minimum) for weldments of modified 9 Cr-1 Mo steel. Weldment data are for both standard and modified 9 Cr-1 Mo filler wire and for all three welding processes (gas tungsten arc, shielded metal arc, and submerged arc). A unity line representing equal strength of base metal and weldment is included. (*a*) Yield strength. (*b*) Ultimate tensile strength.

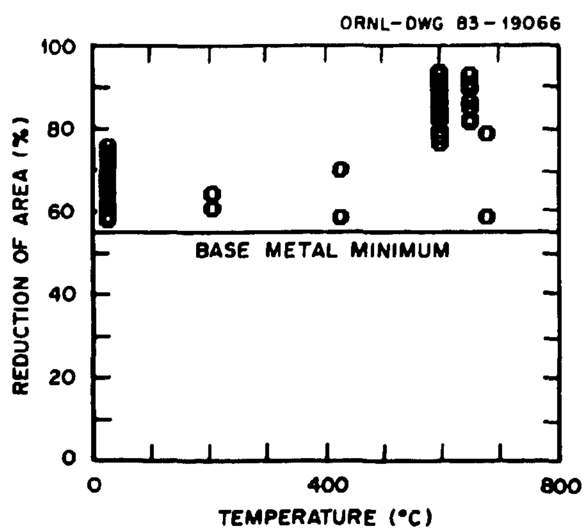

Fig. 9. Reduction of area as a function of test temperature. Weldment data are for both the standard and modified 9 Cr-1 Mo filler wire and for all three welding processes (gas tungsten arc, shielded metal arc, and submerged arc). A base metal minimum value line of 55% at room temperature is included.

1. The yield strengths [Fig. 8(*a*)] of all weldments made by GTA, SMA, and SA processes exceeded the room-temperature minimum values for the base metal. In fact, they exceeded 1.10 times the base metal minimum. The only two points that fell below the minimum were at very high test temperatures.

2. Ultimate tensile strength [Fig. 8(*b*)] for all but two weldments met the base metal minimum value; they ranged from 1 to 1.35 times the base metal minimum value.

3. The reduction of area values for all weldments exceeded the minimum value of 55% for the base metal for all test temperatures.

From the results presented in Figs. 8 and 9, we conclude that modified 9 Cr-1 Mo weldments will have no problem in meeting the base metal minimum properties.

CREEP PROPERTIES

To assess the creep strength of weldments, we have used the following procedure.

For the actual time to rupture of individual weldments, determine the average stress required to rupture the base metal. Take a ratio of the stress required to rupture the weldment to that required to rupture the base metal, and plot the ratio as a function of weldment time to rupture. With this procedure, creep data can be combined for all welding procedures and test temperatures. The ratio procedure was also repeated by replacing the average stress to rupture by minimum stress to rupture for the base metal.

The weldment stress ratio based on the base metal average is plotted in Fig. 10. The equal strength ratio of unity and the basis for allowable stresses in *ASME Boiler and Pressure Vessel Code*, Sect. VIII, are also included in this figure. Data in this figure are for all test temperatures and welding procedures. A few data points on all-weld-metal specimens are also included. Tests in progress are shown by the arrows on the data points. Figure 10 shows that the weldment-to-base-metal stress ratio approaches unity for rupture times of at least 1000 h. At shorter rupture

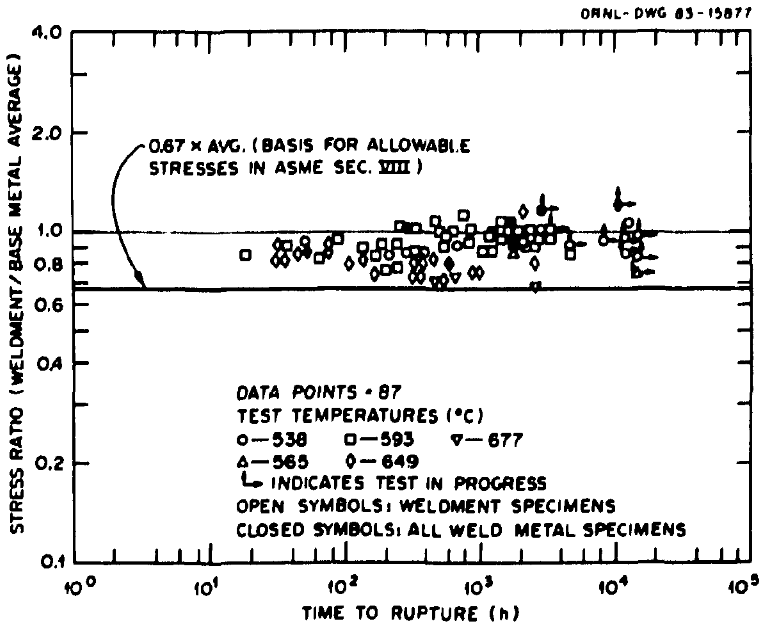

Fig. 10. Stress ratio (weldment to base metal average) as a function of time to rupture. Weldment data are for both the standard and modified 9 Cr-1 Mo filler wire and for all three welding processes (gas tungsten arc, shielded metal arc, and submerged arc). Data are for test temperatures of 538, 565, 593, 649, and 677°C. Stress ratios of unity, representing equal strengths, and 0.67, representing the ASME Sect. VIII criteria for allowable stresses, are also included.

times, the stress ratio is less than unity, with higher temperature (649 and 677°C) data being generally on the lower side. This figure also shows that the basis used for determining the allowable stresses for ASME Code, Sect. VIII, is met well by the creep-rupture data of modified 9 Cr-1 Mo weldments.

Figure 11 shows a stress-rupture plot based on base metal minimum properties. An alternative allowable stress criterion for Sect. VIII (0.80 × min stress to rupture) and the S_t criteria for Code Case N-47 (0.67 × min stress to rupture) are also included in this figure. The 0.80 times minimum stress to rupture is met well by the creep rupture data of modified 9 Cr-1 Mo weldments. This figure also shows that the 0.67 times minimum stress to rupture basis for S_t values in ASME Code Case N-47 is quite conservative for the weldment data.

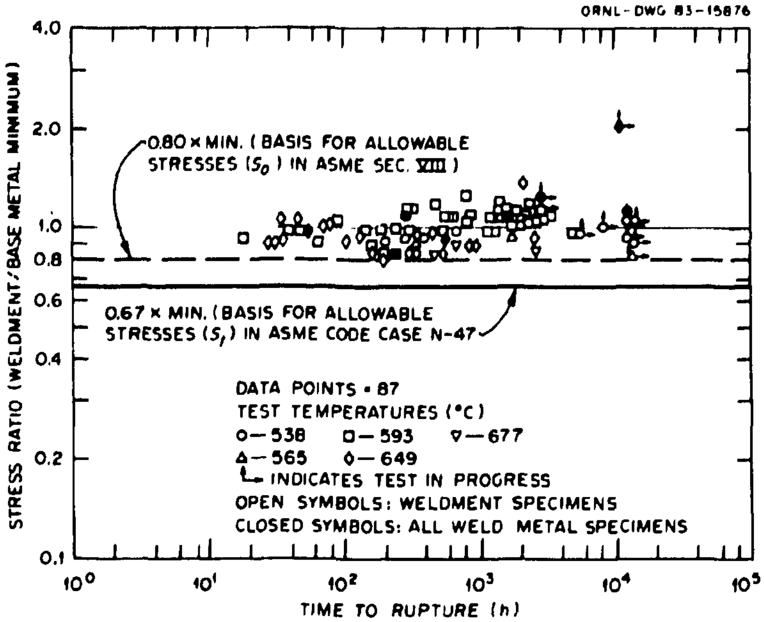

Fig. 11. Stress ratio (weldment to base metal minimum) as a function of time to rupture. Weldment data are for both the standard and modified 9 Cr-1 Mo filler wire and for all three welding processes (gas tungsten arc, shielded metal arc, and submerged arc). Data are for test temperatures of 538, 565, 593, 649, and 677°C. Stress ratios of unity, representing equal strength; 0.80, the criterion for allowable stresses in ASME Sect. VIII; and 0.67, the criterion for allowable stresses in ASME Code Case N-47, are also included.

Figures 12 through 14 show the stress ratio plots (based on base metal average), for the GTA, SMA, and SA processes separately. These plots show that all three welding procedures are equally satisfactory. The plots also show that the stress ratio was not affected by the use of either standard or modified filler wire.

Figure 15 shows a stress ratio plot for weldment specimens of 2 1/4 Cr-1 Mo steel. These data were taken from Klueh and Canonico.[2] Figure 15 shows that, if carbon in the filler wire were not specified, several data points for the 2 1/4 Cr-1 Mo weldment specimens could fall below the line of equal strength. In fact some of the data points would be on the allowable stress criterion line. A comparison of Figs. 10 through 14 with Fig. 15 indicates that the weldment strength ratio for modified 9 Cr-1 Mo weldments behaves very similarly to that observed for 2 1/4 Cr-1 Mo weldments.

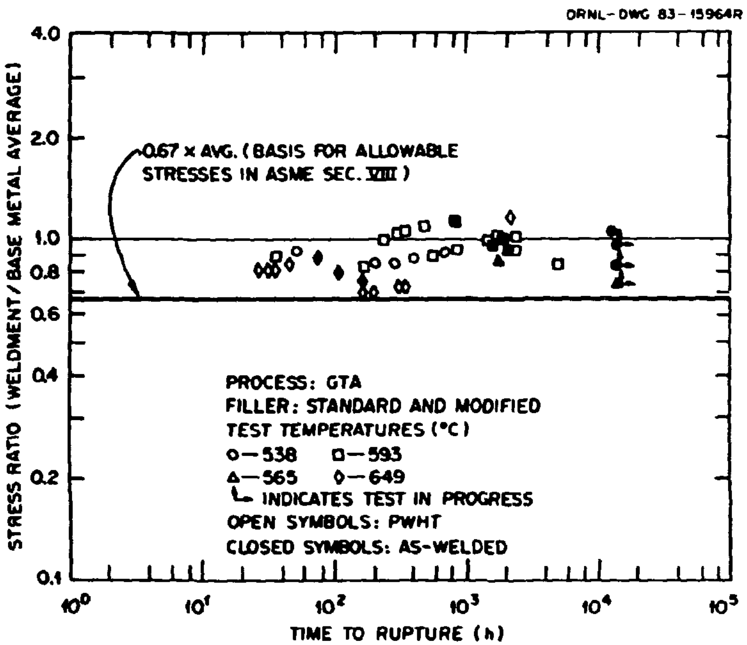

Fig. 12. Stress ratio (weldment to base metal average) as a function of time to rupture for gas tungsten arc weldments of both standard and modified 9 Cr-1 Mo filler wire compositions. Data are for test temperatures of 538, 565, 593 and 649°C. Stress ratios of unity, respresenting equal strength, and 0.67, the criterion for allowable stresses in ASME Sect. VIII, are also included.

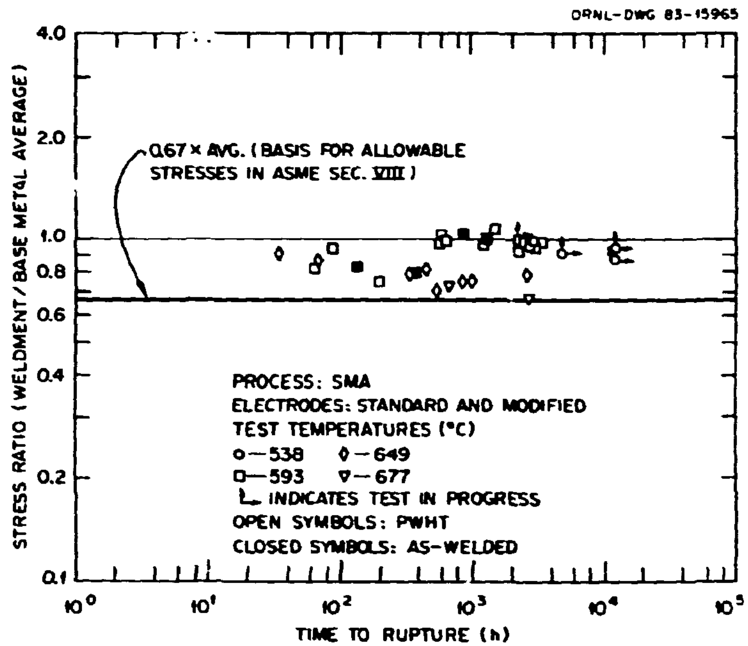

Fig. 13. Stress ratio (weldment to base metal average) as a function of time to rupture for shielded metal arc weldments of both standard and modified 9 Cr-1 Mo filler wire compositions. Data are for test temperatures of 538, 593, 649, and 677°C. Stress ratios of unity, representing equal strength, and 0.67, the criterion for allowable stresses in ASME Sect. VIII, are also included.

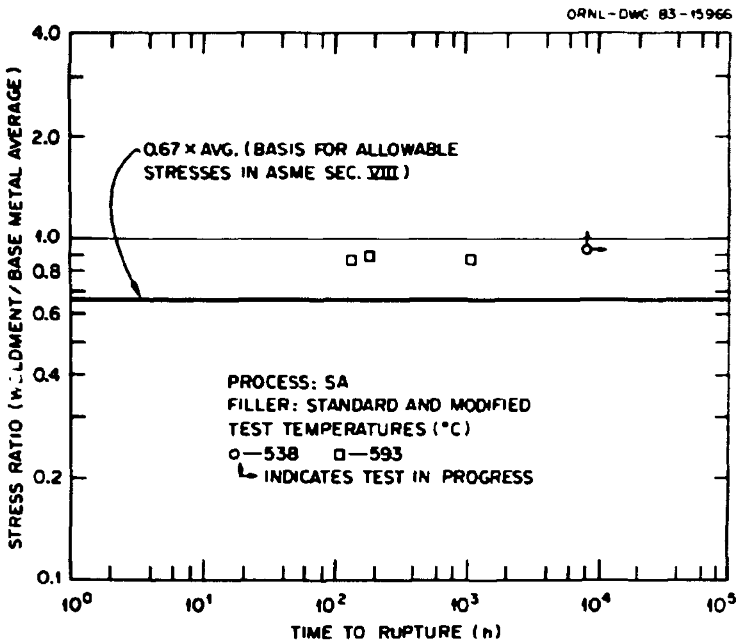

Fig. 14. Stress ratio (weldment to base metal average) as a function of time to rupture for submerged arc weldments of both standard and modified 9 Cr-1 Mo filler wire compositions. Data are for test temperatures of 538 and 593°C. Stress ratios of unity, representing equal strength, and 0.67, the criterion for allowable stresses in ASME Sect. VIII, are also included.

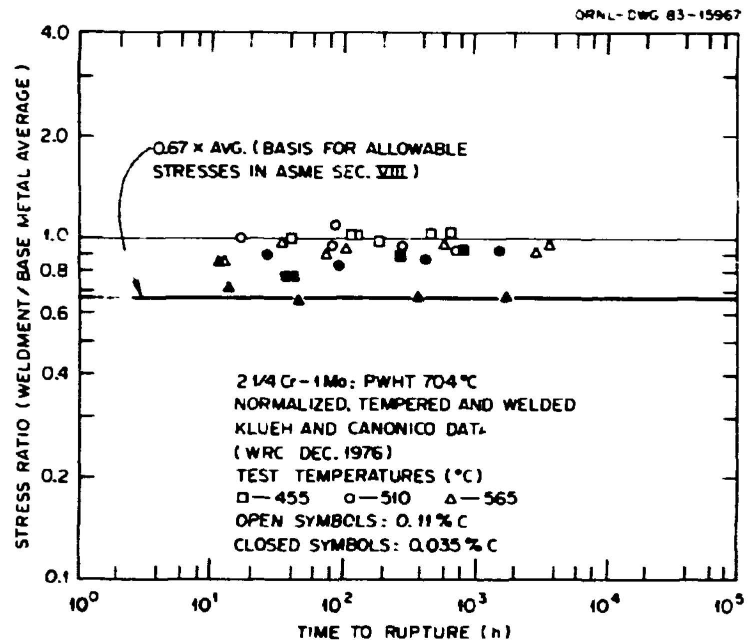

Fig. 15. Stress ratio (weldment to base metal average) as a function of time to rupture for 2 1/4 Cr-1 Mo weldments. Data are for test temperatures of 455, 510, and 565°C. Stress ratios of unity, representing equal strength, and 0.67, the criterion for allowable stresses in ASME Sect. VIII, are also included. *Source of data:* R. L. Klueh and D. A. Canonico, *Weld J. (Miami)* 55(12), 381–88-s (December 1976).

CHARPY IMPACT DATA

Charpy impact data on welds are available for three welding processes, for the standard and modified filler and electrode compositions, and for various PWHT conditions. Figure 16 shows the Charpy impact data on GTA welds tested in the *as-welded condition*. Curves are drawn through the minimum and maximum energy data points. The energy curves are marked to show the range of transition temperatures at 68 J (50 ft-lb); it ranges from 25 to 125°C. When GTA welds are tested after a 732°C PWHT (Fig. 17), the transition temperature decreases to 50°C and below, and the upper-shelf energy increases above 160 J. Limited data on welds heat treated at 760°C (Fig. 18) show an only slightly lower transition temperature than that observed for 732°C PWHT. When GTA welds of standard filler wire composition are tested after 732°C PWHT (Fig. 19), the 68-J transition temperature is below 10°C. Compared with modified 9 Cr-1 Mo filler wire, the standard wire gives about 40°C lower transition temperature. The upper-shelf energies are the same for both cases.

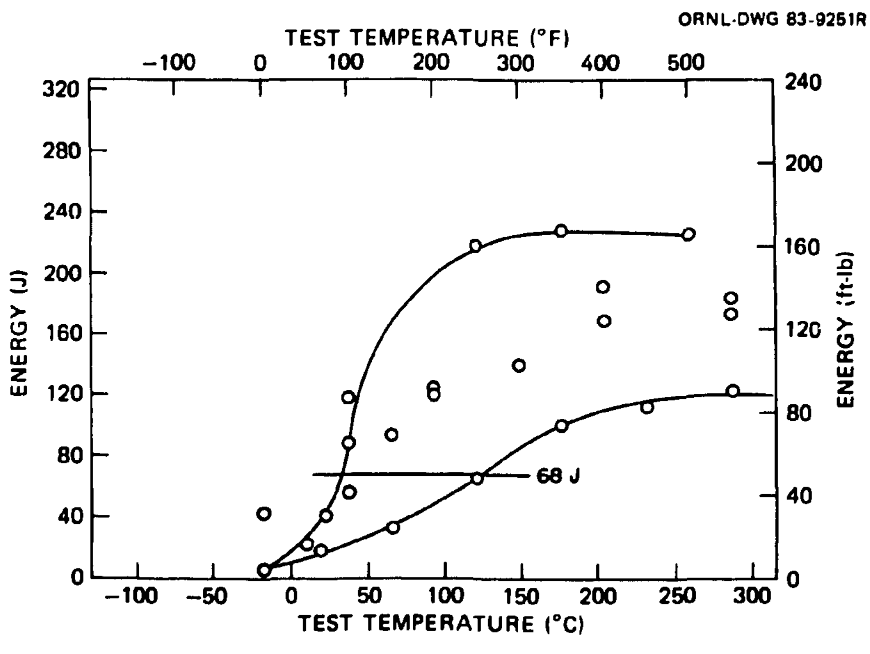

Fig. 16. Charpy impact data on gas tungsten arc welds of modified 9 Cr-1 Mo. The filler wire was modified 9 Cr-1 Mo, and the welds were *not postweld heat treated*. Curves through the data show the upper and lower bounds.

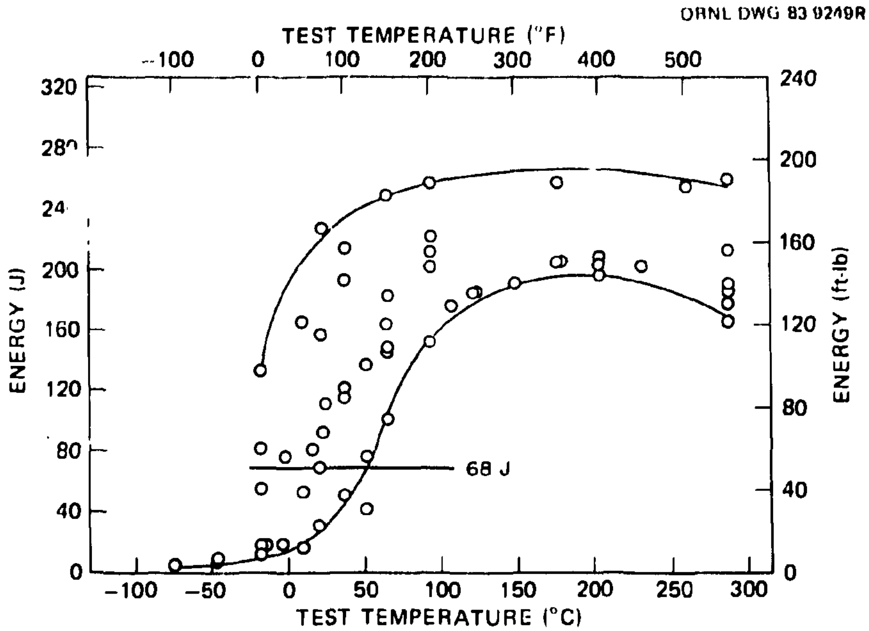

Fig. 17. Charpy impact data on gas tungsten arc welds of modified 9 Cr-1 Mo. The filler wire was modified 9 Cr-1 Mo, and the welds were postweld heat treated 1 h at 732°C. Curves through the data show the upper and lower bounds.

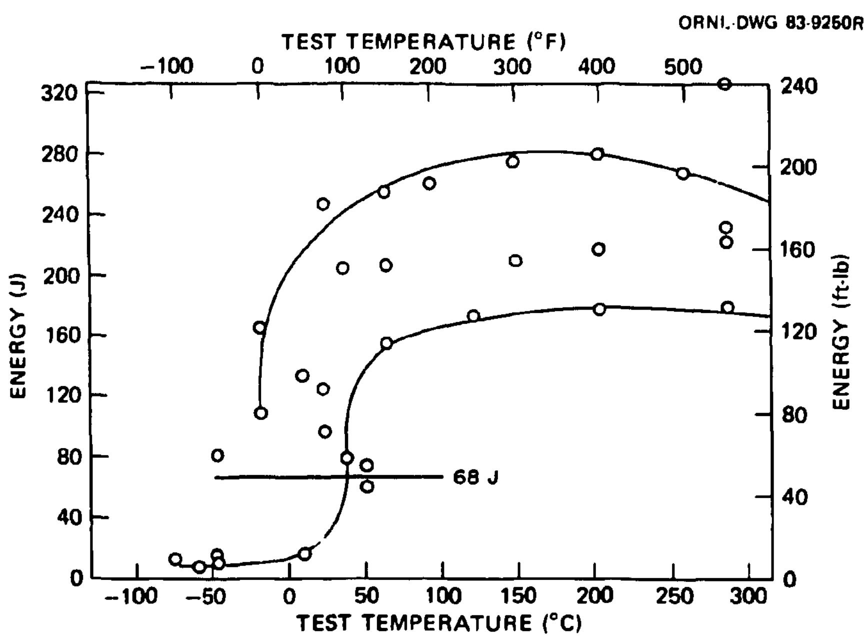

Fig. 18. Charpy impact data on gas tungsten arc welds of modified 9 Cr-1 Mo. The filler wire was modified 9 Cr-1 Mo, and the welds were postweld heat treated 1 h at 760°C. Curves through the data show the upper and lower bounds.

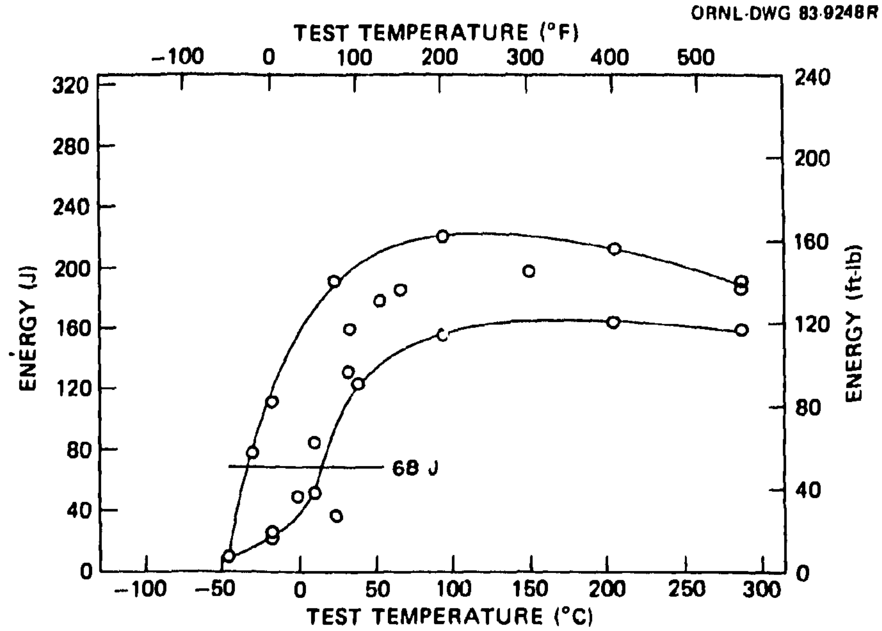

Fig. 19. Charpy impact data on gas tungsten arc welds of modified 9 Cr-1 Mo. The filler wire was standard 9 Cr-1 Mo, and the welds were postweld heat treated 1 h at 732°C. Curves through the data show the upper and lower bounds.

The Charpy impact energy curves for SMA welds of modified and standard composition are shown in Figs. 20 and 21, respectively. In both cases the welds were PWHT at 732°C before testing. Comparison of these two figures shows that the Charpy impact properties of the SMA weld with standard electrodes are significantly better than those with modified electrodes. The 68-J transition temperature for the standard electrodes is 50°C or below. Reasons for less toughness of modified electrodes compared with the standard electrodes are not now clear.

The Charpy impact energy curves for SA welds are shown in Fig. 22. The filler wire used was of standard composition. The 68-J transition temperature for these welds is 5°C or below, and the upper-shelf energy is at least 140 J. Figure 23 compares the Charpy impact energy curve for the base metal, weld metal, and the HAZ for the submerged arc weld made in 203-mm-thick plate of modified 9 Cr-1 Mo steel by Chicago Bridge and Iron. The 68-J transition temperature for the base, weld metal, and HAZ of this weld are −35, 10, and −50°C, respectively. Comparison of

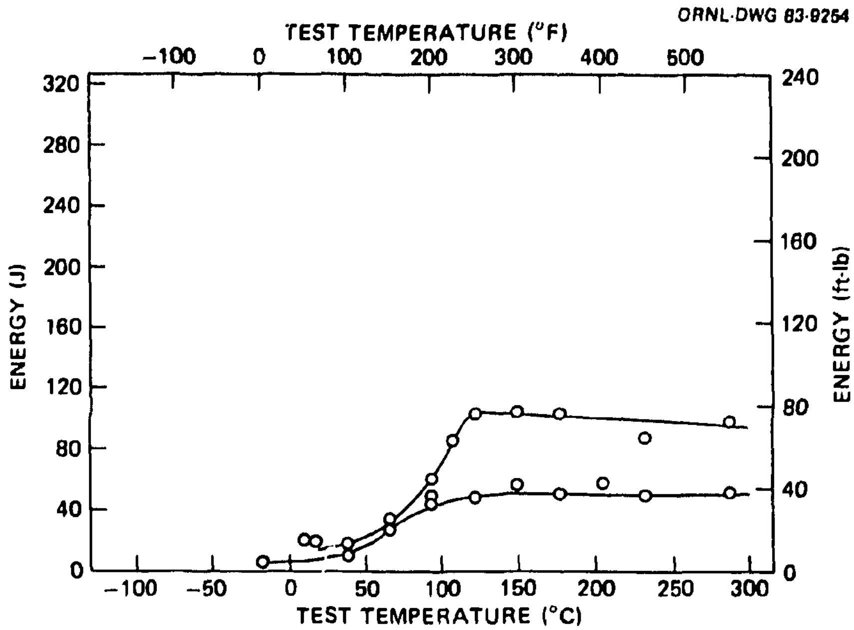

Fig. 20. Charpy impact data on shielded metal arc welds of modified 9 Cr-1 Mo. The filler wire was modified 9 Cr-1 Mo, and the welds were postweld heat treated 1 h at 732°C. Curves through the data show the upper and lower bounds.

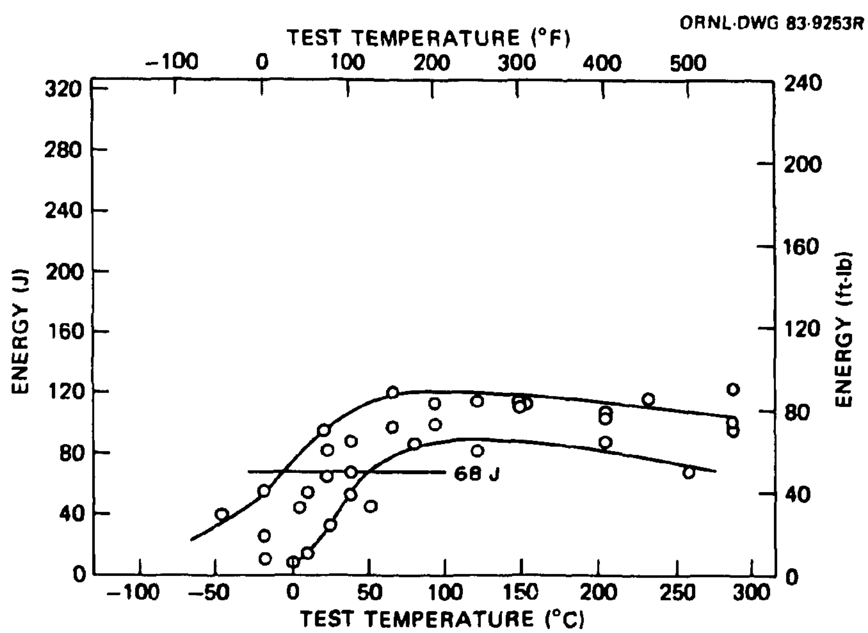

Fig. 21. Charpy impact data on shielded metal arc welds of modified 9 Cr-1 Mo. The filler wire was standard 9 Cr-1 Mo, and the welds were postweld heat treated 1 h at 732°C. Curves through the data show the upper and lower bounds.

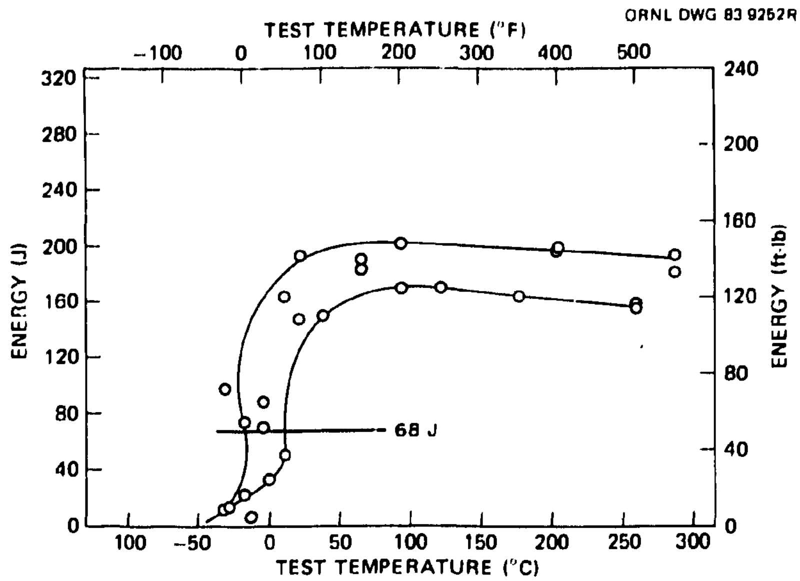

Fig. 22. Charpy impact data on submerged arc welds of modified 9 Cr–1 Mo. The filler wire was standard 9 Cr–1 Mo, and the welds were postweld heat treated 1 h at 732°C. Curves through the data show the upper and lower bounds.

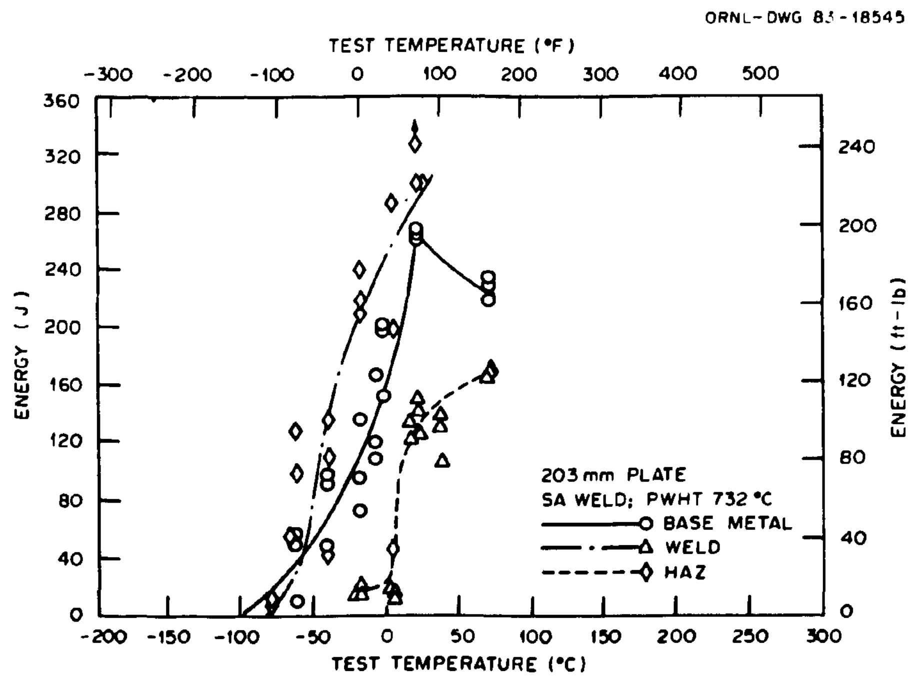

Fig. 23. Comparison of Charpy impact data of base metal, heat-affected zone, and weld metal of a submerged arc weld in a 203-mm-thick plate of modified 9 Cr-1 Mo steel. The weld metal is of standard 9 Cr-1 Mo composition, and the weld was postweld heat treated 6 h at 732°C.

Figs. 22 and 23 shows that increasing the weld thickness from 51 to 203 mm does not affect the Charpy impact properties significantly. Similar results would be expected if the weld thickness were scaled up for the other welding processes.

DISCUSSION

Welds of normalized (quenched) and tempered chromium-molybdenum steel show the transformed zone (where base metal temperature goes above AC_1) and the tempered zone (where base metal temperature goes close to AC_1, but above the base metal tempering temperature). The transformed zone is harder and the tempered zone is softer than the base metal. The weld metal hardness depends on its chemical composition. The higher hardness of the transformed zone is attributed to partial tempering of the freshly formed martensite. The partial tempering occurs because the transformed zone is subjected to a 732°C temper (PWHT) rather than the tempering treatment of 760°C undergone by the base metal. The tempered zone shows lower hardness than does the base metal because it is subjected to a higher tempering temperature. The difference between the tempered zone hardness and the base metal hardness is expected to depend on heat input. The higher the heat input, the greater the difference. Note that the lower hardness of the tempered zone is not unique to modified 9 Cr-1 Mo but also occurs in standard 9 Cr-1 Mo, 2 1/4 Cr-1 Mo, and HT9. The mechanism for the change in hardness is also similar in all cases.

An extended PWHT produces small changes in the hardness of the base metal and of the tempered zone. The transformed zone shows a further drop, and so does the standard 9 Cr-1 Mo filler metal. Similar work is planned on welds made with the modified 9 Cr-1 Mo filler wire. The normalizing and tempering treatment eliminates the difference in hardness among the base metal, tempered zone, transformed zone, and even the weld metal if it is of modified composition. If the filler wire is of standard composition, the hardness of the weld can drop below that of the base metal. Thus, it is recommended that, if a normalizing and tempering treatment is planned after welding, the filler wire be of the modified composition.

With the nominal PWHT, the properties of weldment made with standard or modified filler wire are limited by the tempered zone strength. In all cases the weldment tensile properties exceed the minimum tensile properties specified for the modified 9 Cr-1 Mo base metal.

The weldment-to-base-metal stress ratio was used to analyze the weldment creep data. For rupture times below 1000 h (for which the applied stresses will be high) the weldment strength is lower than the base metal average. At rupture times greater than 1000 h, the weldment strength approaches that of the base metal. This observation is true irrespective of the filler wire composition. More long-term data (>10,000 h) are needed to ascertain that the standard 9 Cr-1 Mo will not become the limiting factor in controlling the weldment strength.

The Charpy impact data on welds made by all three processes (GTA, SMA, and SA) indicate that the standard wire or electrodes have better properties than does the modified composition. We believe that this result is a consequence of faster tempering of the standard composition. As a result, the standard composition weld reduces to lower hardness than does the modified composition during the PWHT.

On the basis of mechanical properties data presented here, we believe that standard 9 Cr-1 Mo wire or electrodes are adequate for welding modified 9 Cr-1 Mo steel. An exception to this recommendation applies when the weld is to be normalized and tempered.

SUMMARY AND CONCLUSIONS

The status of welding and weldability studies on modified 9 Cr-1 Mo steel is presented. Work is in progress at ORNL and other organizations. Analyses of microhardness, tensile, creep, and Charpy impact properties of welds made by GTA, SMA, and SA processes are presented. Microhardness traverses on modified 9 Cr-1 Mo welds have been examined after nominal and extended PWHTs. Microhardness data on modified 9 Cr-1 Mo welds are also compared with similar results on standard 9 Cr-1 Mo, 2 1/4 Cr-1 Mo, and HT9. Tensile and creep data are primarily on weldment specimens in which the gage length contained the base metal, weld metal, and the HAZ.

Charpy impact data are primarily of the weld metal with notch parallel to the welding direction. The following conclusions derive from this work.

1. Welding of chromium-molybdenum steels (modified and standard 9 Cr-1 Mo, 2 1/4 Cr-1 Mo, and HT9) produces a transformed zone and a tempered zone in the base metal. The transformed zone is harder and the tempered zone softer than the base metal. The weldment generally fails in the tempered zone.

2. Tensile properties of weldments made by GTA, SMA, and SA processes exceed the minimum specified properties for the base metal.

3. The creep strength of weldments is lower than the average strength of the base metal for rupture times up to 1000 h. However, at longer rupture times, the weldment strength approaches that of the base metal average.

4. The 68-J (50-ft-lb) transition temperature for welds of modified composition is at most 50°C. However, this temperature drops to 10°C or below for weld metal of standard composition. Upper-shelf energy generally exceeds 160 J (120 ft-lb). Among various welding processes, the SMA process produces the poorest Charpy impact properties. Work is under way to optimize the electrode composition and possibly flux.

5. The standard filler wire composition is recommended to weld modified 9 Cr-1 Mo. This recommendation is valid if the welds are given a nominal postweld heat treatment. However, if the welds are normalized and tempered, we recommend the use of modified filler wire having the base metal composition.

FUTURE WORK

Research is under way to improve welding techniques to minimize the drop in hardness of the base metal due to overtempering during welding. Work is also in progress to examine the effect of filler wire composition (standard versus modified) and various postweld heat treatments on mechanical properties. The completion of this work might alter some of the conclusions in this report.

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