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Weldability of Modified 9Cr-1Mo Steel

J. F. King
V. K. Sikka
M. L. Santella
J. F. Turner
E. W. Pickering

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WELDABILITY OF MODIFIED 9Cr-1Mo STEEL*

J. F. King, V. K. Sikka, M. L. Santella,
J. F. Turner,† and E. W. Pickering†

ABSTRACT

The weldability of modified 9Cr-1Mo steel has been investigated by numerous organizations including Oak Ridge National Laboratory over a period of several years. The results of the various studies are summarized. Weldability evaluations have included hot cracking susceptibility, reheat cracking response, hydrogen-assisted cracking susceptibility, and the selection of consumables for three welding processes. Weldment mechanical properties have been determined for the gas tungsten arc, submerged arc, and shielded metal arc welding processes. Dissimilar metal weldments between modified 9Cr-1Mo steel and austenitic stainless steels have been produced with good results. Evaluation of the weldments and various tests have indicated that there are no major concerns regarding the weldability of modified 9Cr-1Mo steel.

INTRODUCTION

A modified 9Cr-1Mo steel with elevated-temperature mechanical properties that are significantly improved over those of 2.25Cr-1Mo and standard 9Cr-1Mo has been developed jointly by Oak Ridge National Laboratory (ORNL) and Combustion Engineering, Inc., of Chattanooga, Tennessee. The compositional specification for this alloy is presented in Table 1. Specifications for this material and its various product forms are now included in specifications of the American Society for Testing and Materials (ASTM) and in the American Society of Mechanical Engineers (ASME) Code.

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†J. F. Turner and E. W. Pickering are members of the Metallurgical Materials Laboratory, Combustion Engineering, Inc., Chattanooga, Tenn.

Table 1. Compositional specification for modified 9Cr-1Mo steel

Element	Range (wt %)
C	0.08–0.12
Mn	0.30–0.60
P	<0.020
S	<0.010
Si	0.20–0.50
Cr	8.00–9.50
Mo	0.85–1.05
Ni	<0.40
V	0.18–0.25
Nb	0.06–0.10
N	0.030–0.070
Al	<0.04

Early in the development of this alloy it was determined that weldability is an important factor in the acceptance of this material for industrial use. Welding investigations were conducted at laboratories, universities, and commercial fabricators. After the basic weldability of the modified 9Cr-1Mo steel was established, work proceeded with the development of welding consumables and the characterization of weld metal and weldment mechanical properties for three different processes. This report summarizes the welding studies of modified 9Cr-1Mo steel and presents an analysis of weldment mechanical property data.

CRACKING SENSITIVITY

The weldability of modified 9Cr-1Mo steel has been investigated by numerous organizations. Studies have included the evaluation of several welding processes; the determination of preheat and postweld heat treatments (PWHT), cold-cracking and hot-cracking susceptibility, and reheat-cracking response; filler wire and electrode development; and characterization of weldment mechanical properties.

We have prepared 157 weldments of modified 9Cr-1Mo steel at ORNL. Of this total, 91 were produced by the gas tungsten arc (GTA) process, 32 by the shielded metal arc (SMA) process, and 34 by the submerged arc (SA) process. The material thickness ranged from 3 to 50 mm, and the product forms included tubing, plate, and pipe. Dissimilar metal weldments were made between modified 9Cr-1Mo and (1) standard 9Cr-1Mo, (2) 2.25Cr-1Mo, and (3) stainless steels of various compositions. The filler metals for producing these weldments included (1) standard composition 9Cr-1Mo, (2) modified 9Cr-1Mo, (3) 2.25Cr-1Mo, and (4) ERNiCr-3. Extensive testing and mechanical property characterizations have been conducted on the various weldments.

The hot-cracking sensitivity of the modified 9Cr-1Mo alloy was evaluated in Tigamajig tests of 11 experimental heats.[1] This study indicated that hot cracking should not be a problem within the range of compositions included in the investigated heats. That conclusion has been confirmed by both laboratory and commercial fabrications in which no hot cracking of modified 9Cr-1Mo steel has been encountered.

The Y-groove restraint test was used to evaluate the relative weldability of the steel and to examine preheat temperature. In tests at ORNL, weld metal cracking was observed in both non-preheated test plates and those preheated to 93°C. No cracking was observed in a test plate preheated to 204°C prior to welding. Grobner and Wada[2] of the AMAX Research Center reported that preheating to 150°C was sufficient to prevent cracking in this test.

A detailed microstructural analysis of weld metal, heat-affected zone (HAZ), and base metal of 2.25Cr-1Mo and HT-9 was also reported by AMAX.[3] The conclusion was that compared to the base metal, a region of slightly lower hardness develops in the HAZ in all four alloys. The lower hardness is believed to be caused by carbide coarsening due to overtempering of a narrow region.

Lundin and co-workers[4] at The University of Tennessee conducted research on the welding metallurgy of the HAZ of modified 9Cr-1Mo and other Cr-Mo steel alloy weldments to assess the susceptibility to stress-relief cracking (SRC) and hydrogen-assisted cracking (HAC) of the steels. The study showed that the HAZ microstructure in the 9Cr alloy is independent of cooling rates normally encountered during welding. In addition, the SRC susceptibility of the modified 9Cr-1Mo was assessed to be less than for 2.25Cr-1Mo steel and the HAC susceptibility was found to be the about the same. No major weldability concerns from SRC or HAC were identified.

Commercial fabricators have made significant contributions to the welding development of modified 9Cr-1Mo steel. Their work, which has included both the production of weldments by various processes and some basic weldability investigations, reveals no major concerns with the weldability of this steel.

WELDING PROCESS EVALUATION

Weldability studies of the 9Cr-1Mo steels included the GTA, SA, and SMA welding processes and addressed filler materials that produced weld deposits of both standard and modified 9Cr-1Mo. At ORNL, several hundred feet of weld have been made, with a little over one-half being GTA welds and the remainder being SA and SMA welds. The majority of these welds were made to provide material for subsequent chemical, metallographic, or mechanical properties evaluations, but in every case the general welding characteristics also were assessed from a user's standpoint. No unusual weldability problems were encountered in making GTA welds, but some difficulty was experienced for SA or SMA welding.

GAS TUNGSTEN ARC

Since no weldability problems were encountered in either manual or automatic GTA welding, only a few weldments were subjected to the complete testing for certification of filler wire and procedure qualification. One typical heat of modified 9Cr-1Mo filler wire was evaluated.

The filler wire selected for weld deposit evaluation and procedure certification was heat No. 21648 supplied to ORNL by the United States Welding Corporation (USW). The manual GTA welding process with argon shielding gas was used to make weld deposits of this filler wire (2.38-mm diam) in 25-mm-thick plate. A weld preheat temperature of 150°C was maintained for this test, and a maximum interpass temperature of 260°C was measured. A total of 29 passes were required to complete the weldment. Welding parameters for the first 10 passes were nominally 18 V and 170 A, and the remaining passes used 20 V and 220 A. The weldment was given a PWHT of 1 h at 732°C prior to sectioning for test specimens. Data from tensile and Charpy V-notch impact testing of this GTA weld deposit are given in Tables 2 and 3.

Table 2. Data from all-weld-metal tension test of USW heat No. 21648

0.2% Yield strength, MPa	671.25
Ultimate tensile strength, MPa	802.74
Elongation in 50 mm, %	20.12
Reduction of area, %	65.37

Table 3. Data from all-weld-metal Charpy V-notch test of USW heat No. 21648

Test temperature (°C)	Absorbed energy (J)	Lateral expansion (mm)	Fracture appearance (% shear)
−73	8	0.06	3
−46	8	0.14	5
−18	97	1.08	45
−1	73	0.96	27
10	104	1.23	50
23	217	2.10	100
66	235	2.32	100
121	191	1.93	100

Results of a welding procedure tensile test as specified in Section IX of the ASME Code are presented in Table 4. The specimen fractured in the base metal away from the HAZ. Side bend specimens passed with no visible defects.

The Charpy V-notch absorbed energy values for the weld deposit are excellent, particularly in light of its high tensile strength. Based on past experience it is anticipated that this filler wire would have no problem meeting a minimum value of 68 J at room temperature when deposited with the GTA process and appropriately postweld heat-treated.

Table 4. Tensile data from procedure qualification of GTA weld made with USW heat No. 21648

0.2% Yield strength, MPa	637.89
Ultimate tensile strength, MPa	768.29
Elongation in 50 mm, %	18.06
Reduction of area, %	67.48

The results of a chemical analysis of the undiluted weld deposit are given in Table 5. Levels are within the ranges specified for modified 9Cr-1Mo steel, except for nitrogen. These test results show that modified 9Cr-1Mo GTA weldments should meet the requirements of the ASME Code, Sect. IX. Weldability has been shown to be good, and filler metal is available from commercial suppliers.

Table 5. Chemical analyses of all-weld-metal deposit of USW heat No. 21648 (wt %)

Element	Analysis (wt %)	Element	Analysis (wt %)
C	0.082	Co	0.023
Mn	0.55	Cu	0.05
P	0.007	Al	0.007
S	0.003	B	<0.001
Si	0.30	W	0.02
Ni	0.08	As	0.007
Cr	9.13	Sn	0.003
Mo	1.05	Zr	<0.001
V	0.25	N	0.024
Nb	0.06	0	0.0009
Ti	<0.01		

SUBMERGED ARC

Many submerged arc welds have been made on modified 9Cr-1Mo plate using standard 9Cr-1Mo electrode and OP-76, a neutral flux made by Oerlikon. This combination of materials has always given excellent weldability and mechanical properties. An example of its versatility is the weld made on 203-mm-thick modified 9Cr-1Mo plates with standard composition electrode and OP-76 flux. The joint geometry and pass sequence of this weld (ORNL No. PC-93) are shown schematically in Fig. 1. A tandem electrode arrangement was used to make the deposit with the leading electrode on dc-reverse polarity current and the trailing electrode on ac. No weldability problems were encountered during the welding, which was done at the corporate welding center of CBI Industries in Houston, Texas. The mechanical properties of this weld were also very good. For instance, Fig. 2 compares the Charpy V-notch impact energy curve for the base

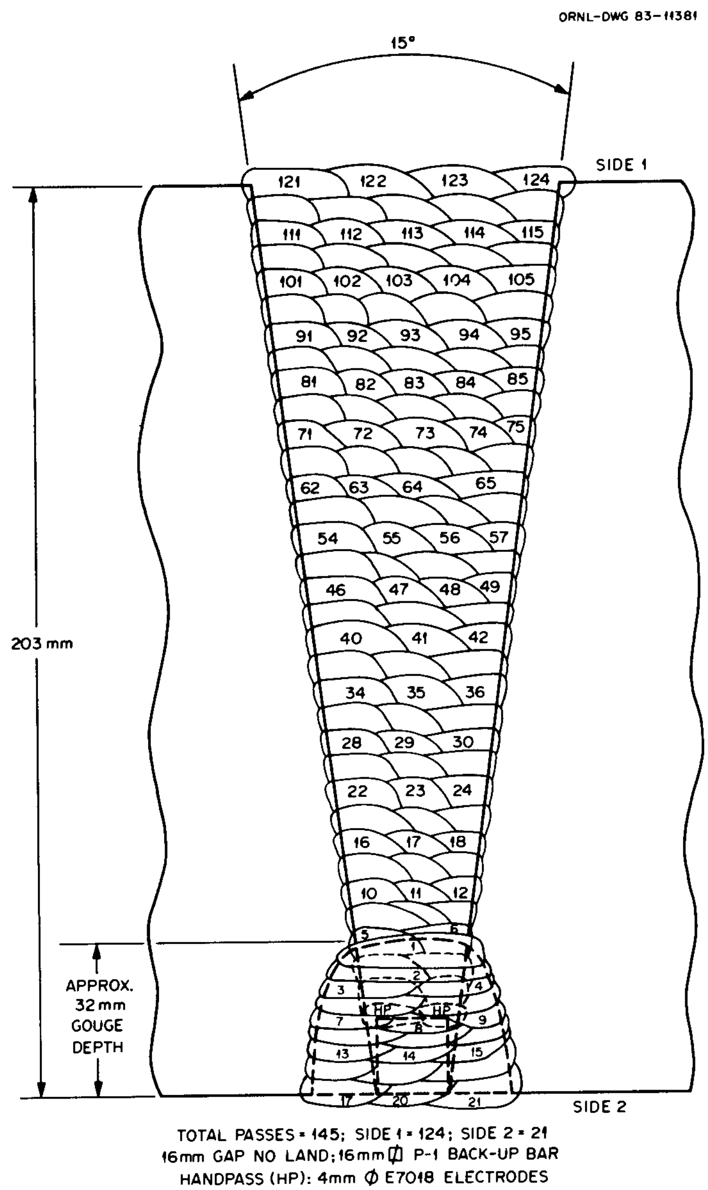

Fig. 1. Weld design and the number of passes used for SA welding of the 203-mm-thick plate of modified 9Cr-1Mo steel at CBI Industries. The preheat and interpass temperatures for this weld were 200 and 315°C, respectively. The weld was heat-treated at 732°C for 6 h.

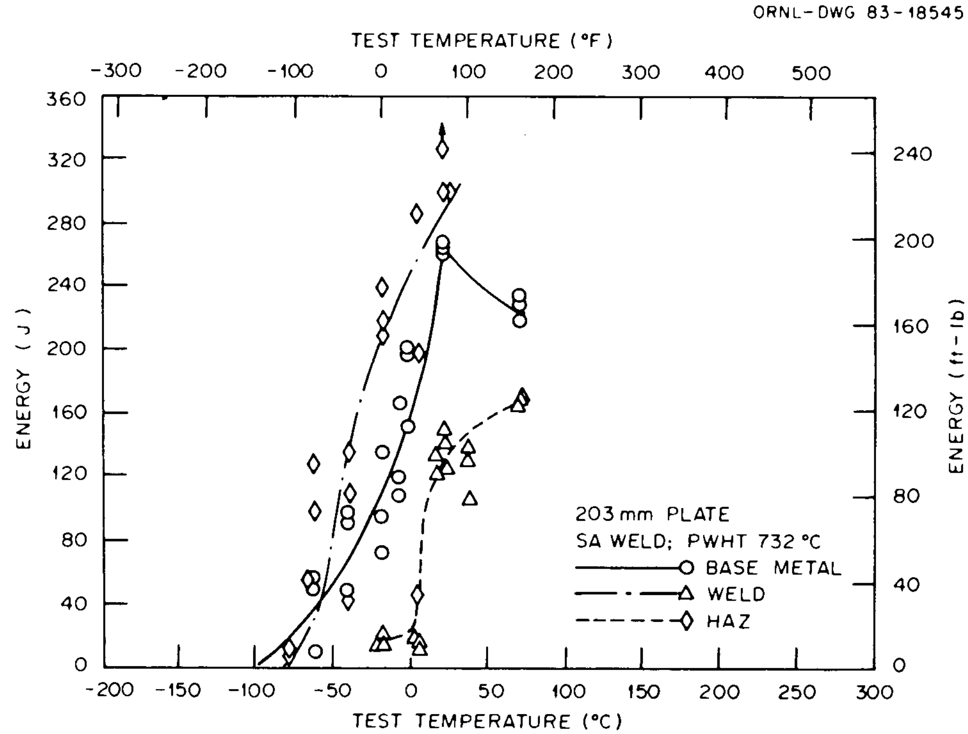

Fig. 2. Comparison of Charpy impact data of base metal, HAZ, and weld metal of a SA weld in a 203-mm-thick plate of modified 9Cr-1Mo steel. The weld metal is of standard 9Cr-1Mo composition, and the weld was post-weld heat-treated 6 h at 732°C.

Table 6. Chemical analysis (wt %) of welding electrode and weld deposit of SA weld in a 203-mm plate

Element	Welding electrode (ORNL No. W-714)	Weld deposit
C	0.08	0.08
Mn	0.51	0.55
Si	0.34	0.35
P	0.030	0.008
S	0.019	0.007
Cr	8.94	8.38
Mo	0.98	0.96
Ni	0.19	0.08
Cu	0.06	0.05

Because OP-76 behaved so well with a standard 9Cr-1Mo electrode, it was used to make the initial SA welds with a modified 9Cr-1Mo electrode. However, the combination of OP-76 flux and modified 9Cr-1Mo electrode resulted in significant weldability problems. Fused OP-76 adheres tenaciously to SA welds made with modified filler wire so that each weld bead must be surface ground to properly descale the weldment. The same result was found for both dc and ac operation.

When this weldability problem first appeared, Oerlikon was consulted for their expertise in formulating and manufacturing fluxes. Oerlikon subsequently provided ORNL with several fluxes they judged would work well with the modified 9Cr-1Mo electrode. The problems encountered using Oerlikon INS-22 flux have been described in a previous report.[5] Of the fluxes provided to ORNL, the one showing the most promise for obtaining good weldability with modified 9Cr-1Mo electrode was IND-24.

Two identical SA welds (PC-147 and PC-148) were made in 25-mm-thick plate for the purpose of evaluating the behavior of modified 9Cr-1Mo electrode and Oerlikon IND-24 flux. The welds, made with dc-reverse polarity current, had no problems with flux adherence. This combination of materials behaved similarly to standard 9Cr-1Mo and OP-76 flux with respect to descaling characteristics. The assemblies were preheated to 200°C and maintained between 175 and 230°C during welding. A total of 20 passes were required to complete the welds; and the parameters used were 300 A, 35 V, 254 mm/min. The 2.4-mm-diam modified 9Cr-1Mo electrode used for the welds was USW heat No. 21078 (ORNL No. W-742). Completed weldments were allowed to cool before they were radiographed and found to be free of significant defects. Both weldments were PWHT at 732°C for 4 h before being submitted to a mechanical property evaluation.

Tensile data from the all-weld-metal specimen, obtained at a nominal strain rate of 9.3×10^{-5}/s, are given in Table 7. All of the tensile data exceed the minimums specified by the ASME Code.

The data from Charpy V-notch impact testing of the SA weld deposit are given in Table 8. The absorbed energy values are acceptable, although the desired minimum of 68-J absorbed energy could not be met.

The weld deposit chemical analyses and with the electrode analysis are given in Table 9.

Table 7. Data from all-weld-metal tension test of SA deposit made with modified 9Cr-1Mo electrode and IND-24 flux

0.2% Yield strength, MPa	560.36
Ultimate tensile strength, MPa	692.52
Elongation in 50 mm, %	21.51
Reduction of area, %	63.59

Table 8. Data from all weld metal Charpy V-notch test of SA weld deposit

Test temperature (°C)	Absorbed energy (J)	Test temperature (°C)	Absorbed energy (J)
−46	8	21	29
−18	8	38	51
21	50	66	125
21	26	107	174
21	18	149	175
21	14	260	171

Table 9. Chemical analyses from SA weld deposits and electrode

Element	Weld No. PC-147	Weld No. PC-148	Electrode No. W-742
C	0.060	0.062	0.079
Mn	0.31	0.32	0.42
P	0.019	0.018	0.020
S	0.004	0.003	0.001
Si	0.38	0.35	0.22
Ni	0.15	0.15	0.16
Cr	8.95	8.99	9.27
Mo	1.00	1.00	1.02
V	0.20	0.19	0.20
Nb	0.04	0.04	0.06
Ti	<0.01	<0.01	<0.01
O	0.046	0.060	0.002
N	0.038	0.037	0.044

Results of the weldment tensile test are presented in Table 10. The specimen fractured in the base metal away from the HAZ.

Table 10. Tensile data from procedure qualification of SA weld made with modified 9Cr-1Mo electrode and IND-24 flux

0.2% Yield strength, MPa	562.57
Ultimate tensile strength, MPa	677.23
Elongation in 50-mm, %	15.70
Reduction of area, %	66.48

All four of the side bend specimens passed, with only one specimen showing a visible defect (probably caused by a slag inclusion).

The series of tests suggests there are no major weldability problems associated with SA welding using a modified 9Cr-1Mo electrode, provided that a suitable flux is chosen. The subject of flux selection continues to be a concern for two reasons. First, the fluxes evaluated so far at ORNL do not operate very well when welding with ac. For welding thick components (over 25 mm), ac is sometimes preferred because it provides much more stable operation in the presence of the magnetic fields generated during welding than does dc. The second concern is that a reproducible means of obtaining the desired Charpy V-notch minimum of 68-J absorbed energy at room temperature has not yet been identified.

SHIELDED METAL ARC

The development of coated electrodes for SMA welding of the modified 9Cr-1Mo steel was conducted mainly at Combustion Engineering's Metallurgical and Materials Laboratory (MML). The emphasis was on improving the charpy V-notch impact strength of the SMA weld deposit while maintaining sufficient high-temperature strength and carbide stability. In the early phases of the program, a total of 191 batches of electrodes were made from 127 different coating formulations to evaluate a wide combination of chemical compositions and fabrication conditions. This work was performed on electrodes formulated by introducing all alloying elements via the electrode coating on a mild steel core wire. This early work on many different weld metal compositions showed the effects of various elements on the Charpy V-notch properties. Boron and zirconium additions were found to be detrimental to impact strength. Tungsten had little noticeable effect on the impact strength of the weld metal in these tests, and 0.05% nitrogen added to the 9Cr-1Mo composition produced only a slight decrease in impact strength. Vanadium additions of 0.17% with 0.08% carbon gave an additional shift in the transition temperature. Niobium additions greater than 0.05% were detrimental to the Charpy V-notch properties. These findings and others established a data base for the final development of an electrode with suitable Charpy V-notch properties.

Later work on electrode development used the modified 9Cr-1Mo alloy composition for the core wire. One commercial heat (14361) and four additional small heats manufactured by MML were used to evaluate the transfer of elements from the core wire composition to the weld deposit. A weld rod coating formulation (mix 10842) was developed for heat 14361. The mix was designed to have no alloying elements in the coating. Comparisons of results on an undiluted weld metal sample and a sample of weld metal plus some plate material for a weldment made using this electrode are shown in Table 11. There was some increase in carbon and niobium in the weld sample due to dilution, but otherwise the analyses of the two weld samples are very similar to each other and to the original core wire composition. A weld test coupon was given a PWHT of 750°C for 1 h prior to mechanical testing. The Charpy V-notch properties at room temperature were excellent, since results for five tests were above the 68-J goal:

Absorbed energy (J)	Fracture appearance (% shear)	Lateral expansion (mm)
77	25	0.86
69	20	0.76
73	25	0.89
85	30	1.02
80	30	0.89

Electrodes have been produced for other fabricators who requested specific compositions for their applications. For example, when Charpy V-notch impact properties were of no concern, the fabricator requested

Table 11. Modified 9Cr-1Mo SMA (mix 10842) weld chemical analysis

Element	Core wire Ht. 14361	Plate weld D-41495	Undiluted weld D-41485	Element	Core wire Ht. 14361	Plate weld D-41495	Undiluted weld D-41485
C	0.12	0.128	0.090	Co	0.017	0.017	0.016
Mn	0.59	0.40	0.36	Cu	0.09	0.09	0.10
P	0.011	0.014	0.014	Al	0.017	0.004	0.003
S	0.001	0.004	0.005	B	<0.001	<0.001	<0.001
Si	0.28	0.25	0.15	W	0.02	<0.01	0.02
Ni	0.13	0.13	0.13	As	0.005	0.004	0.004
Cr	8.88	8.57	8.46	Sn	0.005	0.003	0.003
Mo	1.01	0.99	1.00	Zr	<0.001	0.001	<0.001
V	0.208	0.186	0.180	O_2		0.039	
Nb	0.065	0.028	0.019	N_2	0.040	0.047	0.050
Ti	0.002	0.010	0.008				

higher levels of vanadium (0.18 to 0.25%) and niobium (0.060 to 0.10%). These electrodes showed no significant difference in weldability from the previous electrodes.

This study has shown that compared with the weldability with the original electrodes (which introduced alloying elements through the coating), the weldability of modified 9Cr-1Mo with modified 9Cr-1Mo steel electrodes has been greatly improved by use of alloyed core wire. There has been more consistent alloy transfer from the wire than from the coatings. Welding personnel have also reported improved clarity of the welding arc and better slag-removal characteristics with the newer electrodes. A highly basic slag system was developed for the coating on this electrode to give the operator good control of the weld puddle and yet have low silicon in the weld deposit. Prior to using a moisture-resistant coating binder, slag fluidity and control were problems in electrodes with less than 0.35% silicon in the deposit. The current electrodes now have a typical silicon content of 0.15 to 0.25% in the undiluted weld metal.

Charpy toughness of the SMA weld is influenced more by small changes in carbon and niobium than by other elements in the deposit. A carbon range of 0.090 to 0.125% and a niobium range of 0.018 to 0.030% have given the best room-temperature Charpy V-notch results. As the carbon is decreased or the niobium is increased, the toughness decreases in the SMA welds. A recommended SMA weld deposit chemical analysis is listed in Table 12.

Table 12. Recommended chemical composition range for modified 9Cr-1Mo, SMA-deposited weld metal

Element	Range (wt %)
C	0.090–0.125
Mn	0.3–1.0
P	0.02[a]
S	0.01
Si	0.15–0.35
Ni	0.40
Cr	8.0–9.5
Mo	0.85–1.05
V	0.18–0.25
Nb	0.018–0.030
Cu	0.2
N	0.035–0.055

[a]Single values are maximum percentages.

WELDMENT MECHANICAL PROPERTIES

Extensive mechanical property testing has been conducted on weldments during the 9Cr-1Mo development program. Tests have been conducted for hardness, tensile properties, creep properties, and Charpy impact properties.

HARDNESS

Tests for hardness were used often during the modified 9Cr-1Mo welding investigations to indicate changes in the microstructure and properties of the various weldment regions.[6] A typical microstructure produced during the welding of this normalized and tempered steel is shown in Fig. 3. The various regions shown in this figure are weld zone (W); transformed zone (TZ), which is the region exposed to temperatures above Ac_1 (about 840°C); and tempered zone (TMPZ), which is exposed to temperatures below the Ac_1 and above the tempering temperature. Typical microhardness measurements across these regions (Fig. 4) show variations that were made on a submerged arc weld in modified 9Cr-1Mo produced at Struthers Wells. This weldment was made with standard 9Cr-1Mo filler metal and received a PWHT of 732°C for 2 h before shipping to ORNL.

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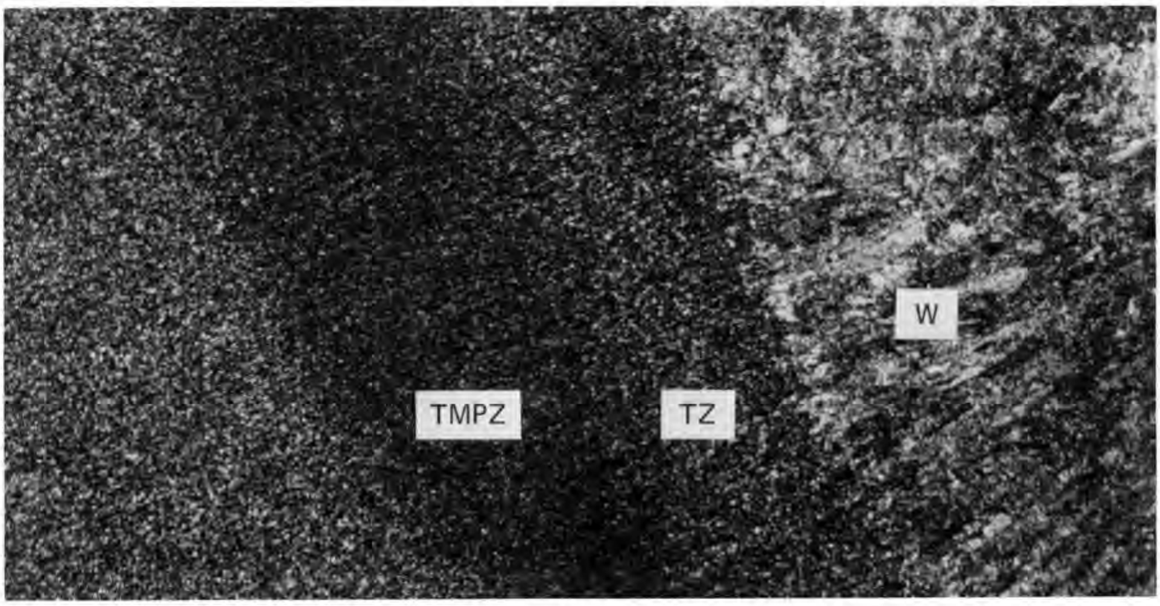

Fig. 3. Typical microstructure produced during welding or normalized and tempered chromium-molybdenum steels. Micrograph shows the weld (W) and two regions of the HAZ, transformed zone (TZ), and tempered zone (TMPZ).

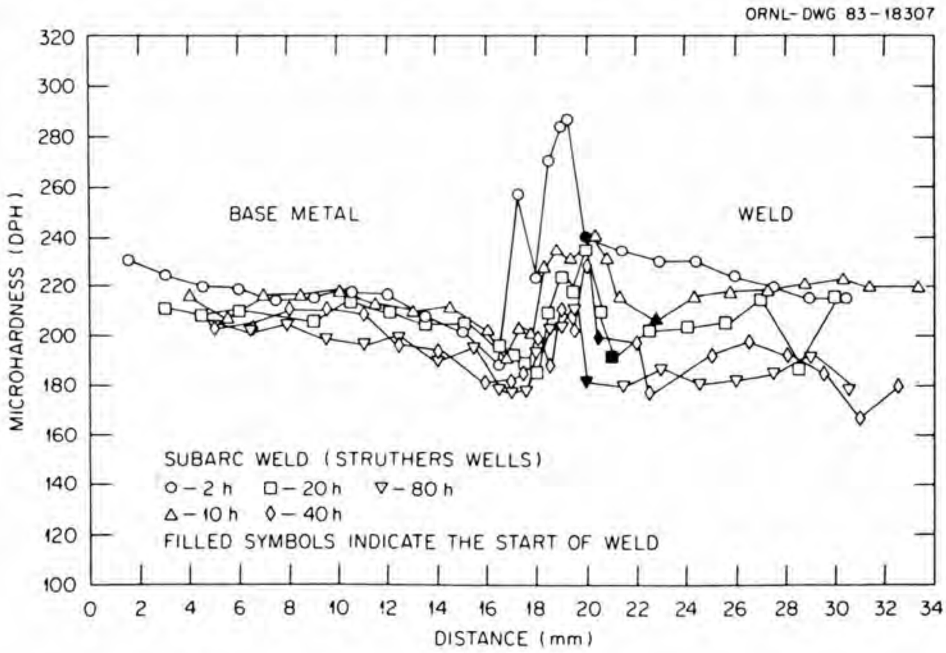

Fig. 4. Microhardness traverse across a submerged arc weldment produced at Struthers Wells. The base plate was modified 9Cr–1Mo, and the filler wire was standard 9Cr–1Mo. The plate was subjected to 2, 10, 20, 40, and 80 h of PWHT at 732°C.

Sections of this weldment were subsequently heat-treated at the same temperature an additional 8, 18, 38, and 78 h to make total times of 10, 20, 40, and 80 h. For comparison, a submerged arc weldment was made at ORNL that was similar except that the weld metal was of the modified 9Cr-1Mo composition. Microhardness measurements for the modified composition weld are shown in Fig. 5.

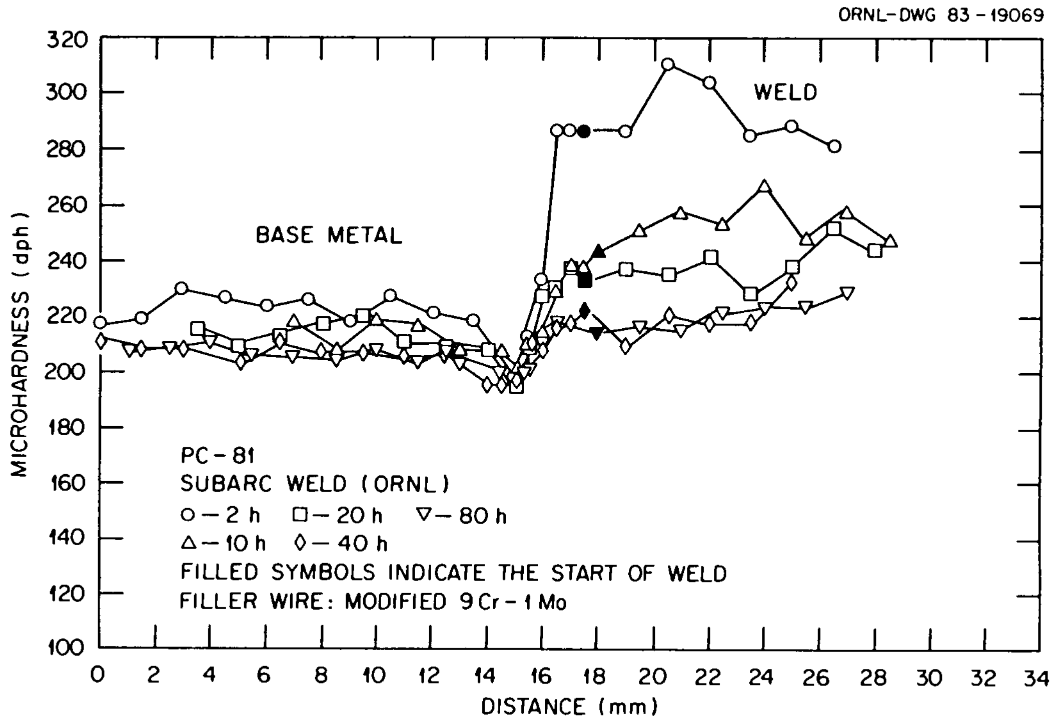

Fig. 5. Microhardness traverse across a SA weldment produced at ORNL. Both the base plate and filler wire were of the modified 9Cr-1Mo composition. Postweld heat treatments were for the times shown at 732°C.

Increasing the PWHT from 2 to 80 h produces changes in the microhardness of the various regions. The base metal, which is very stable, shows only a small decrease in hardness. The TMPZ shows slightly more decrease with increasing PWHT. The TZ, which was partially tempered at 732°C, tempers further with time. The weld region shows the greatest decrease in hardness with additional PWHT time. This observation suggests that if long PWHTs are necessary one should use the modified composition filler wire, since it remains harder than the base metal.

Microhardness traverses for weldments in modified 9Cr-1Mo, standard 9Cr-1Mo, 2.25Cr-1Mo, and HT-9 (12Cr-1MoVW alloy) show that all the alloys contain a TMPZ as a result of welding. Differences in microhardness between the base metal and TMPZ are about the same for modified 9Cr-1Mo and the other alloys (Figs. 6, 7, and 8). Because of the possible effect of these differences in microhardness on the mechanical properties of modified 9Cr-1Mo, two solutions are proposed. Normalizing and tempering at 1040/760°C after PWHT eliminates the hardness variations (Fig. 9) and offers a means of achieving uniform properties. A normalizing and tempering heat treatment (NTT) after welding is not usually possible or practical, but it may be used for certain applications. We caution that this heat treatment should be applied only to weldments made with the modified composition filler metal. Standard composition weld metal is softer than modified composition weld metal and tempers much faster as shown in Fig. 10. Therefore, to avoid overtempering that significantly weakens the weld metal, the NTT should not be applied to standard composition weld metal.

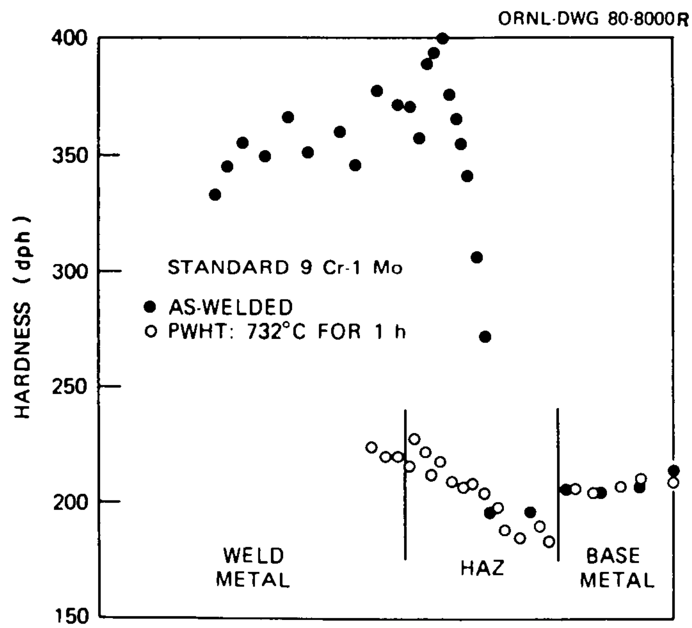

Fig. 6. Microhardness traverse across the GTA weld in standard 9Cr-1Mo base plate. The filler wire was also standard 9Cr-1Mo. The weld was made at ORNL and was examined both as-welded and after 1-h PWHT at 732°C.

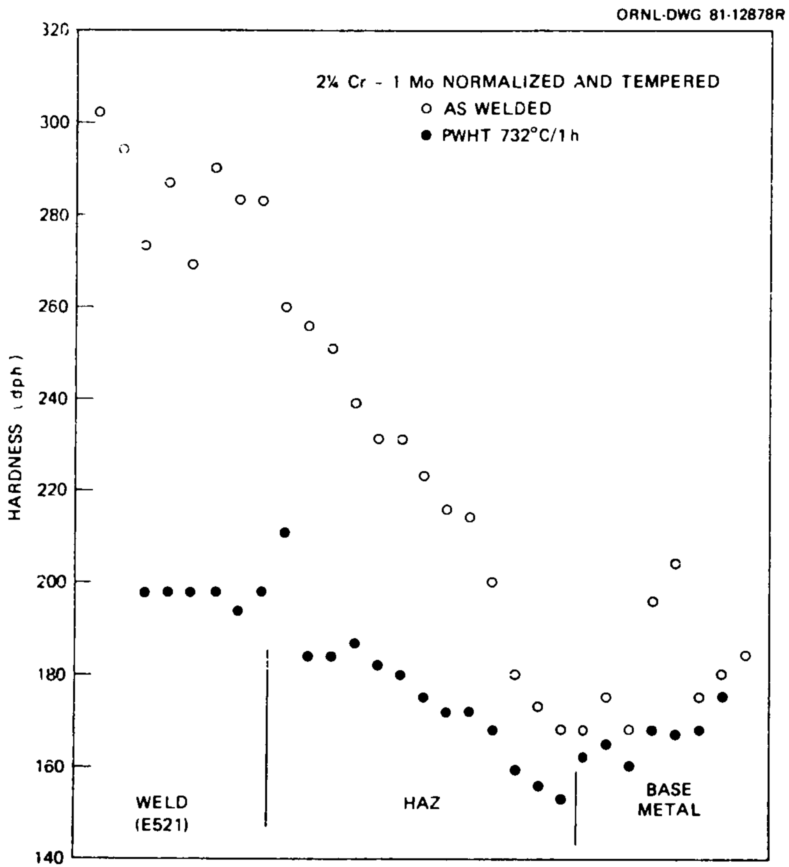

Fig. 7. Microhardness traverse across the GTA weld in standard 2.25Cr-1Mo base plate. The filler wire was also standard 9Cr-1Mo base plate. The filler wire was 2.25Cr-1Mo. The weld was made at ORNL and was examined in both the as-welded condition and after a 1-h PWHT at 732°C.

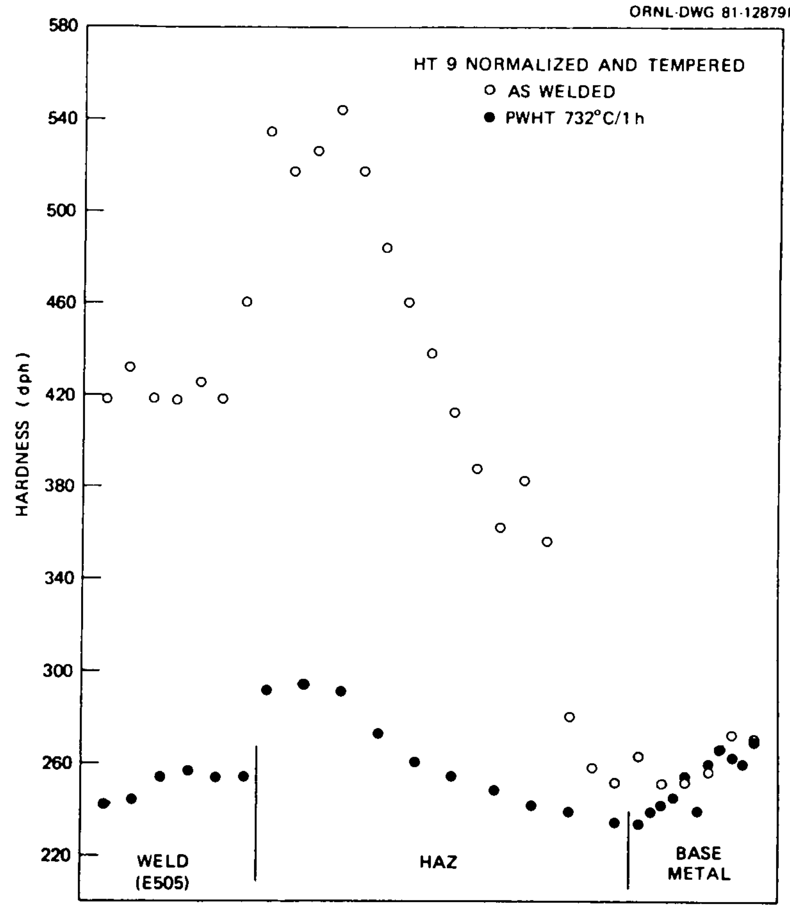

Fig. 8. Microhardness traverse across a GTA weldment in HT-9 base plate. The filler wire was standard 9Cr-1Mo. The weld was made at ORNL and was examined in both the as-welded condition and after a 1-h PWHT at 732°C.

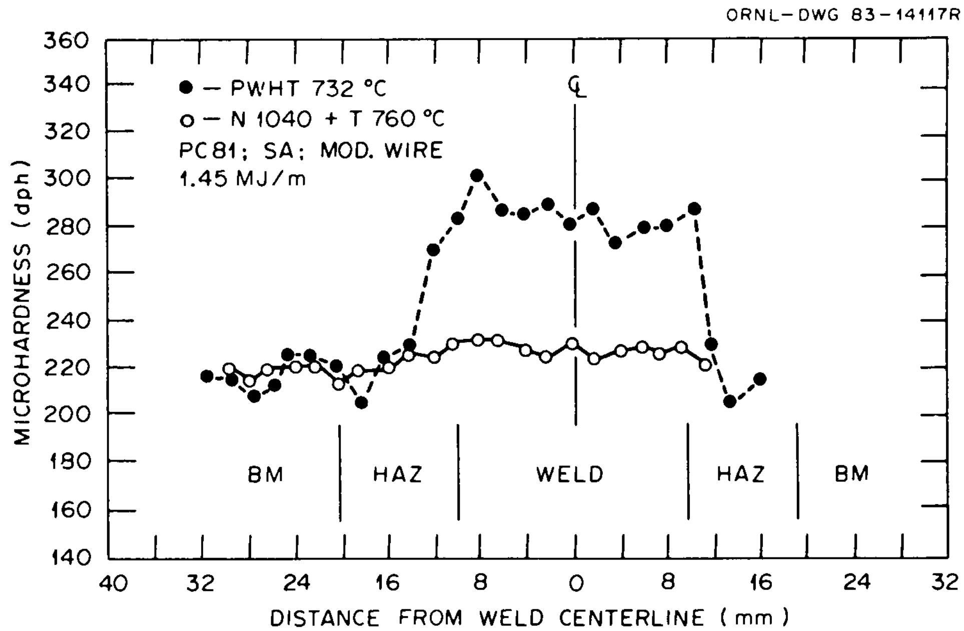

Fig. 9. Microhardness traverse across a SA weldment in modified 9Cr-1Mo steel plate. The filler wire was modified 9Cr-1Mo. The weld was made at ORNL and was examined after a 1-h PWHT at 732°C and after a normalizing for 1 h at 760°C.

A second solution is to select a lower tempering temperature.[6] The overtempered region is believed to originate from heating of the base material to near the Ac_1 during welding. Hardness variations can be minimized by tempering below 760°C before welding, to increase the initial hardness of the base material. Results indicate that tempering at 621°C followed by PWHT at 760°C essentially eliminates the hardness variations across the weldment. However, at a PWHT of 732°C, the overtempered region remains as shown in Fig. 11.

TENSILE PROPERTIES

According to ASME rules, the qualification of 9Cr-1Mo welds 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, data were normalized by dividing weldment properties by base metal

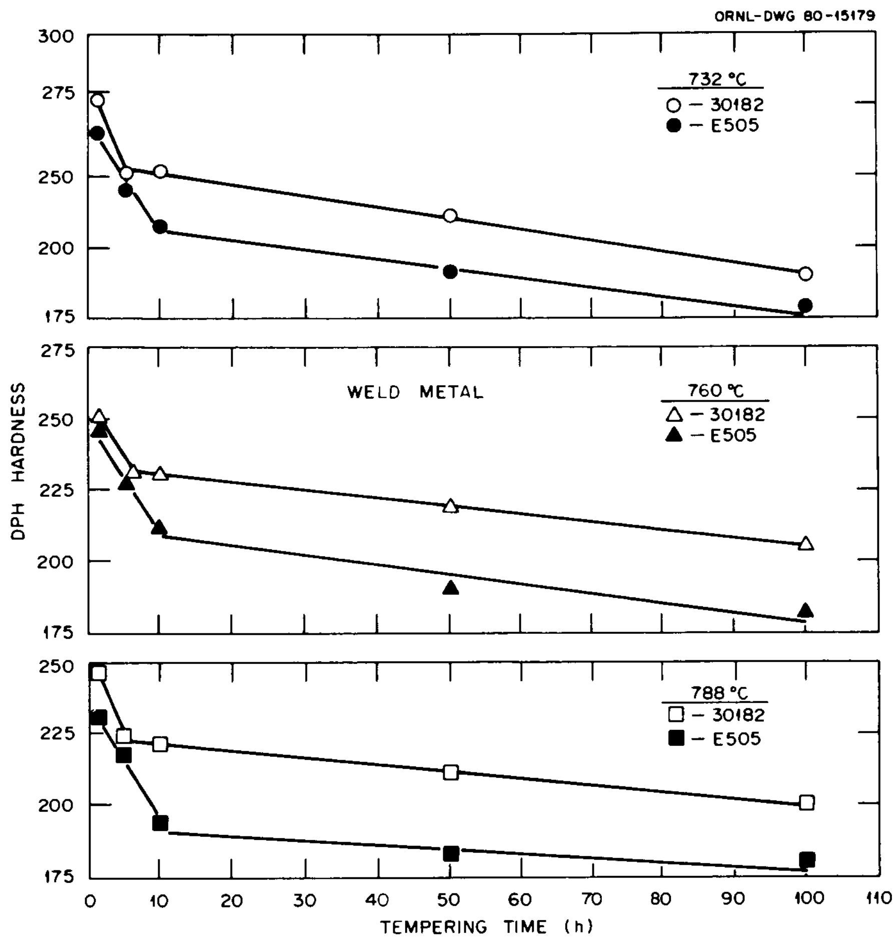

Fig. 10. Effect of PWHT time and temperature on the hardness of modified 9Cr-1Mo steel welds. Note the higher hardness retained in the weld made with modified filler metal (3012) rather than standard filler metal (E505).

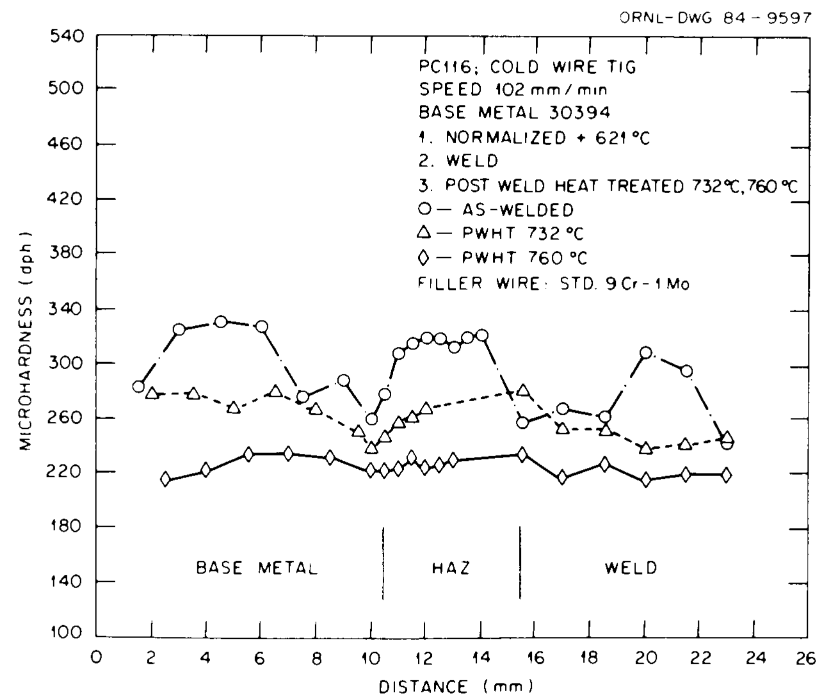

Fig. 11. Hardness traverse data for GTA weld PC-116 showing that a 760°C PWHT is necessary to eliminate the overtempered region in partially tempered base plate.

minimum values and plotting the ratio as a function of test temperature (Fig. 12). Unnormalized reduction of area values are plotted in Fig. 13. These figures show the following:

1. Yield strengths [Fig. 12(*a*)] of all weldments made by GTA, SMA, and SA processes exceed the minimum values for the base metal to 600°C. The only two points that fall below the minimum represent data from tests at very high test temperatures.
2. Ultimate tensile strength [Fig. 12(*b*)] for all but two weldments meet or exceed the base metal minimum value.
3. Reductions of area values for all weldments exceed the minimum value of 55% for the base metal for all test temperatures.

Based on these results, we conclude that modified 9Cr-1Mo weldments should meet the base metal minimum properties.

CREEP PROPERTIES

Creep data for all welding procedures and test temperatures have been combined by normalizing to base metal average or minimum properties. Weldment stress ratios based on the base metal average are plotted in Fig. 14. The lines represent the equal strength ratio and the basis for allowable stresses in ASME Code, Sect. VIII. This figure shows that the basis used for determining the allowable stresses for ASME Code, Sect. VIII, is met by the creep-rupture data of modified 9Cr-1Mo weldments.

Figure 15 is a similar stress-rupture plot, but it is based on normalization by base metal minimum properties. An alternative allowable stress criterion for Sect. VIII (0.80 × minimum stress to rupture) and the S_t criteria for Code Case N-47 (0.67 × mininum stress to rupture) are also included in this figure. The criterion of 0.80 times minimum stress to rupture is met by the creep rupture data of modified 9Cr-1Mo weldments. This figure shows also 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.

Figures 16, 17 and 18 show the stress ratio plots (based on base metal average) for the GTA, SMA, and SA processes, respectively. These

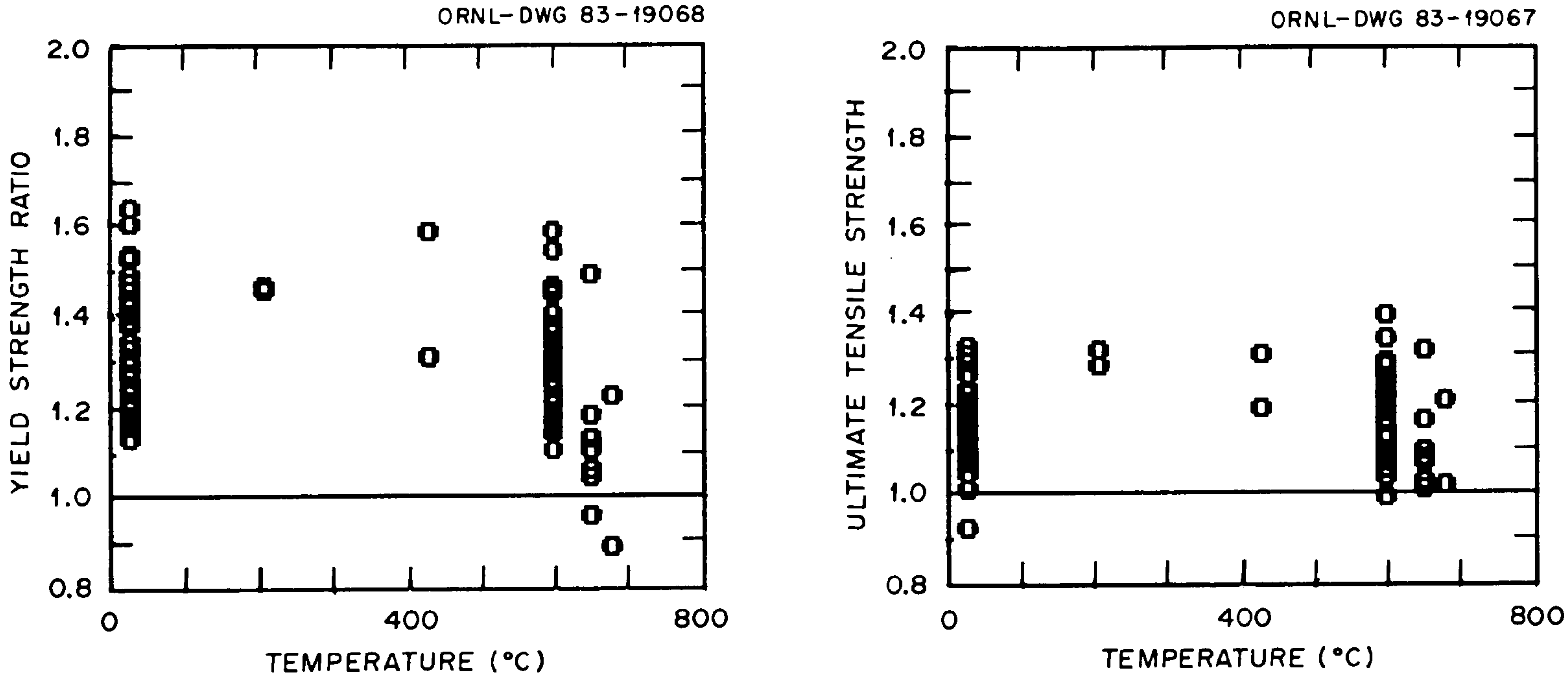

Fig. 12. Strengths ratios (weldment to base metal minimum) for weldments of modified 9Cr-1Mo steel. Weldment data are for both standard and modified 9Cr-1Mo filler wire and for all three welding processes (GTA, SMA, and SA). A unity line representing equal strength of base metal and weldment is included. (*a*) Yield strength. (*b*) Ultimate tensile strength.

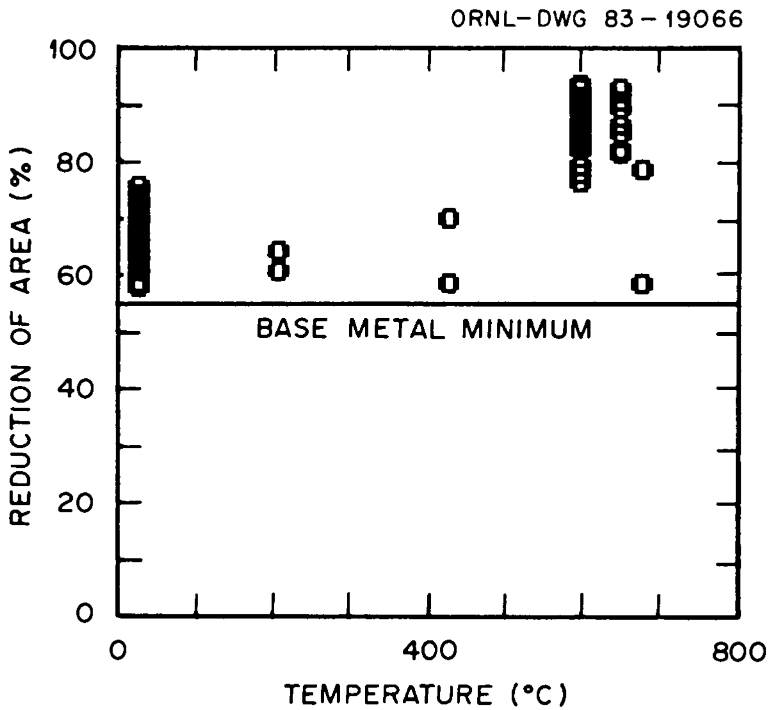

Fig. 13. Reduction of areas as a function of test temperature. Weldment data are for both the standard and modified 9Cr-1Mo filler wire and for all three welding processes (GTA, SMA, and SA). A base metal minimum value line of 55% at room temperature is included.

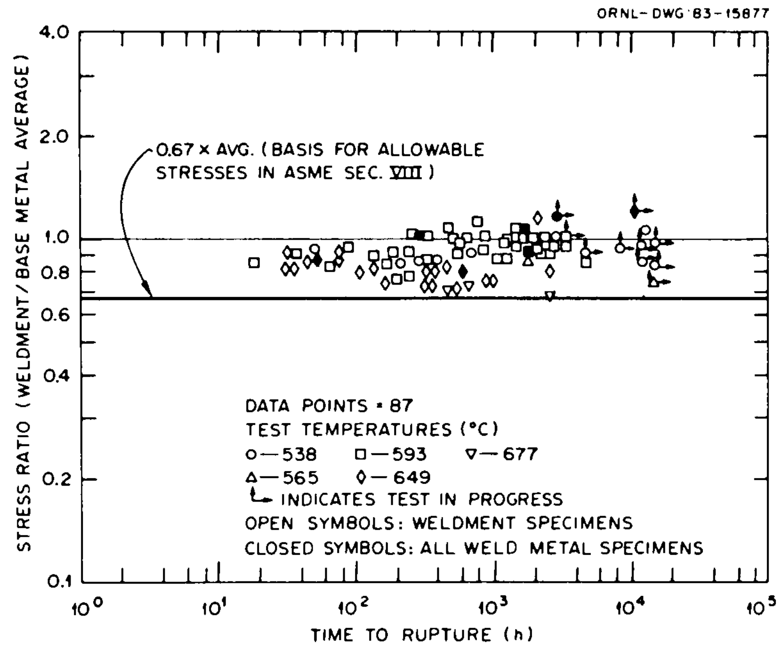

Fig. 14. Stress ratio (weldment to base metal average) as a function of time to rupture. Weldment data are for both the standard and modified 9Cr-1Mo filler wire and for all three welding processes (GTA, SMA, and SA). Data are for test temperatures of 538, 565, 593, 649, and 677°C. Stress ratios of unity, representing equal strengths, and 0.67, representing the ASME Code, Sect. VIII, criteria for allowable stresses, are also included.

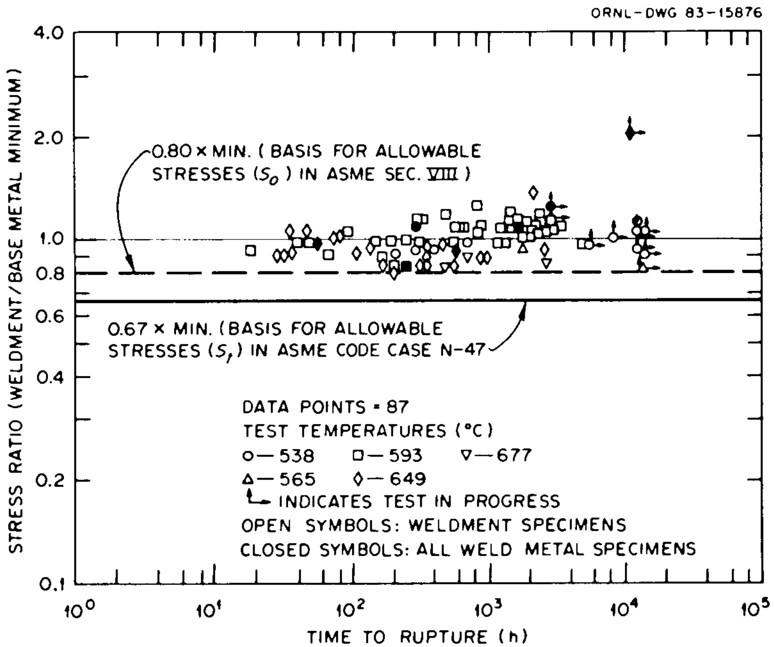

Fig. 15. Stress ratio (weldment to base metal minimum) as a function of time to rupture. Weldment data are for both the standard and modified 9Cr-1Mo filler wire and for all three welding processes (GTA, SMA, and SA). Data are for test temperatures of 538, 565, 593, 649, and 649°C. Stress ratios of unity, representing equal strengths; 0.80, the criterion for allowable stresses in ASME Code, Sect. VIII; and 0.67, the criterion for allowable stresses in ASME Code Case N-47, are also included.

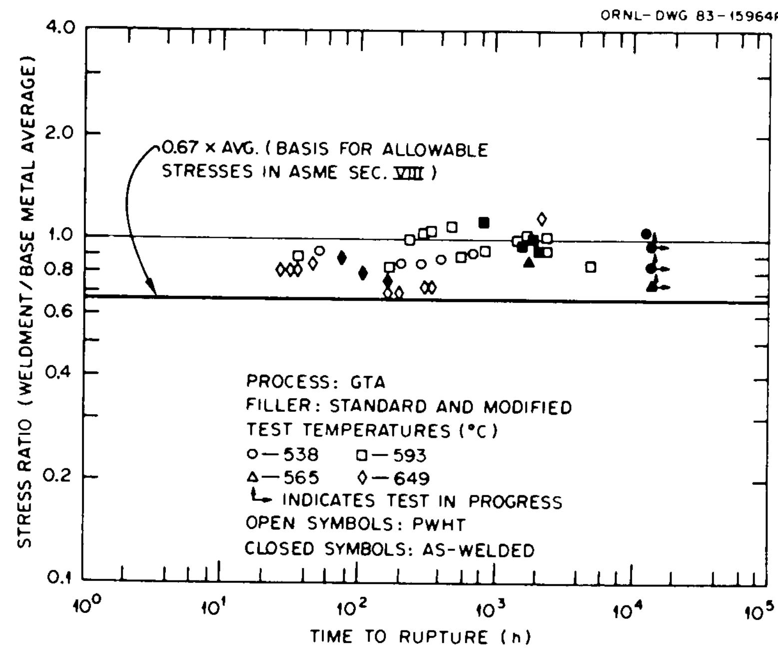

Fig. 16. Stress ratio (weldment to base metal average) as a function of time to rupture for GTA weldments of both standard and modified 9Cr-1Mo filler wire compositions. Data are for test temperatures of 538, 595, 649, and 677°C. Stress ratios of unity, representing equal strength, and 0.67, the criterion for allowable stresses in ASME Code, Sect. VIII, are also included.

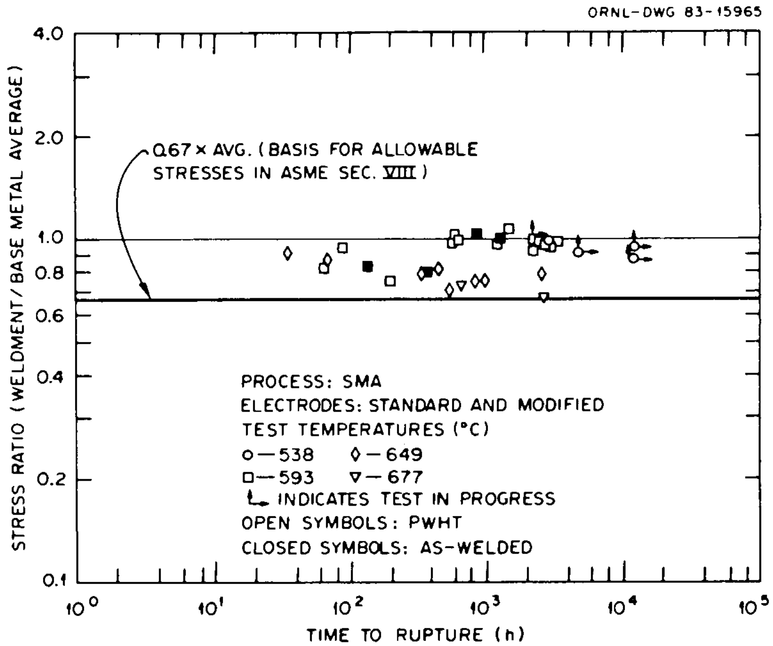

Fig. 17. Stress ratio (weldment to base metal average) as a function of time to rupture for SMA weldments of both standard and modified 9Cr-1Mo filler wire compositions. Data are for test temperatures of 538, 595, 649, and 677°C. Stress ratios of unity, representing equal strength, and 0.67, the criterion for allowable stresses in ASME Code, Sect. VIII, are also included.

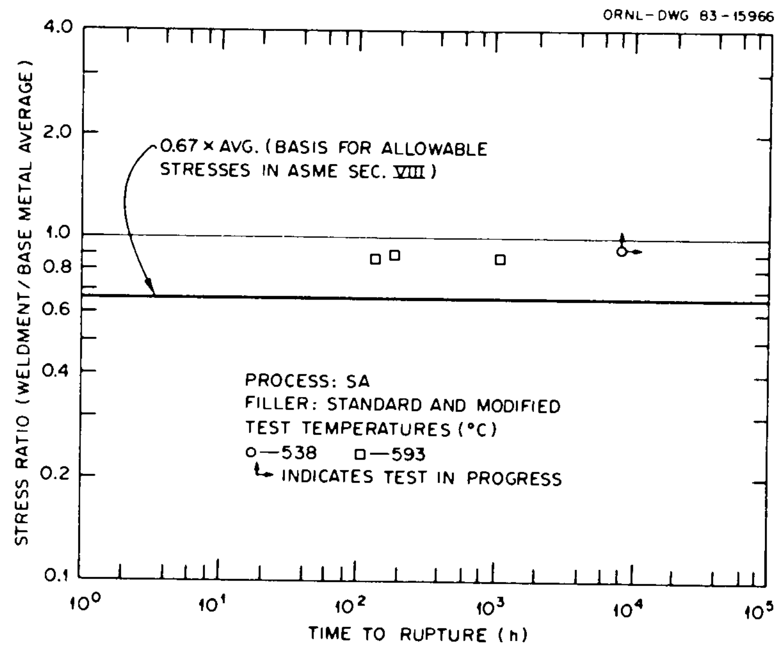

Fig. 18. Stress ratio (weldment to base metal average) as a function of time to rupture for SA weldments of both standard and modified 9Cr-1Mo filler wire compositions. Data are for test temperatures of 538 and and 593°C. Stress ratios of unity, representing equal strength, and 0.67, the criterion for allowable stresses in ASME Code, Sect. VIII, are also included.

Data taken from Klueh and Canonico[7] show that, if carbon in the filler wire is not specified, data for the 2.25Cr-1Mo weldment specimens can fall below the line of equal strength. Data on the weldment strength ratio of modified 9Cr-1Mo weldments appear to behave very similarly to those observed for 2.25Cr-1Mo weldments.

CHARPY IMPACT PROPERTIES

Charpy impact data on welds are available for the standard and modified filler and electrode compositions and for various PWHT conditions. Figure 19 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) with a range from 25 to 125°C. When GTA welds are tested after a 732°C PWHT for 1 h (Fig. 20), 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. 21) show a transition temperature only slightly lower than that observed for 732°C PWHT. When GTA welds of standard filler wire composition are tested after 732°C PWHT (Fig. 22), the 68-J transition temperature is below 10°C. Compared with modified 9Cr-1 Mo filler wire, the standard wire gives about 40°C lower transition temperature. The upper-shelf energies are the same for both cases.

The Charpy impact energy data at room temperature for SMA welds of modified composition are presented in Table 11. This weld was postweld heat-treated at 750°C for 1 h. The data for five tests exceed the 68-J minimum goal established for this alloy when welds are made with the recommended SMA deposit composition.

The Charpy impact energy curves for SA welds are shown in Fig. 23. 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. Charpy data for modified 9Cr-1Mo composition SA weld deposits were discussed in the welding process evaluation section of this report.

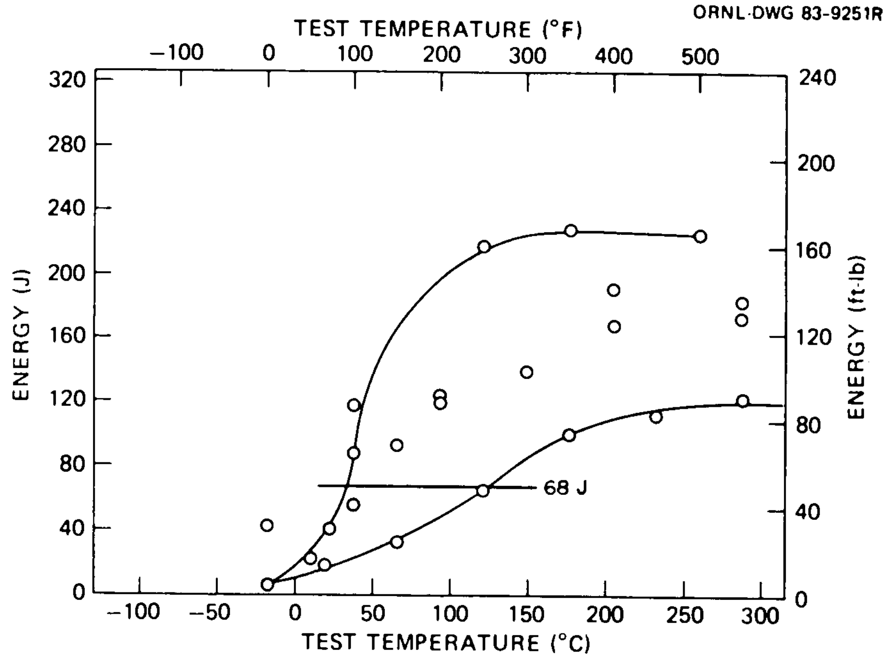

Fig. 19. Charpy impact data on GTA arc welds of modified 9Cr-1Mo. The filler wire was modified 9Cr-1Mo, and the welds were not postweld heat-treated. Curves through the data show the upper and lower bounds.

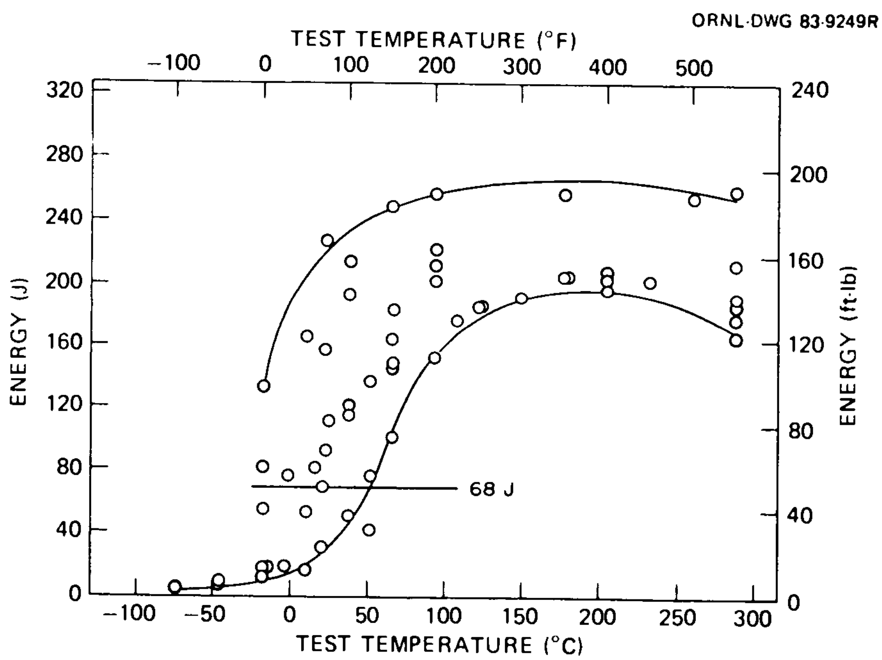

Fig. 20. Charpy impact data on GTA welds of modified 9Cr-1Mo. The filler wire was modified 9Cr-1Mo, and the welds were PWHT 1 h at 732°C. Curves through the data show the upper and lower bounds.

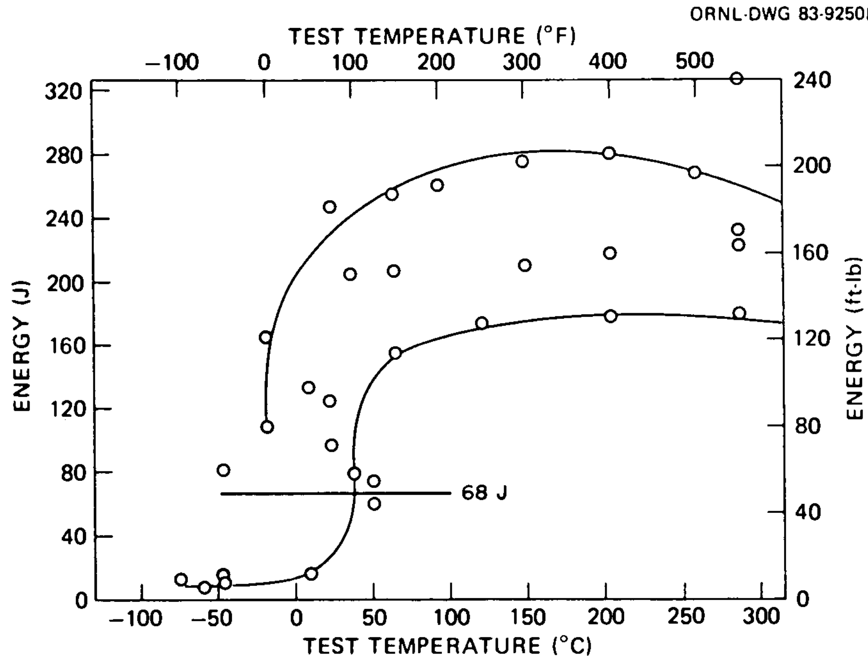

Fig. 21. Charpy impact data on GTA welds of modified 9Cr-1Mo. The filler wire was modified 9Cr-1Mo, and the welds were PWHT 1 h at 760°C. Curves through the data show the upper and lower bounds.

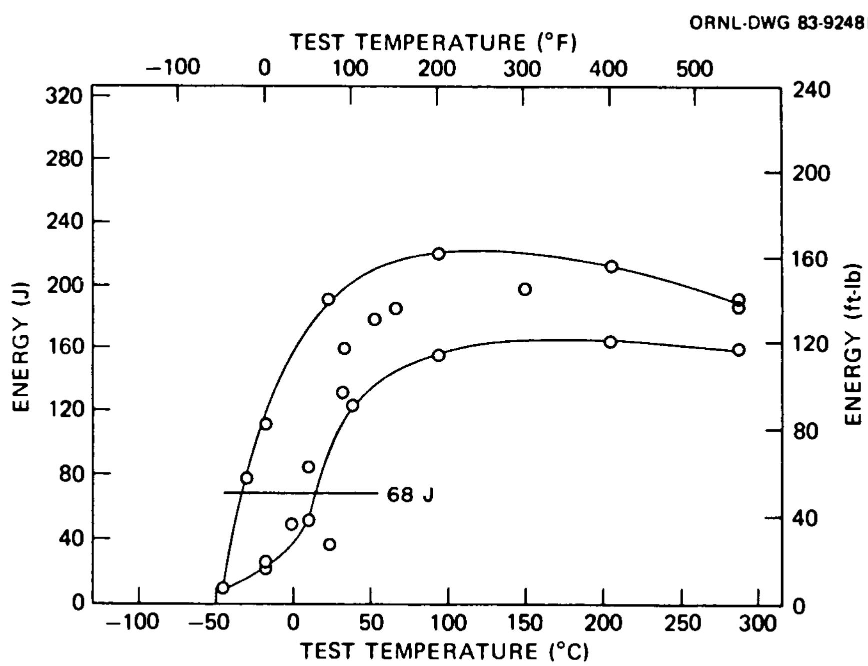

Fig. 22. Charpy impact data on GTA welds of modified 9Cr-1Mo. The filler wire was standard 9Cr-1Mo, and the welds were PWHT 1 h at 732°C. Curves through the data show the upper and lower bounds.

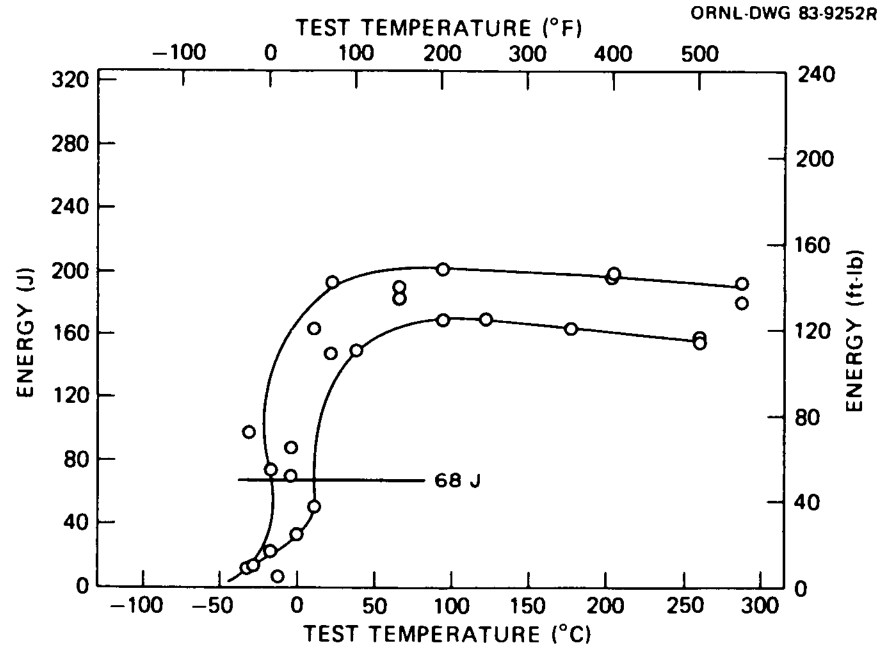

Fig 23. Charpy impact data on SA welds of modified 9Cr-1Mo. The filler wire was standard 9Cr-1Mo, and the welds were PWHT 1 h at 732°C. Curves through the data show the upper and lower bounds.

DISSIMILAR METAL WELDMENTS

PREPARATION

Transition joint welds between modified 9Cr-1Mo steel and austenitic stainless steel were prepared for a pipe test in the Sodium Components Test Loop (SCTL) at the Energy Technology Engineering Center. The test article consisted of modified 9Cr-1Mo steel pipe 232 mm in diam, 12.7-mm wall thickness and a 610 mm long. The pipe was safe ended with type 304L stainless steel spool pieces 152 mm long on each end. The joint between modified 9Cr-1Mo and type 304 was made by GTA welding with ERNiCr-3 filler wire. A PWHT of 732°C for 1 h was given the spool piece after welding. The details of the fabrication and inspection have been reported.[8] No unacceptable defects were present. The 9Cr-1Mo spool piece was installed in the sodium loop and performed satisfactorily for the life of the test.

MECHANICAL PROPERTIES

Mechanical property testing was performed on an additional weldment of the same materials produced by identical procedures. Tensile testing was conducted on specimens from the 9Cr-1Mo pipe, the 304L stainless steel stock used for the safe ends, and the dissimilar metal weldments. Yield and ultimate tensile strength data on modified 9Cr-1Mo/ERNiCr-3/304L, modified 9Cr-1Mo base metal, modified 9Cr-1Mo/ERNiCr-3/316, and modified 9Cr-1Mo/ERNiCr-3/304L aged for 2000 h at 510°C show the following:

1. Both 0.2% yield and ultimate tensile strengths of modified 9Cr-1Mo/ERNiCr-3/304L and modified 9Cr-1Mo/ERNiCr-3/316 stainless steel joints joints were lower than the corresponding values for the 9Cr-1Mo base metal over the entire test temperature range. However, the failures were generally in the stainless steel base metal.
2. Thermal aging for 2000 h at 510°C produced no change in the yield and ultimate tensile strengths of modified 9Cr-1Mo/ERNiCr-3/304L specimens.
3. The total elongation values of weldment specimens were generally higher than those of the modified 9Cr-1Mo steel base metal.

Creep data on transition joints of modified 9Cr-1Mo/ERNiCr-3/304L and modified 9Cr-1Mo/ERNiCr-3/316 are presented in Table 13. These data were compared with modified 9Cr-1Mo base metal data. At 510°C, the rupture life of transition joint specimens equals the average rupture life of modified 9Cr-1Mo base metal. At 593 and 649°C, the rupture life of the transition joints equals or exceeds the rupture life obtained from a plot of stress to rupture versus the average time to rupture minus twice the standard error of estimate (SEE) for the base metal.[8] Creep data on modified 9Cr-1Mo transition joints were also compared with similar data for 2.25Cr-1Mo/ERNiCr-3 joints. This comparison showed that the rupture life of modified 9Cr-1Mo/ERNICr-3 joints is at least an order of magnitude longer than that of 2.25Cr-1Mo/ERNICr-3 joints, and creep rupture strength is double.[8] Additional long-term creep tests should be performed to validate these observations.

Table 13. Creep data on modified 9Cr-1Mo steel transition joint specimens with ERNiCr-3 weld metal

Test	Temperature (°C)	Stress (MPa)	Rupture time (h)
Modified 9Cr-1Mo/ERNiCr-3/304L			
23718	510	276	8046
23756	593	172	1368
23769	593	124	5014
23733	593	97	14042
23759	649	76	1092
Modified 9Cr-1Mo/ERNiCr-3/316			
23762	593	172	838
23684	593	145	2304

SUMMARY AND CONCLUSIONS

Two important objectives of the modified 9Cr-1Mo development program were to demonstrate the weldability of the alloy and to establish a weldment mechanical property data base. Through the interaction of government and private industry, these objectives have been accomplished. Hundreds of weldments have been produced for testing and evaluation, including the installation of modified 9Cr-1Mo tubing in steam plants. Considerable fabrication experience with the alloy has been gained through this work as has been shown in this report. Weldability has been found to be good.

Characterization of modified 9Cr-1Mo weldments has shown that with the nominal PWHT of 732°C the properties of weldments made with standard or modified filler wire are limited by the tempered zone strength. Weldment tensile properties exceed the minimum tensile properties for the 9Cr-1Mo base metal. Creep data analyses have shown that for rupture times below 1000 h, 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 for both filler wire compositions. Long-term creep data are needed on weldments for this alloy, but it appears that standard composition weld metal is adequate for welding modified 9Cr-1Mo steel. If the weldment is to be normalized and tempered or if other considerations require the strength, the modified composition weld metal should be used.

The availability of welding consumables can be a problem with a new material until producers manufacture adequate supplies of electrodes and filler wire in various diameters. Availability does not appear to present a serious concern at this time. As indicated, the standard 9Cr-1Mo composition weld metal provides adequate mechanical properties for many applications. Standard composition electrodes and filler wire are available from several sources. The modified composition consumables are being produced by a few suppliers now, and the number should increase depending on demand.

The following conclusions are derived from this work.

1. No major weldability problems are found with the modified 9Cr-1Mo steel. Testing and welding by several organizations has confirmed this conclusion.
2. Welding produces a tempered region of reduced hardness compared with the base metal in the HAZ of normalized and tempered chromium-molybdenum steels. Modified and standard 9Cr-1Mo, 2.25Cr-1Mo, and HT9 all exhibited similar behavior.
3. Both standard and modified composition filler metals and electrodes have been used to join modified 9Cr-1Mo steel with the GTA, SMA, and SA welding processes. Consumables of both types are available from commercial suppliers.
4. Tensile properties of weldments made by GTA, SMA, and SA welding processes usually exceed the minimum specified properties of the base metal.
5. The creep strength of weldments is lower than the average strength of the base metal for rupture times up to 1000 h, but it approaches the base metal average at longer times.
6. Transition joint weldments between modified 9Cr-1Mo steel and austenitic stainless steel have been successfully made and tested.

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REFERENCES

1. D. P. Edmonds and P. L. Sturgill, *Weldability of Modified 9Cr-1Mo Steels*, ORNL/TM-6890, August 1979.

2. P. J. Grobner and T. Wada, *Testing of 9Cr-1Mo-V-Nb Steel*, Climax Report J-4617, Climax Molybdenum Company, Ann Arbor, Mich., 1981.

3. V. Biss, *Metallographic Investigation of Soft Regions Near Heat Affected Zones of Modified 9 Cr-1 Mo, HT-9, and 2.25 Cr-1 Mo Steel Weldments*, Report J-4747, AMAX Materials Research Center, Ann Arbor, Mich., Mar. 8, 1982.

4. C. D. Lundin, M. W. Richey, and J. A. Henning, *Transformation, Metallurgical Response and Behavior of the Weld Fusion Zone and Heat Affected Zone in Cr-Mo Steels for Fossil Energy Applications, Final Report for Period April 1983 to December 1984*, ORNL/Sub/81-7685/0177, April 1986.

5. M. L. Santella and V. K. Sikka, "Weldability of Modified 9 Cr-1 Mo Steel," pp. 2-69–2-80 in *Advanced Alloy Technical Program Annual Progress Report for Period Ending September 30, 1984*, ORNL/MSP/1.7-84/1, January 1985.

6. V. K. Sikka and P. Patriarca, *Analysis of Weldment Mechanical Properties of Modified 9Cr-1Mo Steel*, ORNL/TM-9045, May 1984.

7. R. L. Klueh and D. A. Canonico, "Creep-Rupture Properties of 2.25Cr-1Mo Steel Weldments with Varying Carbon Content," *Weld. J. (Miami)* **55**(12), 381-88-S (December 1976).

8. V. K. Sikka, G. M. Goodwin, J. F. King, and K. V. Cook, *Fabrication of Modified 9Cr-1Mo Steel Test Article for Exposure in Sodium Components Test Loop at Energy Technology Engineering Center*, ORNL-6034, April 1984.

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