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Weldability of Modified 9 Cr-1 Mo Steels

D. P. Edmonds
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WELDABILITY OF MODIFIED 9 Cr-1 Mo STEELS

D. P. Edmonds and P. L. Sturgill

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WELDABILITY OF MODIFIED 9 Cr-1 Mo STEELS*

D. P. Edmonds and P. L. Sturgill†

ABSTRACT

We are evaluating modified 9 Cr-1 Mo steels with improved mechanical properties for use in advanced breeder reactor systems. Additions of niobium, vanadium, and a reduction of silicon have resulted in good high-temperature creep strength and ductility. However, high concentrations of some minor elements have contributed to hot cracking during welding of ferritic steels. Therefore, we have performed Tigamajig (modified Varestraint) tests to investigate heat-affected-zone (HAZ) hot cracking in these experimental heats. We investigated ten small (36 kg each) electroslag remelted (ESR) heats, one large (2300-kg) ESR heat, and one heat of 2 1/4 Cr-1 Mo steel (for a reference material). Highly restrained welds were made with the most crack-sensitive experimental heat (from Tigamajig results) to determine the relevance of the Tigamajig tests.

We determined that under normal welding conditions HAZ hot cracking should not be a problem with any of the 11 experimental heats. However, care should be taken with high concentrations of minor elements since they tend to increase sensitivity to cracking. There were no obvious correlations between crack sensitivity and either chromium equivalent, δ-ferrite content, or the amount of very large grains (elephant grains) in the structures.

INTRODUCTION

We are developing modified 9 Cr-1 Mo steels for use in advanced breeder reactor systems. Minor alloy additions of niobium and vanadium significantly improve the elevated-temperature properties of the 9 Cr steels. Also, additions of silicon (over 0.5% for some British steels) significantly improve breakaway oxidation resistance of these steels. Programs are under way in the U.S. to assess how alloy modifications affect the mechanical properties, corrosion resistance, and ease of

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*Work performed under DOE/RRT 189 OH038, Development of Ferritic 9%-Cr Alloy.

†Student at the University of Tennessee.

fabrication of these steels. The effects of alloy additions on weldability of the modified 9 Cr-1 Mo steels are also being investigated.

Several factors are being considered for welding of these steels:

1. mechanical properties of the weldment (weld metal, HAZ, and base metal);
2. hot cracking and cold cracking in the weld metal and HAZ;
3. reheat cracking in the HAZ, and
4. effects of preheat, postweld heat treatment (PWHT), and hydrogen on mechanical properties of weld metal and HAZ.

Optimum shielded metal-arc (SMA) weld metal compositions (based on creep and impact resistance) are being developed as part of another program. Therefore, early work in the ORNL program has been confined to base metal HAZ studies. To date, we have concentrated on HAZ hot cracking in electroslag remelted (ESR) heats of modified 9 Cr-1 Mo steels.

Several minor elements have been associated with liquation cracking (hot cracking) in the ferritic steels. Sulfur has long been recognized[1] as an element that can lead to hot cracking in ferritic steels. Excess sulfur forms a low-melting-point FeS eutectic, which collects at grain boundaries and reduces the strength of the boundaries at high temperatures.[2] Manganese is often added to these steels since it has a greater affinity for sulfur than iron and forms a sulfide with a melting temperature higher than the bulk solid. These manganese additions (usually 50 or more times greater than the sulfur contents) successfully eliminate hot cracking in most cases. Other elements that contribute to hot cracking are silicon, phosphorus, and nickel.[3] Increases in carbon content produce strengthening of grains and higher localized stresses at grain boundaries, thereby increasing the tendency for hot cracking. In general, elements (including niobium and silicon) that form low-melting compounds or phases can contribute to liquation cracking in these steels. Therefore, in modified 9 Cr-1 Mo steels (where niobium and boron are added purposely) hot cracking could become a problem if these minor element contents are too high.

DEVELOPMENT PROGRAM

We have performed Tigamajig (modified Varestraint) tests on selected ESR heats to determine relative crack susceptibilities of these materials and to determine general liquation cracking tendencies, resulting from microstructural and/or compositional changes. Similar tests (Varestraint) have been performed on 9 Cr-1 Mo steels in other countries, including the Netherlands,[4] Japan,[5] and France.[6] The Varestraint test was first developed by Savage and Lundin[7] at Rensselaer Polytechnic Institute to quantitatively evaluate susceptibility to hot cracking. A later modification of this test, the Tigamajig test,[8] permits smaller specimens to be tested. For our program we used the spot Tigamajig test, as shown schematically in Fig. 1. In this test a gas tungsten-arc (GTA) spot weld is made on the surface of a 5 by 25 by 114 mm specimen (Fig. 2), which is then strained to a predetermined value during solidification of the weld pool. Since limited material was available for this study, we used a modified Tigamajig specimen (which had previously been used at ORNL[9]). Test sections (5 by 25 by 38 mm) were machined from each of the heats of material, and end pieces (cold-rolled steel) were welded in place by using the electron beam (EB) process (Fig. 3). Since the end pieces were not killed steel, a small amount of aluminum powder was added to the EB weld to eliminate porosity.

Specimens taken parallel and perpendicular to the rolling direction for each selected heat were tested at two strain levels each (four specimens per heat), 2.89 and 4.92% (Fig. 4). Insufficient test material made it impossible to run the complete range of strain values to determine a cracking threshold. Therefore, we chose relatively high strains to ensure that cracking would occur. Cracks in the spot-weld HAZ were measured with a toolmaker's microscope (at 50× magnification). We recorded the total crack length and longest crack per specimen.

We tested ten small ESR heats (36 kg each) made at Combustion Engineering, Chattanooga, Tennessee, and a large (2300-kg) ESR heat (heat 91887) made at Carpenter Technology (Cartech), Reading, Pennsylvania. We chose the ten small heats because either they had chemical compositions

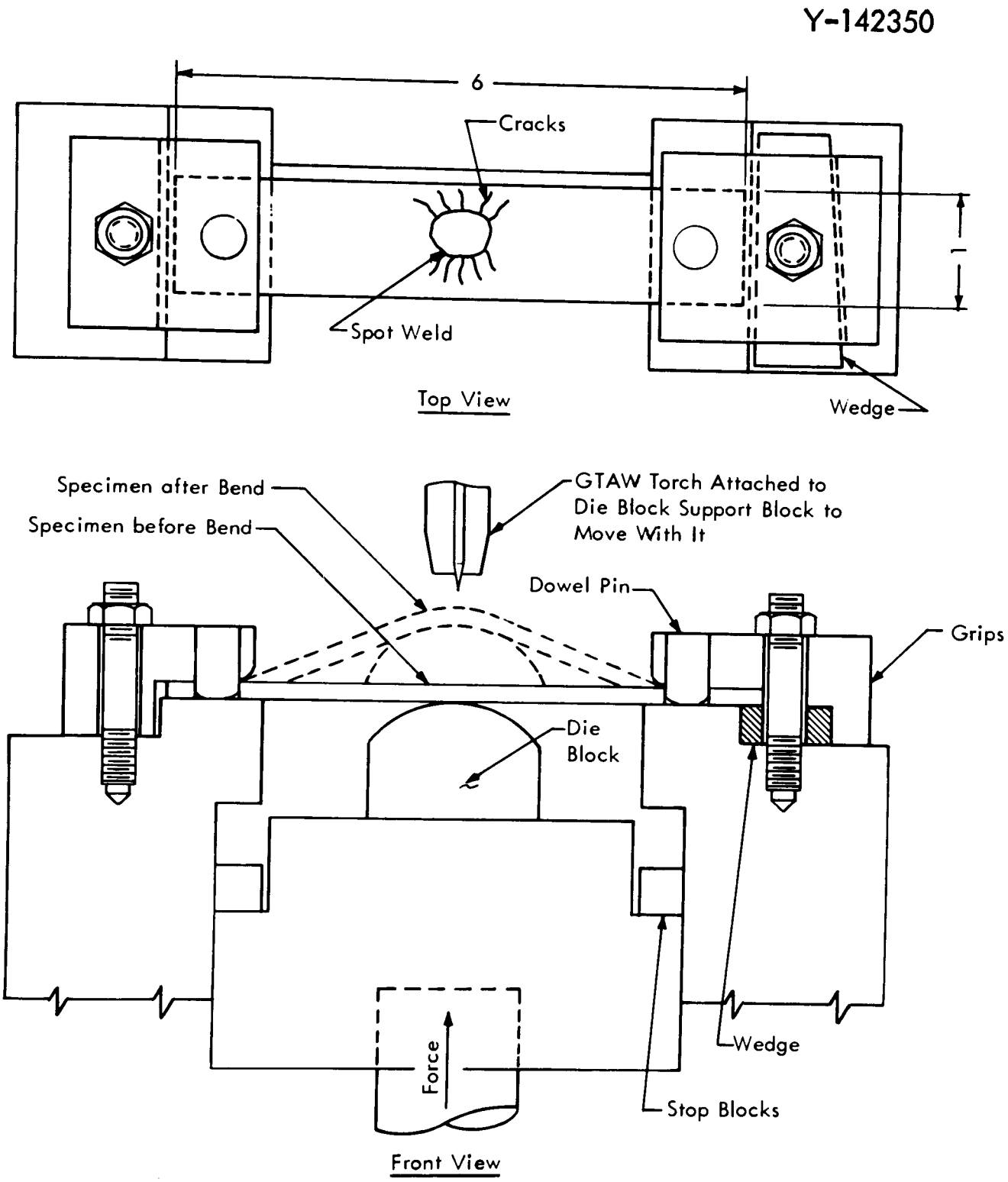

Fig. 1. The Tigamajig Test Device. Dimensions in top view are in inches. 1 in = 25 mm.

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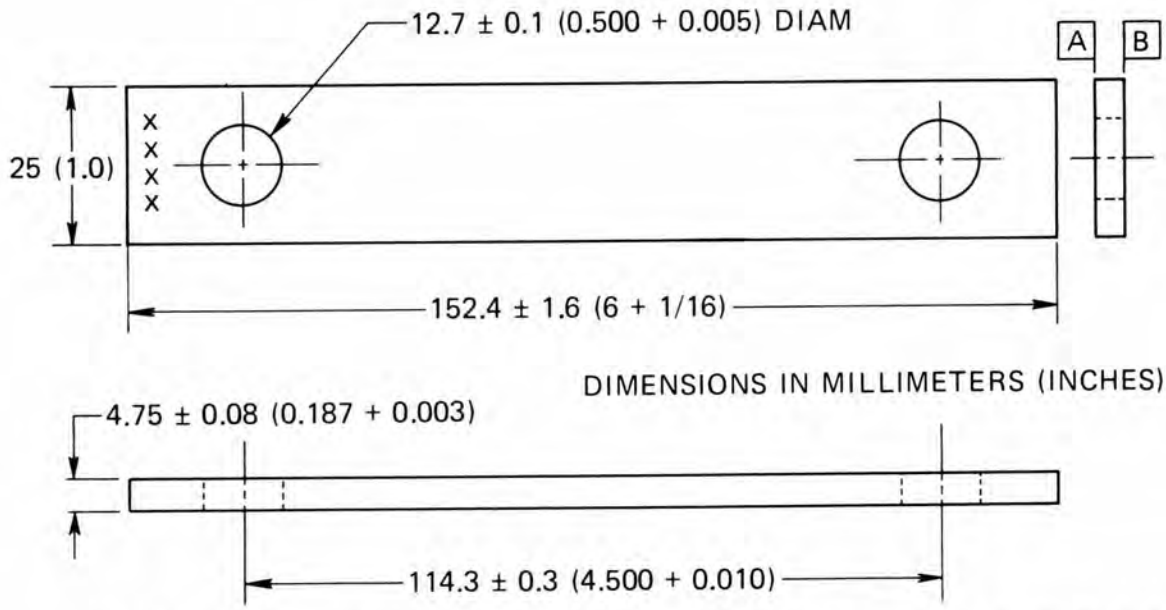

Fig. 2. Tigamajig Specimen Specification: 0.81-μm (32-μin.) Finish on Surfaces A and B, Edges Flat and Parallel to Within 0.38 mm (0.015 in.), and Surfaces A and B Flat and Parallel to Within 0.13 mm (0.0051 in.).

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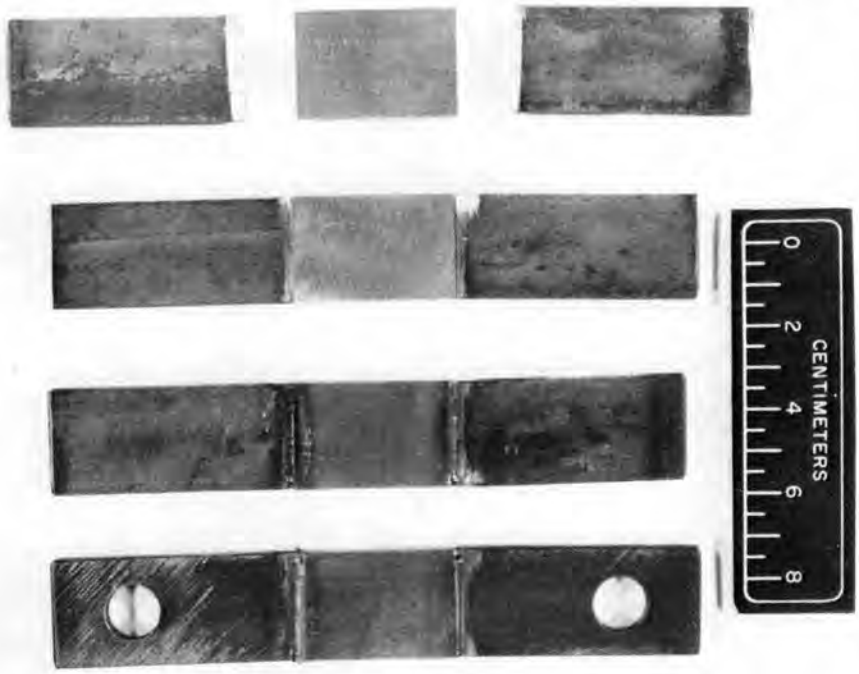

Fig. 3. Sequence of Fabrication of Modified Tigamajig Specimens for this Study.

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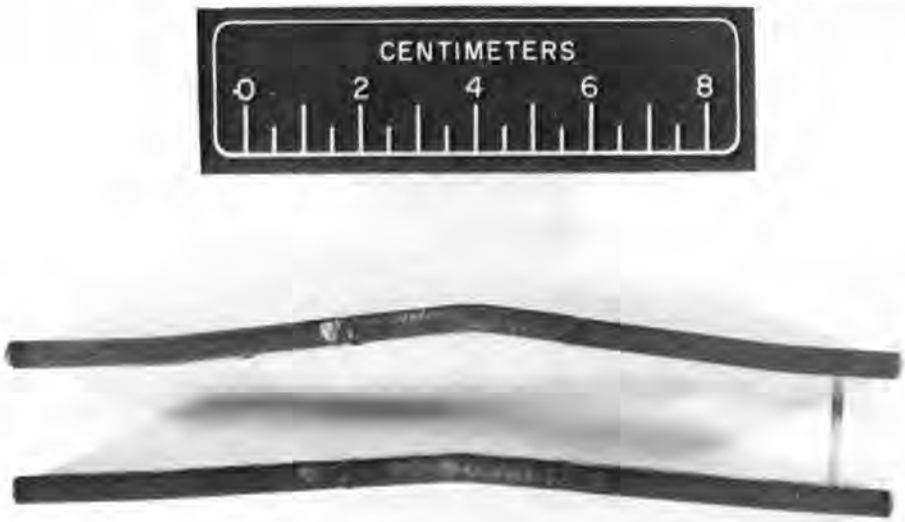

Fig. 4. Typical Tested Tigamajig Specimens (Side View) with Augmented Strains of 2.89% for the Bottom Specimen and 4.92% for the Top Specimen.

and/or structures where hot cracking may be likely, or they exhibited good mechanical properties (i.e., might be similar to optimum composition and structure). Also, one heat of 2 1/4 Cr-1 Mo steel was tested as a reference material. Chemical analyses of each of these heats were performed by using spectrographic, x-ray, and wet chemical techniques. These results are presented in Table 1. The 9 Cr-1 Mo test materials were in the normalized and tempered condition (austenitized at 1083°C for 3.6 ks, air cooled, and tempered at 760°C for 3.6 ks). Pertinent information (Cr equivalent, δ-ferrite content, total residual element content, silicon content, relative number of elephant grains, and relative grain size) for each of these heats is listed in Table 2. The elephant-grained materials have a duplex structure with very large grains surrounded by much smaller ones. A small percentage of elephant grains in the structure does not appear to affect mechanical properties of these materials.

The Tigamajig spot welds were made with a dc strait polarity gas tungsten-arc welder. A weld spot approximately 3 mm in diameter was obtained by using a large electrode to work distance and accurate control of the current and arc time (Table 3). These welding parameters made consistent arc spot welds (Fig. 5) on the 9 Cr-1 Mo specimens and achieved

Table 1. Chemical Compositions of 9 Cr-1 Mo Heats Used in Weldability Test

Heat	Content, wt %																			
	C	Si	Mn	S	P	Cr	Mo	W	Nb	V	Ti	Ni	N	Al	B	Cu	Co	As	Sn	O
91887	0.097	0.08	0.38	0.005	0.007	9.22	1.01	<0.01	0.15	0.22	<0.01	0.08	0.038	0.003	0.001	0.01	0.018			0.005
370	0.0515	0.02	0.35	0.0085	0.0055	8.25	0.79	<0.01	0.045	0.11	<0.01	0.05	0.038	0.003	<0.001	0.02	0.0155	<0.001	<0.001	0.0095
366	0.0805	0.03	0.335	0.0105	0.0085	8.595	1.02	<0.01	0.050	0.21	<0.01	0.05	0.0345	0.0045	<0.001	0.02	0.016	<0.001	0.001	0.012
374	0.0595	0.06	0.345	0.009	0.0065	8.585	0.995	<0.01	0.080	0.12	<0.01	0.05	0.053	0.0065	0.001	0.02	0.015	<0.001	0.001	0.0110
371	0.0480	0.095	0.545	0.0085	0.0080	9.8	2.055	<0.01	0.065	0.125	<0.01	0.05	0.0265	0.0105	0.0015	0.02	0.0165	0.001	0.001	0.0095
367	0.0820	0.03	0.345	0.0115	0.0085	8.275	1.020	<0.01	0.060	0.135	0.01	0.05	0.0345	0.0035	0.001	0.02	0.0145	<0.001	0.001	0.0145
383	0.0555	0.075	0.810	0.0065	0.008	8.92	1.425	<0.01	0.08	0.030	<0.01	0.06	0.0270	0.0080	0.0015	0.040	0.0225	<0.001	0.001	0.0095
382	0.0805	0.09	0.745	0.004	0.008	9.040	1.185	<0.01	0.125	0.170	<0.01	0.05	0.0290	0.0095	0.002	0.035	0.0180	<0.001	<0.001	0.0120
376	0.0820	0.065	0.36	0.0090	0.0065	8.65	1.03	<0.01	0.060	0.105	<0.01	0.06	0.0665	0.0065	0.0015	0.020	0.0150	<0.001	<0.001	0.0115
378	0.0660	0.080	0.385	0.0080	0.0085	8.615	0.855	<0.01	0.065	0.120	<0.01	0.05	0.0395	0.0105	0.0015	0.020	0.0150	<0.001	0.001	0.007
377	0.0695	0.110	0.40	0.0085	0.0076	8.805	1.025	<0.01	0.065	0.130	<0.01	0.05	0.0385	0.0085	0.0015	0.020	0.0150	<0.001	0.001	0.014
KB154	0.110	0.03	0.51	0.007	0.011	2.25	0.99	<0.01	<0.01	0.006	<0.01	0.07	0.015	0.018	<0.001	0.06	0.010	0.011	0.007	

Table 2. Heats of Steel Used for Tigamajig Study

Heat	Cr Equivalent	δ-Ferrite	Total Residuals[a] (wt %)	Si Content	Elephant Grains (Relative)	Grain Size[b]	Comments
370	8.9	None	0.128	0.020	None	Coarse	Coarse grains
366	10.3	None	0.155	0.050	None	Coarse	High S
KB154							2 1/4 Cr-Mo reference
374	9.8	None	0.209	0.060	None	Fine	Poor mechanical properties
887	10.1	None	0.283	0.080	None	Fine	Large ESR heat, high Nb
371	16.4	∿40%	0.235	0.095	None	Fine	High δ-ferrite
367	9.1	None	0.160	0.030	Many	Fine	Elephant grains
383	11.0	∿1%	0.253	0.075	None	Fine	Good toughness, poor creep
382	11.1	∿3%	0.302	0.090	None	Fine	High B
376	8.3	None	0.194	0.065	Medium	Fine	Good mechanical properties
378	9.4	None	0.220	0.080	Few	Fine	Good mechanical properties
377	10.3	None	0.324	0.110	None	Fine	High Si

[a]Total P + S + Nb + Ti + Al + B + Cu + Co + As + Sn + Si.

[b]Coarse — ASTM grain size 5–6, fine — ASTM grain size 7–8.

Table 3. Tigamajig Parameters Used in Testing the 9 Cr-1 Mo Alloy

Electrode to work distance	12.7 mm
Electrode type	AWS EWTH-2
Electrode diameter	1.6 mm
Current, A	87 ± 2
Voltage, V	17 ± 1
Arc time, s	26 ± 1
Shielding gas	Argon (99.995% pure)
Gas flow rate	0.39 ± 0.004 liters/s

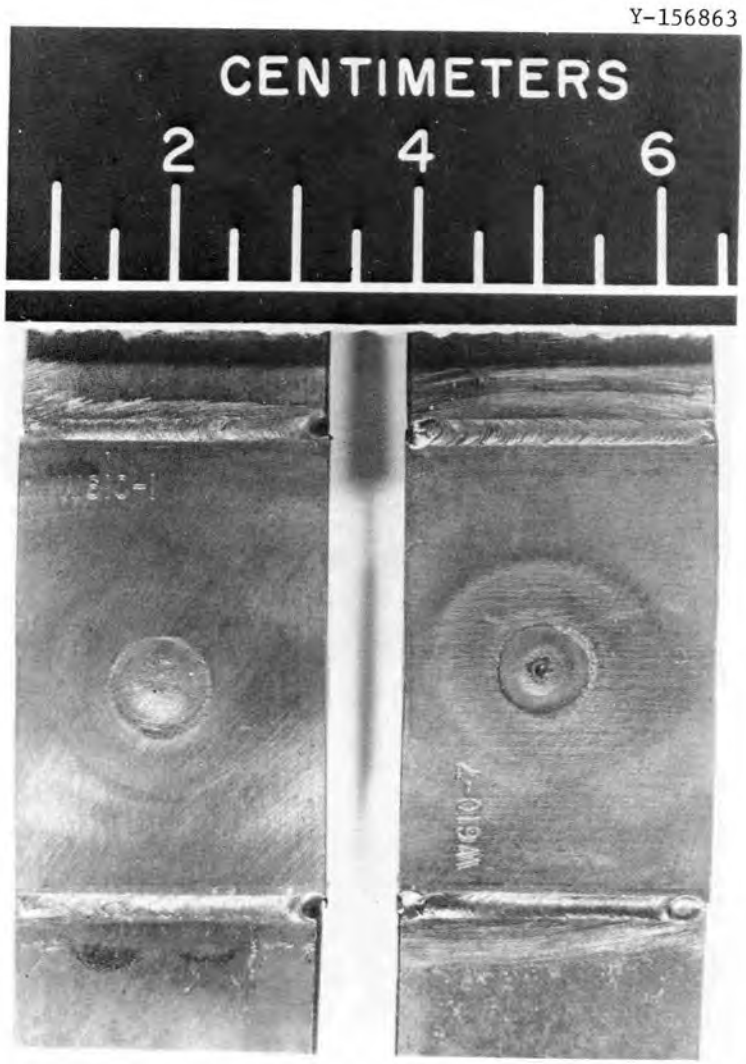

Fig. 5. The Consistency of the Tigamajig Spot Welds.

sufficient thermal stability for reproducible cracking data. Specimens were strained before the weld puddle was completely solidified so that most of the cracks occurred in the weld HAZ (fusion zone cracks backfilled with liquid).

TIGAMAJIG RESULTS

Results of this study are presented in Table 4, and the data are arranged in the order of the least to most susceptible to hot cracking (on the basis of total crack length). Specimens taken transverse to the rolling direction tended to have higher total crack lengths than longitudinal specimens. Also, higher strain values produced much higher total crack lengths than lower strains, except for the more crack-sensitive heats of material. Specimen orientation and strain values did not significantly affect the longest crack values.

The least crack sensitive was heat 370, which has a coarse grain structure (ASTM grain size 5–6) and a low total residual element concentration. The most crack sensitive was heat 377, which has a fine grain structure (ASTM grain size 7–8) and a high total residual element concentration. In the least to most susceptible sequence the reference 2 1/4 Cr-1 Mo heat ranked third, while the large Cartech heat was fifth out of the 12 heats. There were no obvious correlations between crack sensitivity and either chromium equivalent, δ-ferrite content, or amount of elephant grains. In general, coarse grain materials appear to be less sensitive to cracking than the finer grain materials. Furthermore, crack sensitivity tended to increase both with total residual element content (Fig. 6) and with increases in silicon (Fig. 7). We should note that the data shown in Figs. 6 and 7 may not be definitive since the expected variation (resulting from measuring accuracy) in total residual element content is ±0.09% and in the silicon content is ±0.02%. The wide scatter band in these two figures results partly from these variations in concentration data. There were no correlations between cracking and concentration of any other element.

Table 4. Results from Tigamajig Testing of Modified 9 Cr-1 Mo heats

Heat	Average Total Crack Length per Specimen, mm[a]					Longest Crack, mm				
	Longitudinal Specimens	Transverse Specimens	2.89% Strain	4.92% Strain	All Specimens	Longitudinal Specimens	Transverse Specimens	2.89% Strain	4.92% Strain	All Specimens
370	6.7	5.5	4.0	8.2	6.1	0.69	0.69	0.69	0.53	0.69
366	12.5	15.3	12.2	15.6	13.9	0.80	0.70	0.69	0.80	0.80
KB154					14.7					0.50
374	17.8	21.6	18.0	21.4	19.7	0.84	1.02	1.02	0.84	1.02
887	20.2	25.0	18.8	26.4	22.6	0.90	0.84	0.75	0.90	0.90
371	23.7	31.0	23.9	30.7	27.4	0.84	1.29	0.87	1.29	1.29
367	26.8	31.9	31.7	27.0	29.4	1.11	1.38	1.38	1.11	1.38
383	31.8	36.9	29.7	38.9	34.4	1.00	1.42	1.42	1.36	1.42
382	38.1	33.6	25.8	45.9	35.8	1.58	1.63	1.63	1.58	1.63
376	46.1	35.1	40.1	41.2	40.6	0.92	1.18	0.95	1.18	1.18
378	39.3	42.8	43.0	39.1	41.0	1.03	1.05	1.05	0.94	1.05
377	56.9	62.4	63.6	55.7	59.6	1.06	1.02	0.93	1.06	1.06

[a]For each heat one longitudinal specimen and one transverse specimen were tested for each strain. Averages are given for pairs with common orientation or common strain.

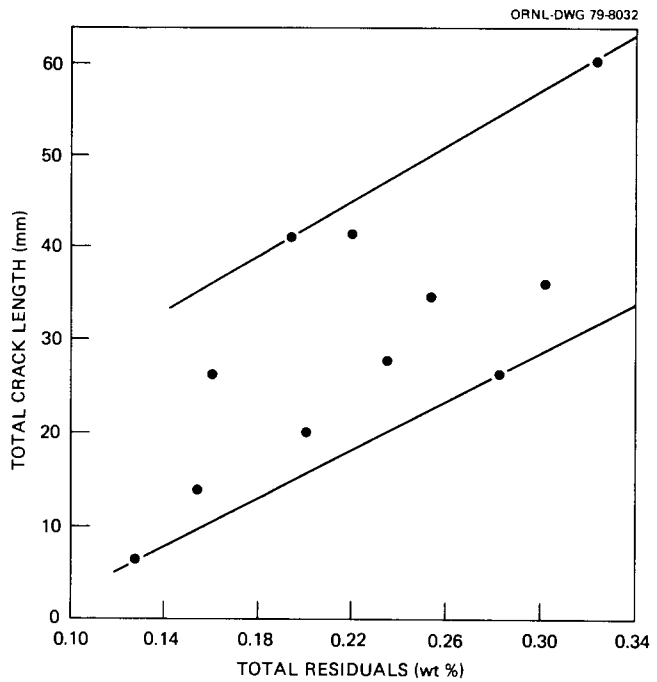

Fig. 6. Effect of Residual Element Concentration on Hot Cracking of Modified 9 Cr-1 Mo Steel.

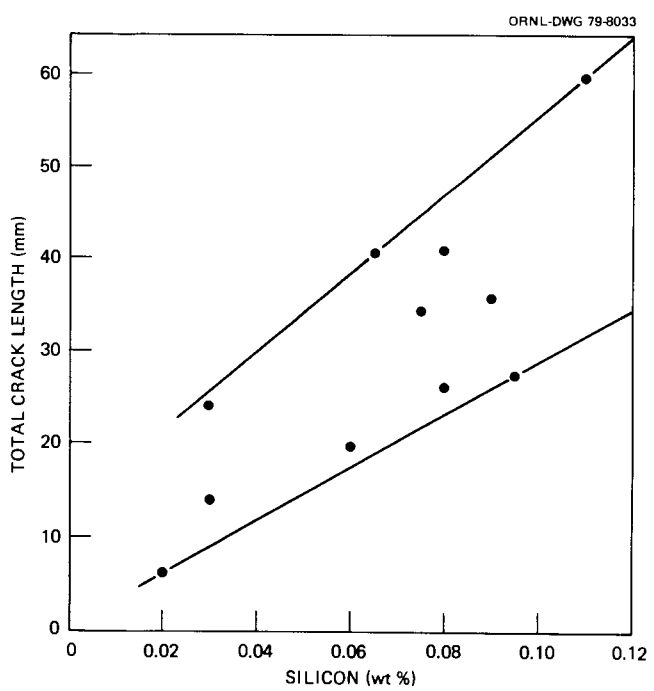

Fig. 7. Effect of Silicon Content on Hot Cracking of Modified 9 Cr-1 Mo Steel.

METALLOGRAPHIC EVALUATION

Metallographic evaluations have been performed for selected tested Tigamajig specimens. Cracks in the HAZ of all the experimental modified 9 Cr-1 Mo heats propagated along strings of precipitate, apparently along previous austenite boundaries. These precipitate particles and associated cracks were often surrounded by islands of δ-ferrite lining the previous austenite boundaries (Fig. 8). The regions of the HAZ where most of the cracking occurs consist primarily of martensite, tempered martensite, and small areas of δ-ferrite (except for heats 376 and 378). Microprobe evaluation failed to reveal the nature of this precipitate. However, it is probably rich in niobium and/or vanadium as a result of the relatively high concentrations of these elements.

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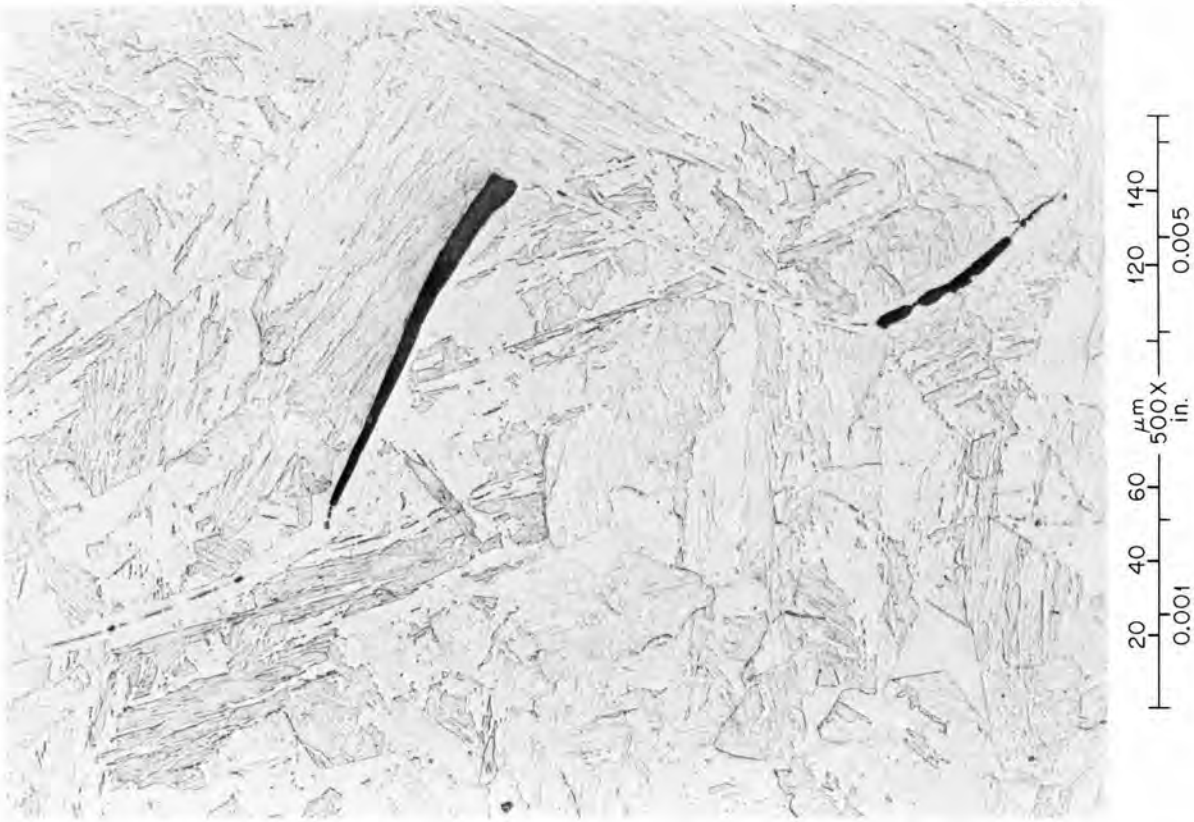

Fig. 8. Typical HAZ Cracks in Modified 9 Cr-1 Mo Steel Tigamajig Specimens (Etchant: 50 HCl, 10 HNO_3).

AUXILIARY STUDY

It is difficult to compare the results from the Tigamajig and other weldability tests to actual weldments and to results from other laboratories. Therefore, we made gas tungsten-arc (GTA) and shielded metal-arc (SMA) welds with the most crack-sensitive heat of material (heat 377), as indicated by the Tigamajig evaluation. Welds were made under very highly restrained conditions, with the base plates welded solidly to a strongback. These conditions represent very high residual stress and, therefore, result in very good possibilities for hot cracking. The GTA weld was made with conventional 9 Cr-1 Mo filler wire (ER 505) and the SMA weld was made with E9018-B3 electrodes (no E505 electrodes were available at the time). The plates were heated to 204°C before welding with a maximum interpass temperature of 316°C. Postweld heat treatment was performed at 732 to 760°C for 1 h. Extensive centerline (liquation) cracking occurred in the ER505 GTA weld metal; no such cracking occurred in the E9018-B3 SMA weld metal. The weldments were removed from the strongback and sectioned transverse to the welding direction. Guided side bend tests were then performed for the SMA weldment (the cracks in the GTA weld metal prevented bending of these specimens) to open any HAZ cracks that might be present. No hot cracks occurred in the HAZ of either weld, as determined by visual and dye penetrant examination (of the bent specimens for the SMA weld).

CONCLUSIONS

Our study suggests that HAZ hot cracking in the modified 9 Cr-1 Mo steels is related to the total residual element concentration and, particularly, the silicon content. Coarse grain materials appear to be less sensitive to cracking than fine grain materials. There were no obvious correlations between crack sensitivity and either chromium equivalent, δ-ferrite content, or amount of elephant grains. Hot cracks in the HAZ occurred along strings of precipitate at prior austenite boundaries.

Welds were made with the most crack-sensitive heat (as determined by the Tigamajig test) under very highly restrained conditions. There were no HAZ hot cracks in these welds after side bend testing and dye penetrant examination. Therefore, under normal welding conditions hot cracking will not likely be a problem in the HAZ of any of the heats that we tested. Results of the highly restrained welds indicate that hot cracking should not be a problem with the modified 9 Cr-1 Mo steel compositions being investigated. The Tigamajig tests indicate that sensitivity to cracking tends to increase with increases in residual element contents (particularly silicon).

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