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Performance of 9—12% Cr-1 Mo Steels During Flattening Test

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CONTENTS

PERFORMANCE OF 9–12% Cr-1 Mo STEELS DURING FLATTENING TEST*

V. K. Sikka and R. E. McDonald

ABSTRACT

The performance of modified 9 Cr-1 Mo, HT9, and types 316 and 321 stainless steel in the ASTM flattening test (A 530) is reported. The modified 9 Cr-1 Mo tubes tested were made by centrifugal casting and cold pilgering and by hot extrusion. The modified 9 Cr-1 Mo and HT9 were tested in the normalized and tempered condition and after aging for 3000 h at 482, 538, 593, 649, and 704°C. Both alloys were also tested in the welded condition. Type 316 stainless steel was tested in the mill-annealed condition. Type 321 was tested as removed from the superheater section of the TVA Kingston power plant and after solution annealing. Modified 9 Cr-1 Mo tubes made by two different processes flattened until the sides met without any cracking when tested in the normalized and tempered condition (1038°C, 1 h; 760°C, 1 h); after aging for 3000 h at 482, 538, 593, 649, and 704°C; and after welding. The tube flattening characteristics of this alloy are similar to those of type 316 stainless steel tested in the mill-annealed condition.

Both heats of HT9 tubes cracked during flattening in the normalized and tempered condition. Tubes from one heat also cracked after aging for 3000 h at 482, 538, 593, or 649°C, but did not crack after aging at 704°C. Also, HT9 tubes cracked while flattening after welding. The cracking in the welded tube initiated in the base metal.

Extensive precipitate coarsening in HT9 after aging for 3000 h at 704°C is believed to be responsible for preventing cracking during flattening under those conditions.

INTRODUCTION

The advanced alloy technology task of the breeder reactor program is aimed at developing a modified 9 Cr-1 Mo alloy having both low- and elevated-temperature mechanical properties exceeding those of the

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available 9–12% Cr steels and approaching the creep strength of type 304 stainless steel. Several tasks under way on this program include

1. melting and fabrication,
2. physical and mechanical properties,
3. design methods,
4. welding studies,
5. steam corrosion and air oxidation, and
6. microstructural analysis.

Progress is being made on each of the tasks, and we expect to prepare data packages by the end of 1982 for the acceptance of this alloy in Sects. I and VIII of the *ASME Boiler and Pressure Vessel Code*. The purpose of this report is to present the response of modified 9 Cr-1 Mo alloy and Sandvik HT9 (12 Cr-1 Mo) tubes to the ASTM flattening test. Results are presented for alloys after several heat treatments and compared with the results of the same test conducted on types 316 and 321 stainless steel tubing.

The HT9 tubes are included in this program because this alloy is being investigated as a first-wall material for fusion reactors and as a cladding and duct material for breeder reactors. We judge that the modified 9 Cr-1 Mo alloy is better suited than HT9 for both these applications because of its better fabricability, weldability, toughness, and elevated-temperature properties. Results of this study show that the modified 9 Cr-1 Mo tubes satisfied the flattening test requirements in the unaged, aged, and welded conditions, while HT9 cracked extensively in most instances.

The flattening test provides a measure of ductility and soundness of tubing, and satisfying the criteria is required for procurement of the tubing. The ASTM requirements of the flattening test are described in the next section.

FLATTENING TEST (ASTM A 530) REQUIREMENTS

A section of pipe not less than 63.5 mm in length is flattened cold between parallel plates in two steps. During the first step, which is a test for ductility, no cracks or breaks on the inside, outside, or end surfaces should occur during compression until the distance between the plates is less than the value of H calculated as follows:

$$H = \frac{(1 + e)tD}{De + t} , \tag{1}$$

where

H = distance between the flattening plates,

t = wall thickness,

D = outside diameter,

e = deformation per unit length. It is a constant for a given grade of steel: 0.08 for ferritic alloy steel and 0.09 for austenitic steel.

During the second step, which is a test for soundness, the flattening process is continued until the specimen breaks or the opposite walls of the pipe meet.

Evidence of laminated or defective material that is revealed during the entire flattening test is cause for rejection.

MATERIALS AND TESTING

Flattening tests were conducted on two heats of modified 9 Cr-1 Mo alloy (XA3602 and F5349), two heats of HT9 (410301 and 451774), and one heat each of types 316 (8092297) and 321 (TVA Kingston power plant tubing) stainless steel.

The modified 9 Cr-1 Mo tubes of heat XA3602 were made at Combustion Engineering (CE) by centrifugal casting and cold pilgering. In that process, a centrifugal casting is poured from an air induction melt. The casting is tempered at 800°C for 20 min, machined, and cold reduced approximately 50% to an intermediate size. This size is again tempered at 800°C for 20 min, and the tubing is cold finished to the final size. The finished tube is generally normalized at 1038°C for 1 h and tempered at 760°C for 1 h.

The tubes of this heat (XA3602) were tested in these conditions: normalized (fully martensitic or fully hardened), normalized and tempered, normalized and softened or normalized and tempered and softened, and normalized and tempered and aged. The normalizing treatment consisted of taking the tube to 1038°C, holding for 1 h, and air cooling. The tempering treatment consisted of taking the normalized tube to 760°C, holding for 1 h, then air cooling to room temperature. The softening treatment involved taking the tube to 900°C, holding for 1 h, dropping the furnace to 700°C, holding at this temperature for 16 h, then air cooling. The aging treatment involved 3000-h exposure at temperatures of 482, 538, 593, 649, and 704°C. All exposures were in air on tubes wrapped in stainless steel foil.

The second tube (heat F5349) of modified 9 Cr-1 Mo alloy was made at ORNL by hot extruding a hollow billet at 1150 to 1200°C. This tube was tested in the normalized and tempered and normalized, tempered, and softened conditions. The treatment conditions were the same as described above for heat XA3602.

Cold-rolled tubes of HT9 (heats 410301 and 451774) were obtained from the Sandvik Company. Tubes from heat 410301 were tested in the normalized and tempered; normalized, tempered, and softened; and thermally aged conditions. They were normalized and tempered at Sandvik at reported temperatures of 1050°C and 790°C, respectively. The softening treatment schedule was the same as used for heat XA3602 of modified 9 Cr-1 Mo. These tubes were aged at ORNL for 3000 h at 482, 538, 593, 649, and 704°C. Once again the tubes were wrapped in stainless steel foil before aging. Tubing from heat 451774 was tested only in the normalized and tempered condition.

Type 316 stainless steel came from the ORNL test program[1–3] on the reference heat (8092297) of this material. The heat was melted at Republic Steel,[1] and the tubing was made by the Mannesman process, in which the round, after being heated to temperature, is squeezed between rotating rolls while being rotated at high speed and drawn through the mill over a piercing point located between the rolls. After the piercing operation the pipe is reduced by either plug rolling or bar rolling and sizing. All pipe lengths were solution annealed at 1065° ± 28°C before shipment. This pipe length was tested only in the solution annealed condition.

Type 321 stainless steel tube was received from the TVA Kingston power plant. The pipe was removed from service after it had developed a leak following a repair of the transition joint between type 321 and 2 1/4 Cr-1 Mo steel. The flattening test on this tube was conducted in the as-removed condition and after a solution anneal for 0.5 h at 1065°C.

The modified 9 Cr-1 Mo tubes from heat XA3602 and the HT9 tubes from heat 410301 were also tested in the welded condition. Pieces of both alloys were welded by the gas tungsten-arc process with modified 9 Cr-1 Mo filler wire. The HT9 tubes should have been welded with HT9 filler wire. However, such filler wire was not available at the time of welding. No preheat was used in welding either of the alloys. Welded tubes of both alloys were postweld heat-treated for 1 h at 732°C before the flattening test.

Flattening tests on tubes were conducted in a 4.4-MN (500-ton) forging press. The test was stopped after flattening to *H* values to check for any cracks and then continued until cracks were observed or the tube was completely flattened.

The alloy compositions are given in Table 1. The dimensions of the tubes tested along with calculated *H* values are in Table 2.

Table 1. Alloy compositions

	Content, wt %					
	9 Cr-1 Mo		HT9		Type 316	Type
	XA3602	F5349	410301	451774	8092297	321
C	0.086	0.10	0.20	0.20	0.068	0.061
Mn	0.040	0.41	0.48	0.50	1.90	1.74
P	0.005	0.007	0.018	0.017	0.024	0.019
S	0.009	0.017	0.007	0.006	0.020	0.010
Si	0.19	0.34	0.34	0.32	0.64	0.52
Ni	0.05	0.10	0.52	0.51	13.36	12.05
Cr	9.21	8.80	11.4	11.2	17.01	17.98
Mo	0.93	0.93	0.96	0.97	2.49	0.24
V	0.197	0.205	0.27	0.29	0.04	0.04
Nb	0.059	0.060			0.01	<0.01[a]
Ti	0.005	0.008			<0.01	0.49
Co	0.019	0.019			0.02	0.03
Cu	0.02	0.09			0.07	0.08
Al	0.003	0.001			0.01	<0.01
B	<0.001	0.001			0.002	<0.001
W	<0.01	<0.01	0.47	0.51		
As	<0.001	0.002				
Sn	<0.001	0.004				
Zr	<0.001	<0.001				
N	0.65	0.0108			0.034	0.007

[a]Nb + Ta.

Table 2. Tube dimensions

Alloy	Heat	Dimensions, mm		
		OD	Wall	*H*
9 Cr-1 Mo	XA3602	50.8	8.66	37.3
	F5349	59.2	11.8	44.8
		58.7	10.3	43.6
HT9	410301	50.8	6.45	33.6
	451774	31.6	3.7	20.4
Type 316	8092297	63.5	13.7	50.06
Type 321		50.8	4.3	26.9

RESULTS AND DISCUSSION

The flattening characteristics for each tube are related to heat treatment and surface finish in Table 3.

Figure 1 shows that when tested in the normalized condition, modified 9 Cr-1 Mo cracked even after a slight flattening. This is an important result because it shows the need for tempering the hard martensite for use in the unwelded or welded condition. Figure 2 shows the results of the flattening test on both heats of modified 9 Cr-1 Mo. Both tubes were tested in the normalized and tempered and normalized and softened conditions. After each heat treatment the specimen was cooled to room temperature. The softening treatment consisted of holding the specimen for 1 h at 900°C, furnace cooling, holding at 700°C over 16 h, and air cooling to room temperature. This treatment produced a condition softer than produced by tempering (Rockwell B 60–65 vs 85–95). For both heats (fabricated by two significantly different processes) and heat treatments, modified 9 Cr-1 Mo tube could be flattened until the sides met without any cracking. Heat XA3602, when tested in the normalized and tempered condition, showed a small surface defect as circled on Fig. 2. This surface defect is not too different from that observed for type 316 stainless steel, which will be shown later.

Table 3. Flattening characteristics for various heat treatments and surface conditions

Alloy (heat)	Heat treatment[a]	Surface finish	Height[b] at which Cracking occurred (mm)	(×H)	Nature and number of cracks
9 Cr-1 Mo (XA3602)	Normalized	Bright	49.7	1.33	2 full-length cracks
	All others[c]	c	Total flattening		No cracks[d]
(F5349)	Normalized and tempered	Machined and polished	Total flattening		No cracks
	Softened	Mach. + pol.	Total flattening		No cracks
HT9 (401301)	Normalized and tempered	Slightly oxidized	21	0.62	1 long crack on 1 side and several short cracks on other
	Normalized and tempered	Polished	17.5	0.52	1 long crack on each side
	Softened	Polished	17.2	0.51	Many short cracks on 1 side
	Softened	Polished	Total flattening		Many fine cracks on both sides
	Aged 482°C	Polished	Total flattening		Large wide cracks on both sides
	Aged 538°C	Polished	21.7	0.65	1 large crack on each side
	Aged 593°C	Polished	23.6	0.70	Large wide cracks on both sides
	Aged 649°C	Polished	29.5	0.88	1 long crack on 1 side
	Aged 704°C	Polished	Total flattening		Surface oxide cracked. No cracks in wall
	Welded	Slightly oxidized	24.8	0.74	1 crack on each side, wide in base metal, narrow in weld
	Welded	Polished	29.1	0.87	Same as above
(451774)	Normalized and tempered	Polished	19.9	0.98	Several fine cracks on both sides
Type 316 (8092297)	Solution annealed	Machined	Total flattening		No cracks
Type 321	As removed from service	Oxidized	26.9	1.00	1 long crack on 1 side
	As removed from service	Polished	26.9	1.00	Large wide crack on 1 side
	Reannealed[e]	Oxidized	Total flattening		No cracks
	Reannealed[e]	Oxidized	Total flattening		No cracks

[a]Heat treatments as described in text. Normalizing and tempering precede softening, aging, and welding. Welding was followed by postweld heat treatment at 732°C for 1 h.

[b]Measured at the middle of the flat.

[c]Tested after the same treatments as HT9 heat 401301, except, of course, for the different normalizing and tempering temperatures.

[d]Aging at 704°C produced an oxide scale that appeared highly polished at the beginning of the test but cracked at several places near the test end.

[e]Solution annealed 0.5 h at 1065°C.

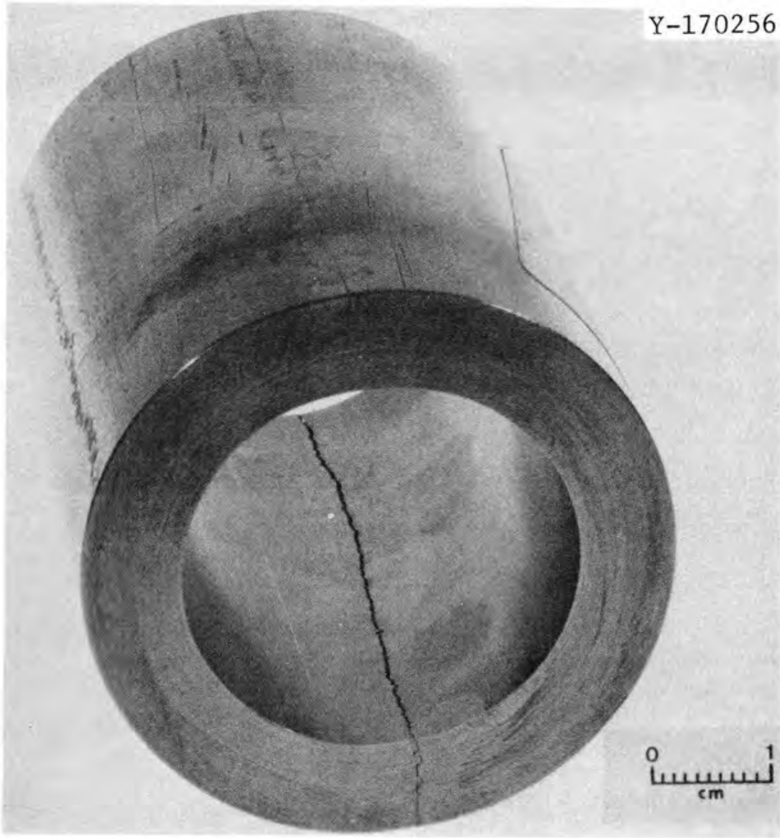

Fig. 1. Response to flattening test of normalized tube of modified 9 Cr-1 Mo steel, heat XA3602.

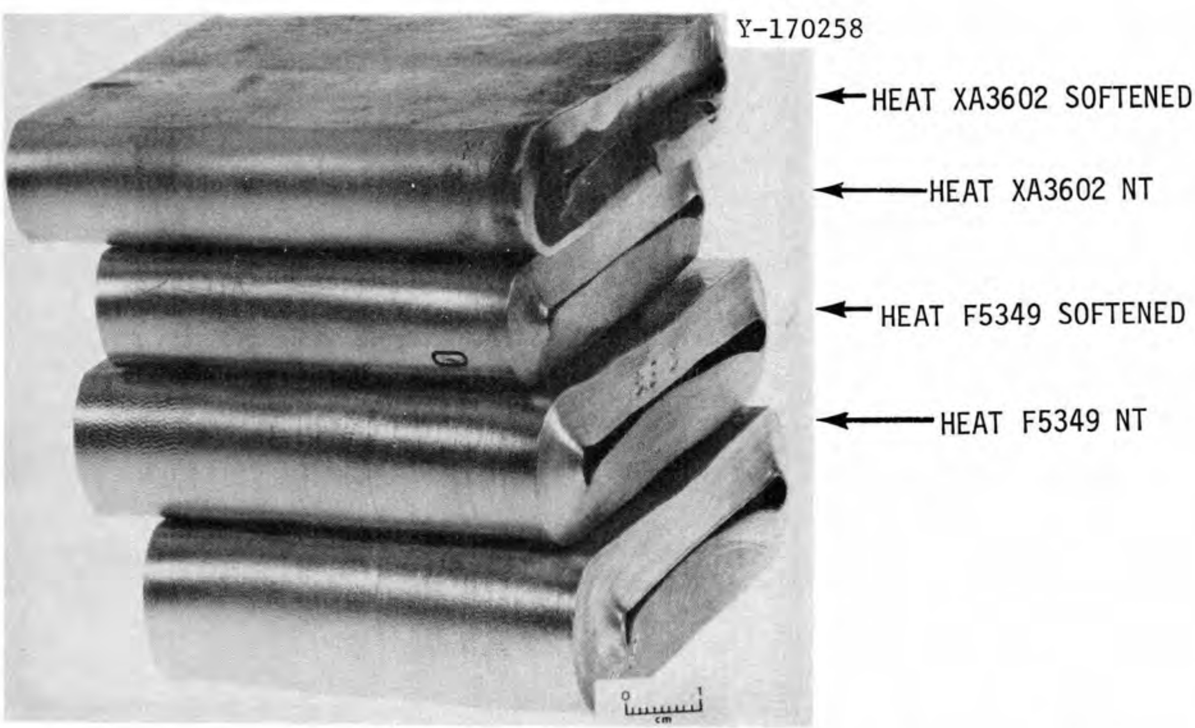

Fig. 2. Response to flattening test of two heats of modified 9 Cr-1 Mo steel, one each tested in normalized and tempered condition and softened condition.

Figure 3 shows the flattening test response on two heats (410301 and 451774) of HT9 tested in the normalized and tempered condition. Tubes from heat 410301 were tested in both the oxidized and machined surface conditions. The tubes from both heats cracked much before complete flattening. It should be mentioned that these tubes cracked only during the second step of the flattening test, indicating that the cracking was not a result of insufficient ductility but probably a result of inadequate soundness.

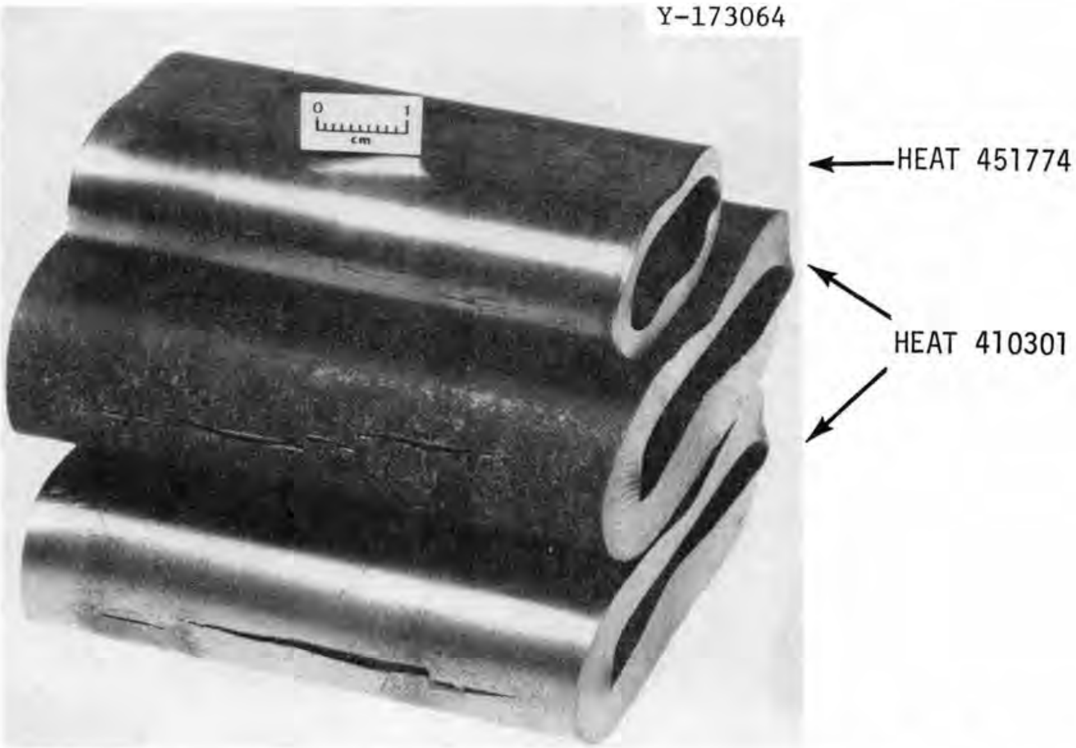

Fig. 3. Response to flattening test of two normalized and tempered heats of HT9. Heat 410301 was tested in two different surface conditions: oxidized and machined.

Figure 4 compares the flattening test response on modified 9 Cr-1 Mo (from Fig. 2) with HT9 (from Fig. 3) and type 316 stainless steel. The response of modified 9 Cr-1 Mo is much superior to that of HT9 and as good as that of type 316 stainless steel. Note that the stainless steel specimen shows a surface flaw similar to that seen on heat XA3602 of modified 9 Cr-1 Mo steel. The type 316 stainless steel had come from a lot given this test by the manufacturer.

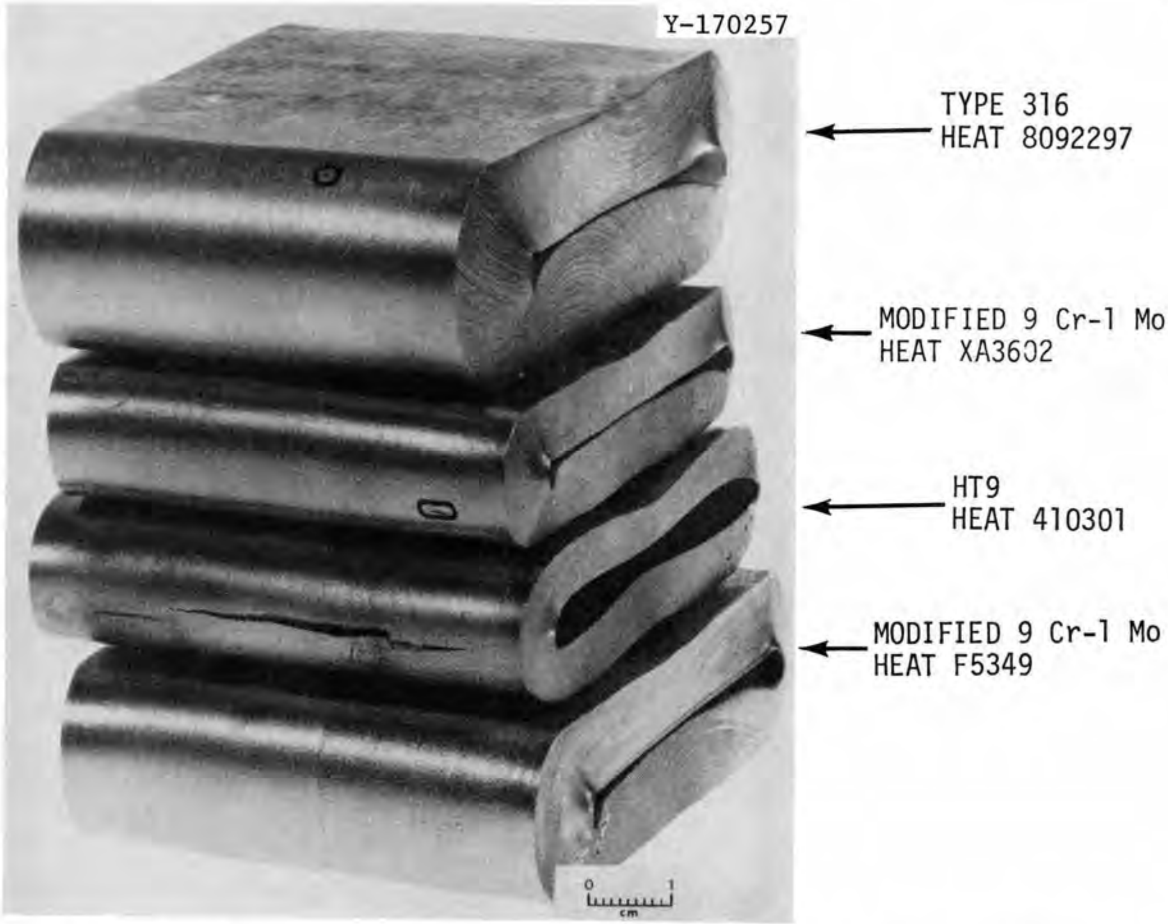

Fig. 4. Response to flattening test of two normalized and tempered heats of modified 9 Cr-1 Mo, one normalized and tempered heat of HT9, and one solution annealed heat of type 316 stainless steel.

Figures 5 and 6 show the flattened tubes of modified 9 Cr-1 Mo and HT9 after 3000-h exposures at 482, 538, 593, 649, and 704°C. Since the tubes were aged in air (wrapped in stainless steel foil), they had oxidized. The oxidized layer (one of possibly three) was removed by buffing the tube surfaces of both alloys. Modified 9 Cr-1 Mo tubes remained uncracked after aging at all five temperatures. The HT9 cracked after aging at four of the temperatures. The only aging temperature for which HT9 did not crack was 704°C.

Transverse and longitudinal sections from each of the flattened tubes were cut and mounted for metallographic observations. The transverse sections for the unaged and aged modified 9 Cr-1 Mo and HT9 are shown in Figs. 7 and 8.

Fig. 5. Response to flattening test of the aged tubes of modified 9 Cr-1 Mo. Normalized and tempered tubes were aged 3000 h at 482, 538, 593, 649, and 704°C (from bottom to top, respectively).

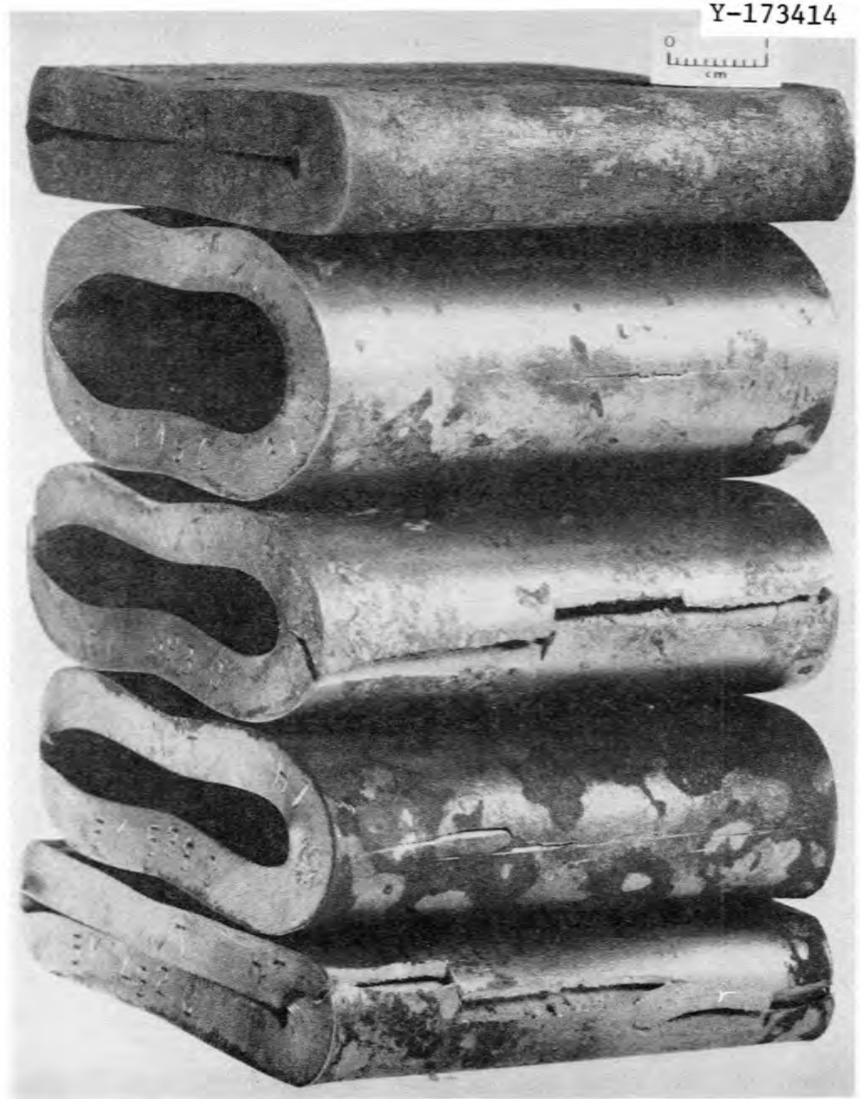

Fig. 6. Response to flattening test of the aged tubes of HT9. Normalized and tempered tubes were aged 3000 h at 482, 538, 593, 649, and 704°C (from bottom to top, respectively).

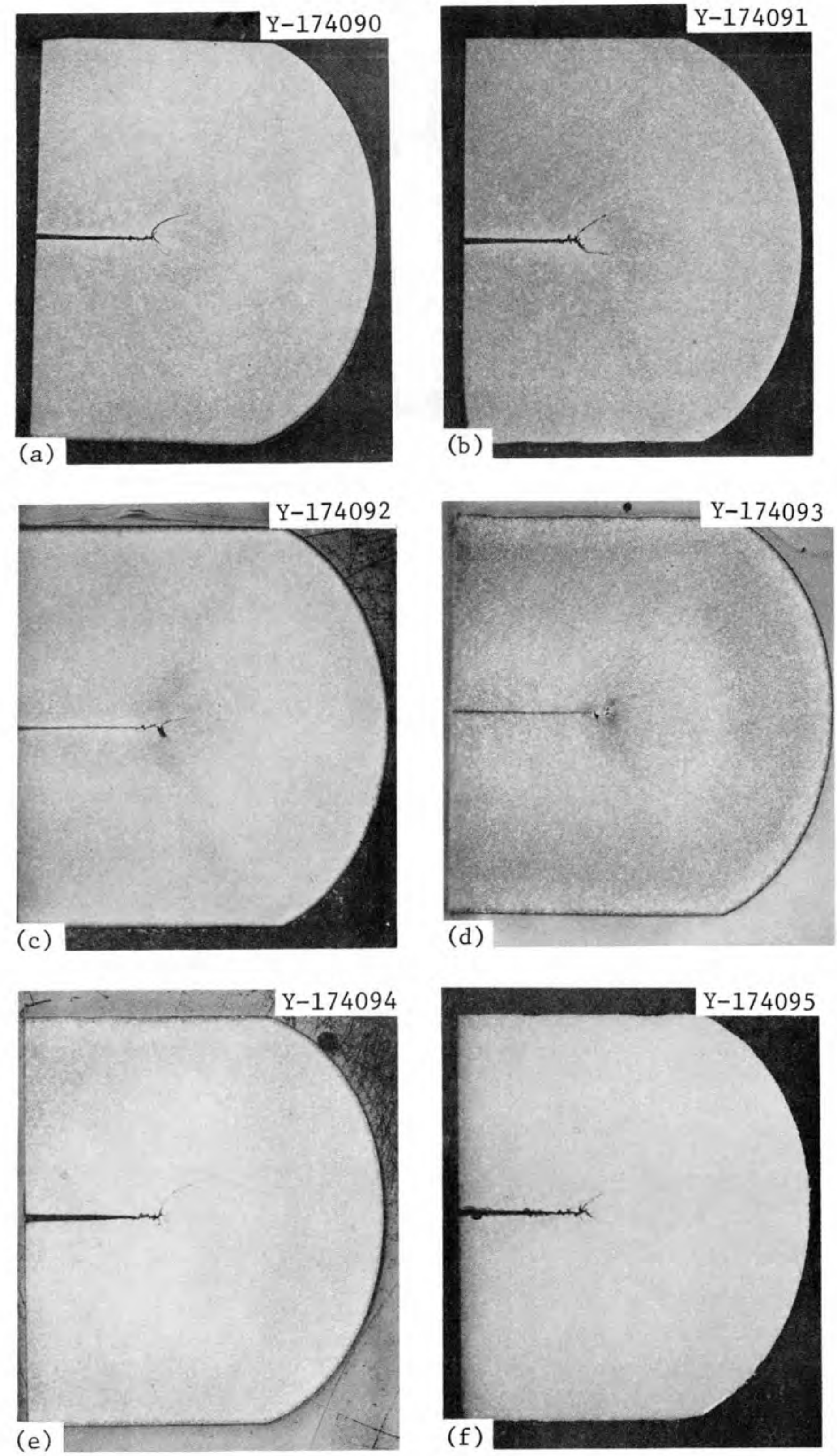

Fig. 7. Transverse sections of the flattened tubes of modified 9 Cr-1 Mo. (a) Unaged; (b) through (f) aged 3000 h at 482, 538, 593, 649, and 704°C, respectively.

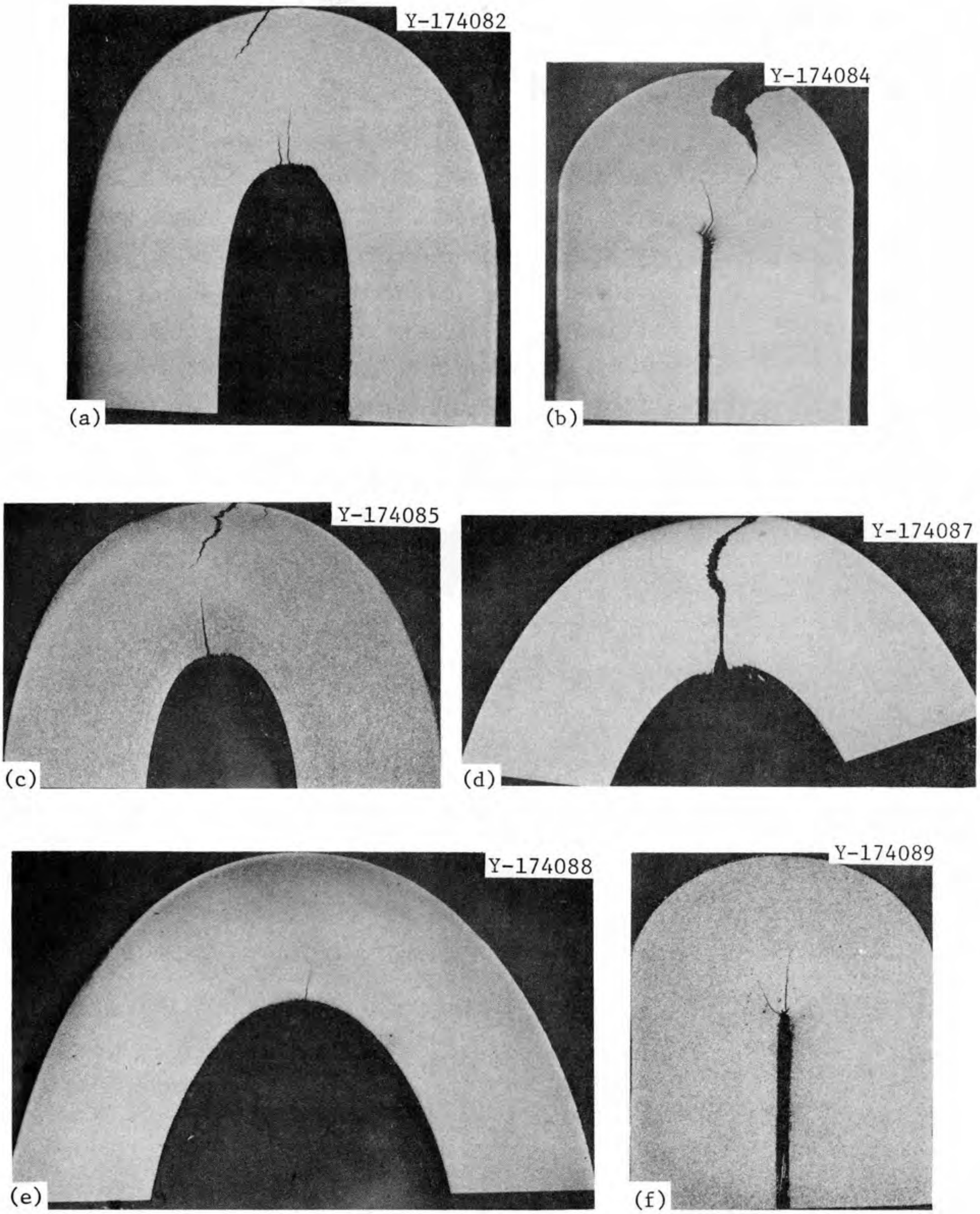

Fig. 8. Transverse sections of the flattened HT9 tubes. (a) Unaged; (b) through (f) aged 3000 h at 482, 538, 593, 649, and 704°C, respectively.

In agreement with Fig. 5 the transverse sections in Fig. 7 showed no evidence of cracking on the outer surface of either the unaged or aged tubes of modified 9 Cr-1 Mo alloy. The complete flattening of modified alloy tubes produced sufficient compressive deformation to initiate cracks on the inner surface. For HT9, cracks are seen on both surfaces of the tubes after flattening both in the normalized and tempered condition and after aging at 482 through 649°C. Aging at 704°C resulted in only cracks on the inner surface similar to those observed for modified 9 Cr-1 Mo alloy. The lack of outer surface cracks in Fig. 8(e) compared with Fig. 6 is just a result of metallographic specimen location along the tube. If the specimen had been cut from near the tube center, we would have observed the outer surface cracks. Comparison of Figs. 7 and 8 shows that HT9 is much more susceptible to cracking at both surfaces than modified 9 Cr-1 Mo alloy. This is true for the alloy in both the unaged and aged conditions.

Photomicrographs of the cracked tubes of HT9 unaged and after aging for 3000 h at 538°C are shown in Fig. 9. This figure shows that the cracks in both cases are transgranular.

Figures 10 through 13 show the microstructural changes as a result of thermal aging for HT9. Similar photomicrographs for modified 9 Cr-1 Mo are shown in Figs. 14 through 17. Figures 10 through 12 and 14 through 16 are longitudinal sections of the flattened tubes. These sections show the least amount of deformation during flattening. Figures 13 and 17 were taken on transverse sections of flattened tubes near the outer surface. This region is subjected to tensile deformation during flattening.

Figures 10 through 12 show that only small changes occur in HT9 as a result of thermal aging for 3000 h at 482, 538, 593, and 649°C. However, aging at 704°C produces a significant amount of coarsening of precipitate particles in the matrix and at the grain boundaries. Figure 13 shows that coarse precipitate particles help relieve the strains during flattening by void formation at their interfaces. Also significant strains can be taken up by the relatively precipitate-free matrix. Both these conditions are responsible for preventing cracking during flattening HT9 tubing aged for 3000 h at 704°C.

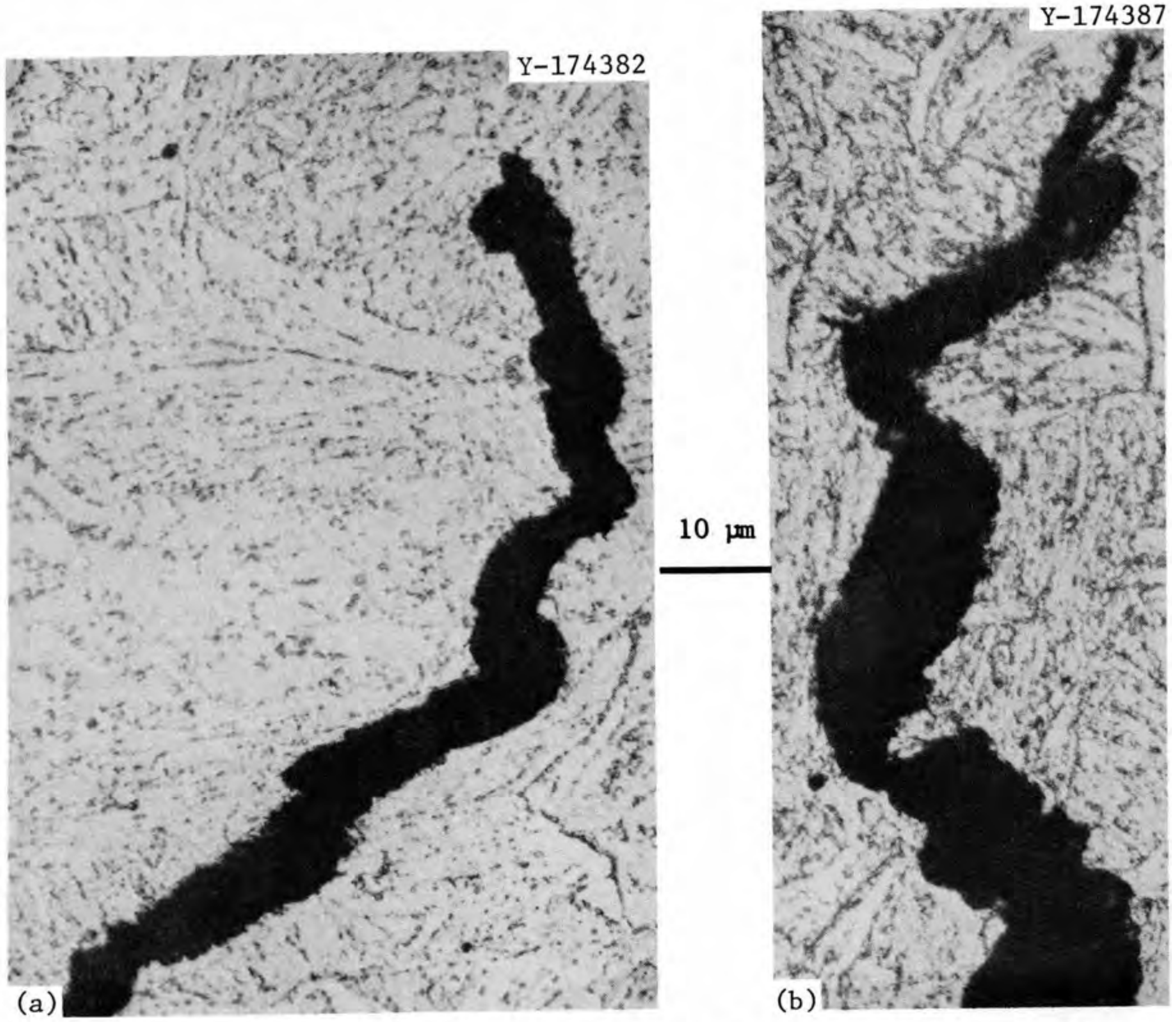

Fig. 9. Crack path in flattened tubes of HT9. (a) Unaged. (b) Aged 3000 h at 538°C.

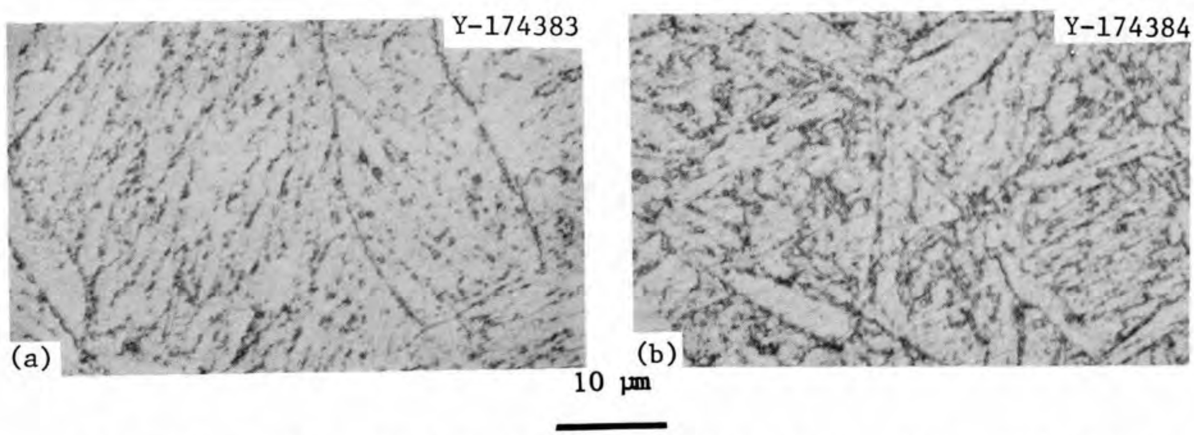

Fig. 10. Longitudinal sections of flattened HT9 tubes. (a) Unaged. (b) Aged 3000 h at 482°C.

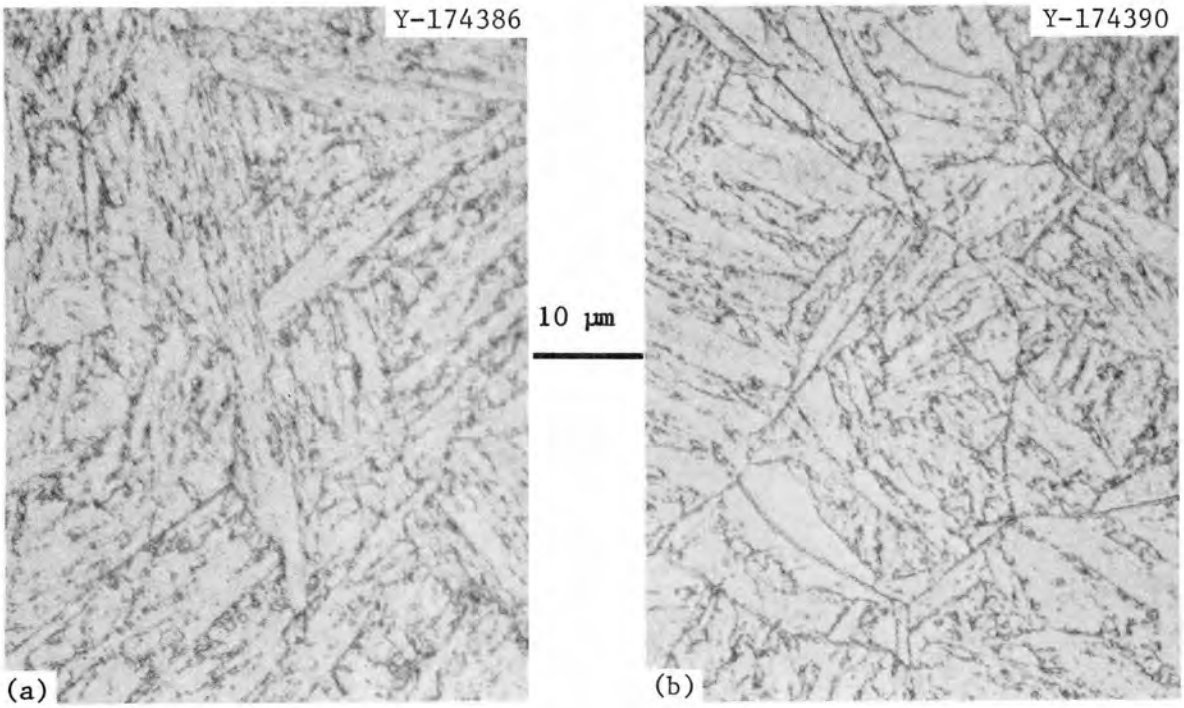

Fig. 11. Longitudinal sections of HT9 tubes flattened after aging 3000 h at (a) 538 and (b) 593°C.

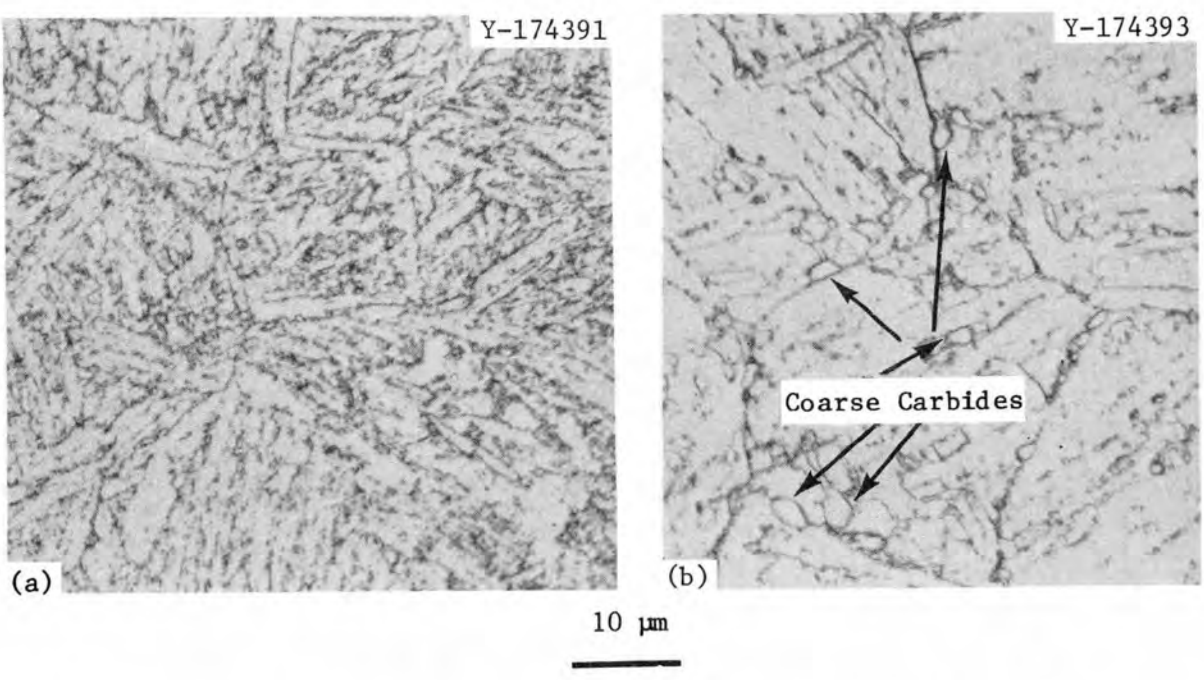

Fig. 12. Longitudinal sections of HT9 tubes flattened after aging 3000 h at (a) 649 and (b) 704°C.

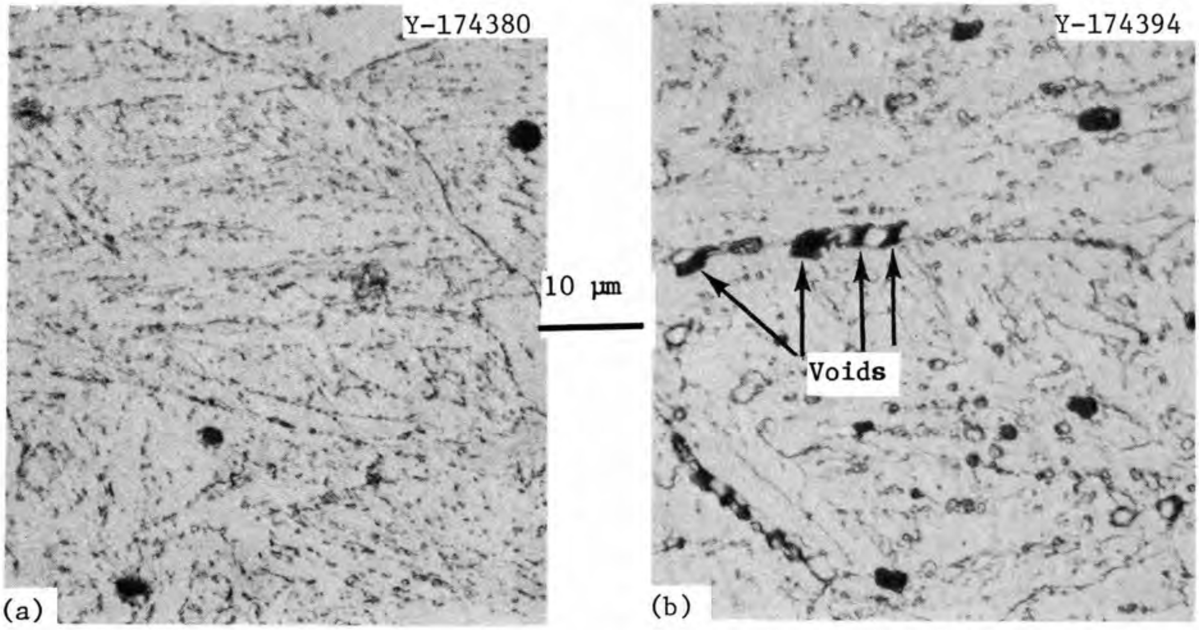

Fig. 13. Transverse sections near outer surface of flattened HT9 tubes. (a) Unaged. (b) Aged 3000 h at 704°C.

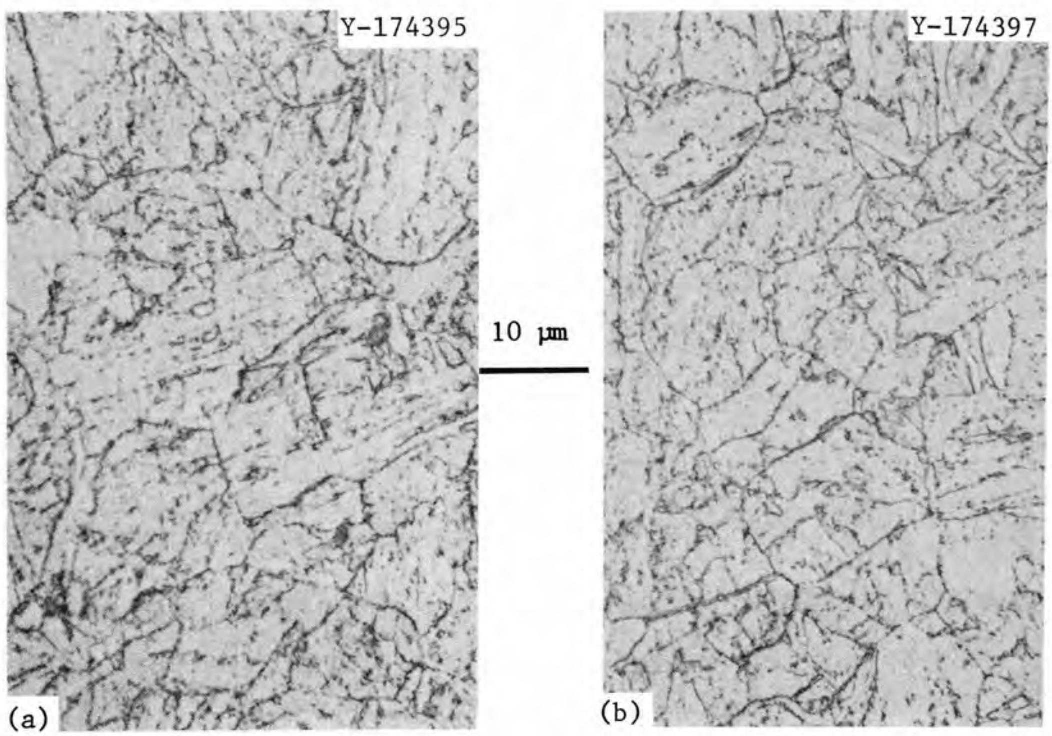

Fig. 14. Longitudinal sections of flattened modified 9 Cr-1 Mo tubes. (a) Unaged. (b) Aged 3000 h at 482°C.

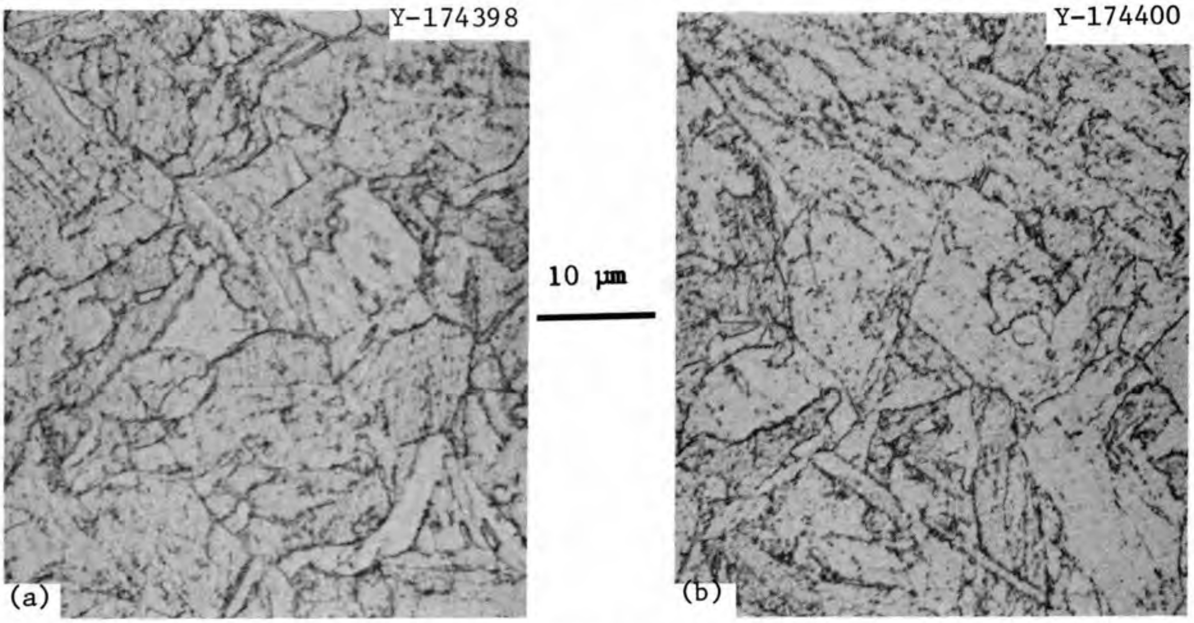

Fig. 15. Longitudinal sections of modified 9 Cr-1 Mo tubes flattened after aging 3000 h at (a) 538 and (b) 593°C.

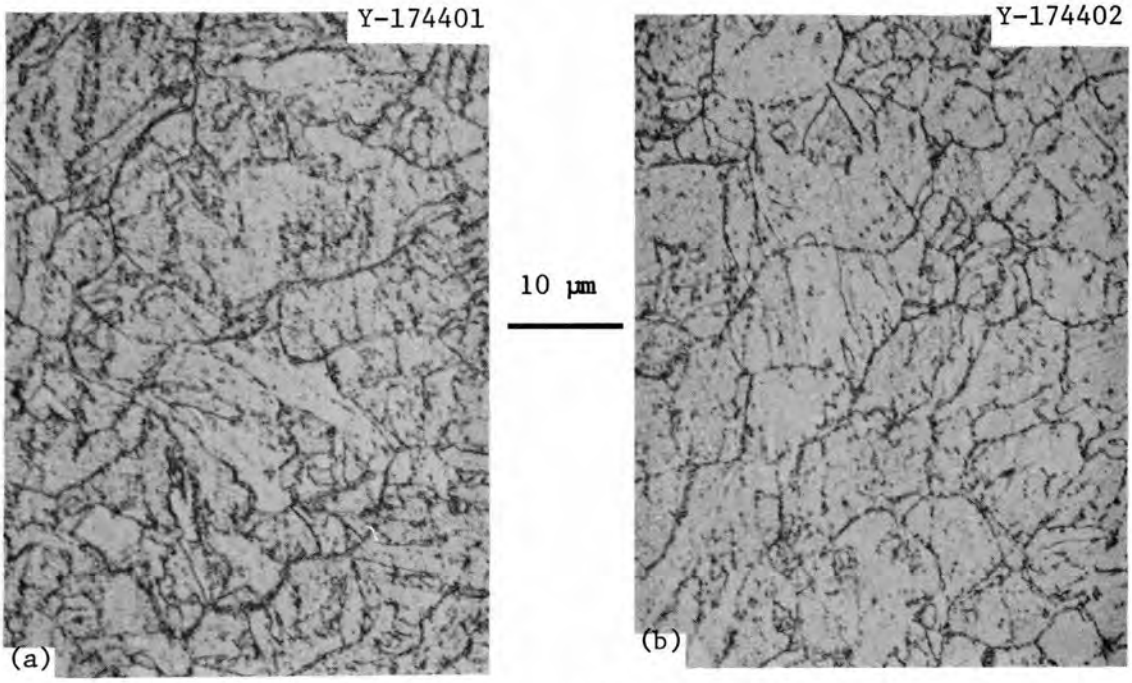

Fig. 16. Longitudinal sections of modified 9 Cr-1 Mo tubes flattened after aging 3000 h at (a) 649 and (b) 704°C.

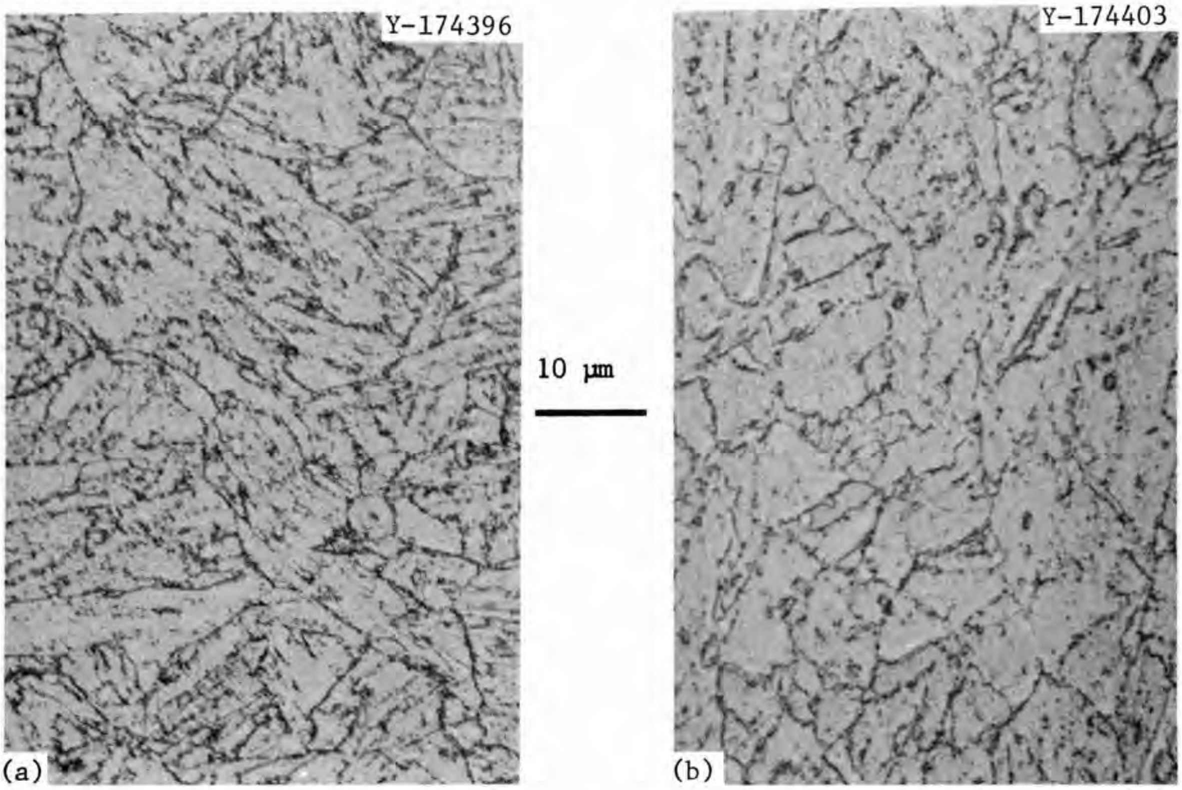

Fig. 17. Transverse sections of flattened modified 9 Cr-1 Mo tubes. (a) Unaged. (b) Aged 3000 h at 704°C.

Figures 14 through 17 show only small changes in the microstructure of modified 9 Cr-1 Mo after aging for 3000 h at 482, 538, 593, and 649°C. The aging treatment of 704°C produced a relatively cleaner matrix. However, the grain boundary carbide was still fine. This is in contrast to HT9, where significant carbide coarsening occurred as a result of this aging treatment. Of course, the microstructure of modified 9 Cr-1 Mo alloy is such that it remains crackfree in the unaged and aged conditions.

Results of the flattening test on welded tubes of modified 9 Cr-1 Mo and HT9 are presented in Fig. 18. Both alloys were welded by identical procedures using modified 9 Cr-1 Mo filler wire. Both tubes were postweld heat-treated at 732°C for 1 h. Figure 18 shows that the welded tube of modified 9 Cr-1 Mo can be flattened until the sides meet, without evidence of any cracking. However, HT9 tubes cracked in the base metal much before total flattening. The cracks initiated in the base metal appeared to be propagating through the weld metal. However, the weld metal is expected

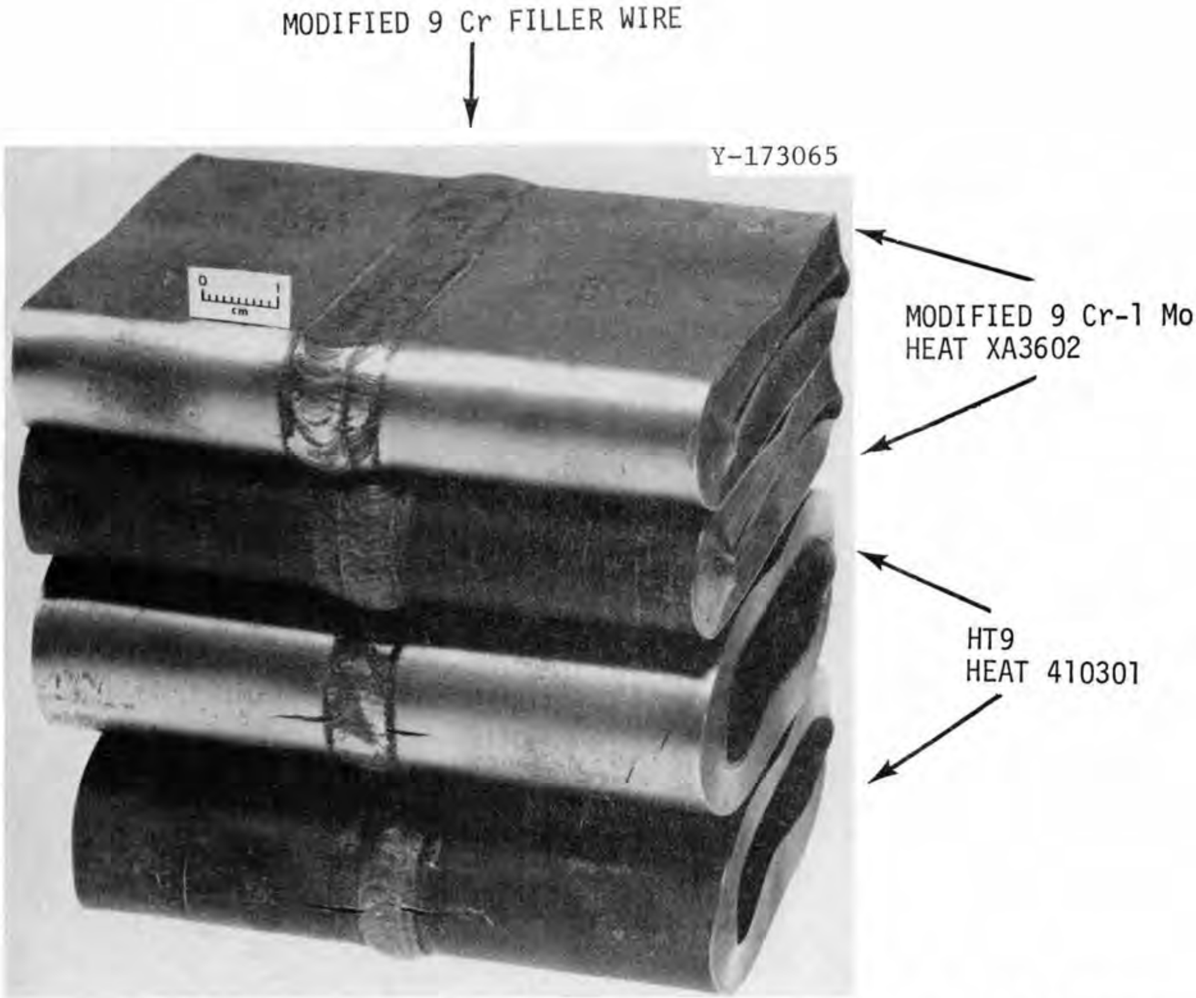

Fig. 18. Response to the flattening test conducted on welded tubes of modified 9 Cr-1 Mo and HT9. Both materials were welded with modified 9 Cr-1 Mo filler wire and postweld heat-treated at 732°C for 1 h.

to resist crack propagation because of its good toughness, as evidenced by the total flattening of modified 9 Cr-1 Mo tubes containing the weld made out of the same filler wire.

Type 321 stainless steel tubes are used currently in the superheater sections of power plants because of their higher creep strength. However, modified 9 Cr-1 Mo tubes with creep strength exceeding that of types 304 and 321 up to 600°C may in the future replace the currently used stainless steel tubes. The use of modified 9 Cr-1 Mo tubes will eliminate the need for the currently required transition joint between the stainless steel tubes in the superheater section and ferritic steel tubes in the reheater section. When the transition joints between type 321 and ferritic steel tubes are repaired and tubes put back in service, leaks develop in type 321 tubes about 300 mm from the joint. To determine the reason for these leaks, we conducted a flattening test on a tube (Fig. 19) removed from the TVA Kingston power plant. Some pieces of this tubing were also flattened after solution annealing for 0.5 h at 1065°C. Results of the flattening tests are presented in Fig. 20 and in Table 3., p. 7.

Y-172514

SECTION A

SECTION B

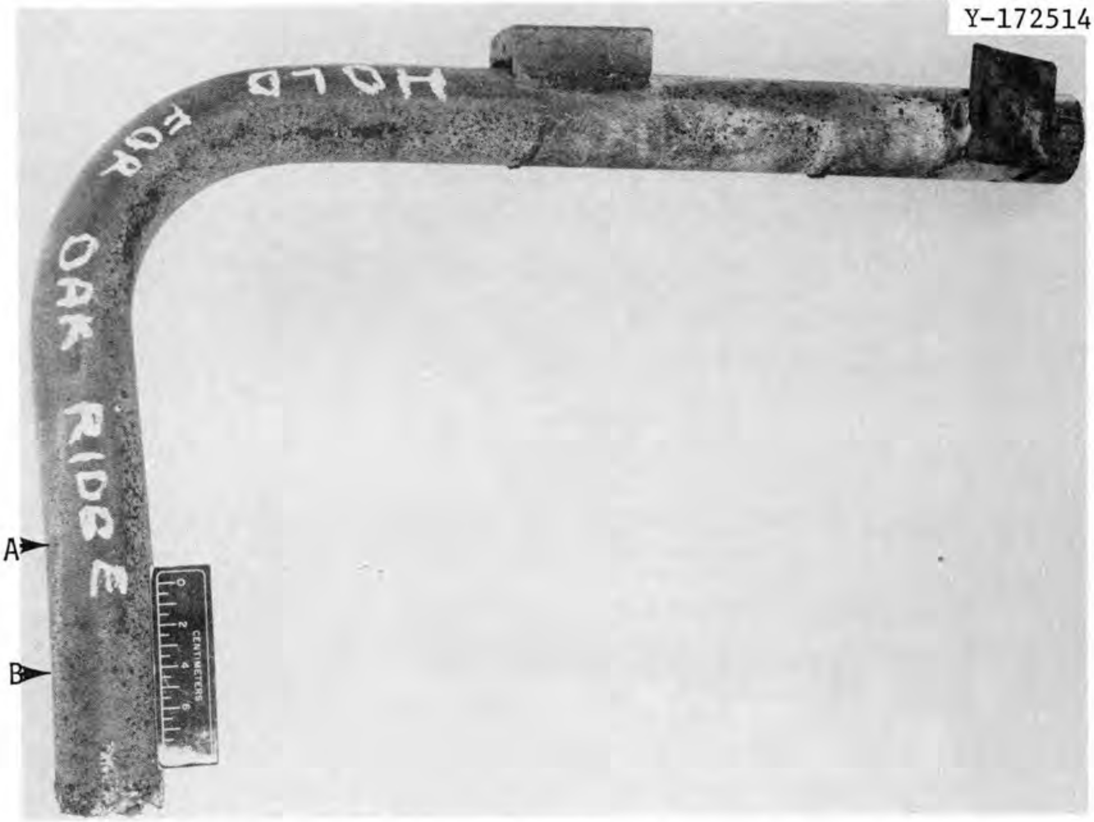

Fig. 19. Type 321 stainless steel tubing removed from the TVA Kingston plant.

Figure 20 shows that as-removed tubes of type 321 stainless steel cracked during flattening at approximately the "*H*" value, indicating that the tube possessed only limited ductility. Once solution annealed, the tubes flattened until the sides met without cracking, a characteristic expected of this alloy.

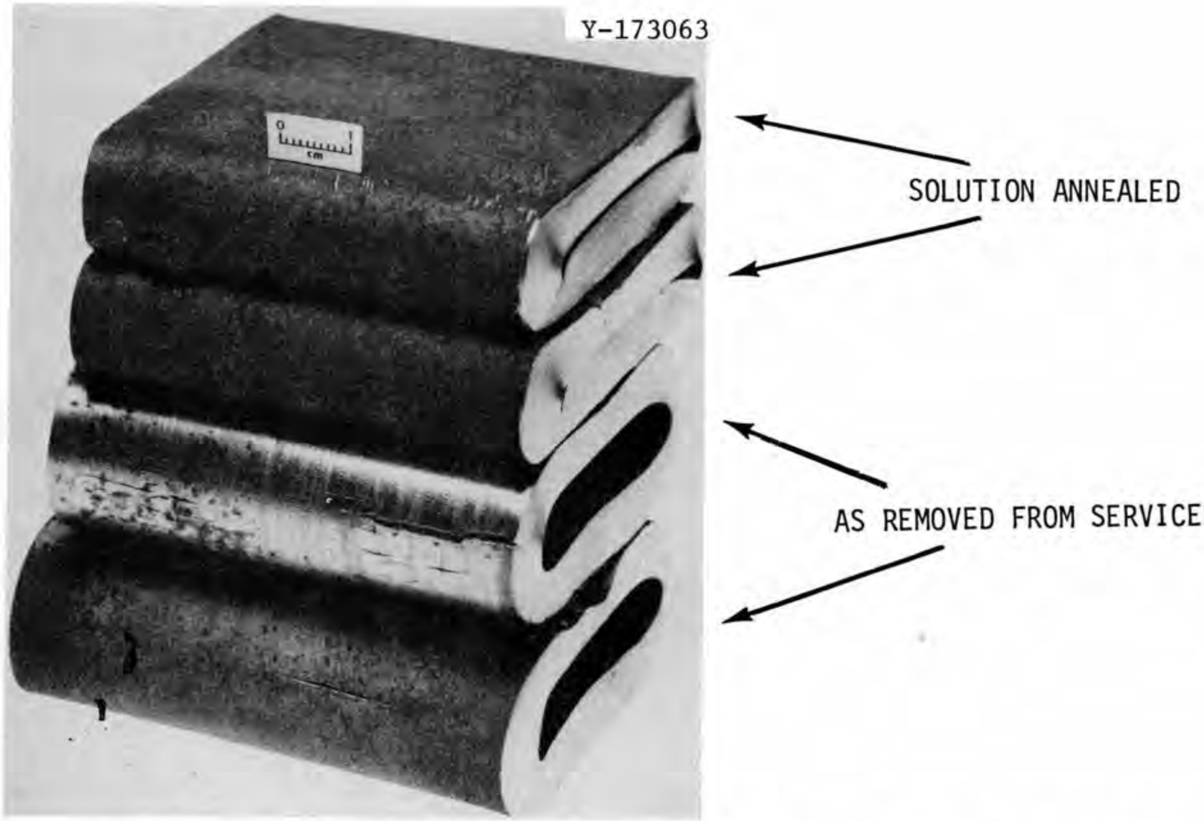

Fig. 20. Response to flattening test of type 321 stainless steel removed from the TVA Kingston power plant. Two pieces each were tested as removed from service and after solution annealing for 0.5 h at 1065°C.

Low- and high-magnification photomicrographs of the outside, center, and inside of the as-removed tube of type 321 from two different locations (A and B in Fig. 19) are shown in Figs. 21 through 24. These micrographs show the following features:

1. very fine grain size on the inside and coarse grain size on the outside and midthickness of the tube,
2. oxide scale on both surfaces of the tube,
3. continuous film of sigma phase on the grain boundaries of tube inner surface,
4. cracking at grain boundaries near the outer surface, and
5. sigma-phase particles at grain boundaries across the entire tube thickness.

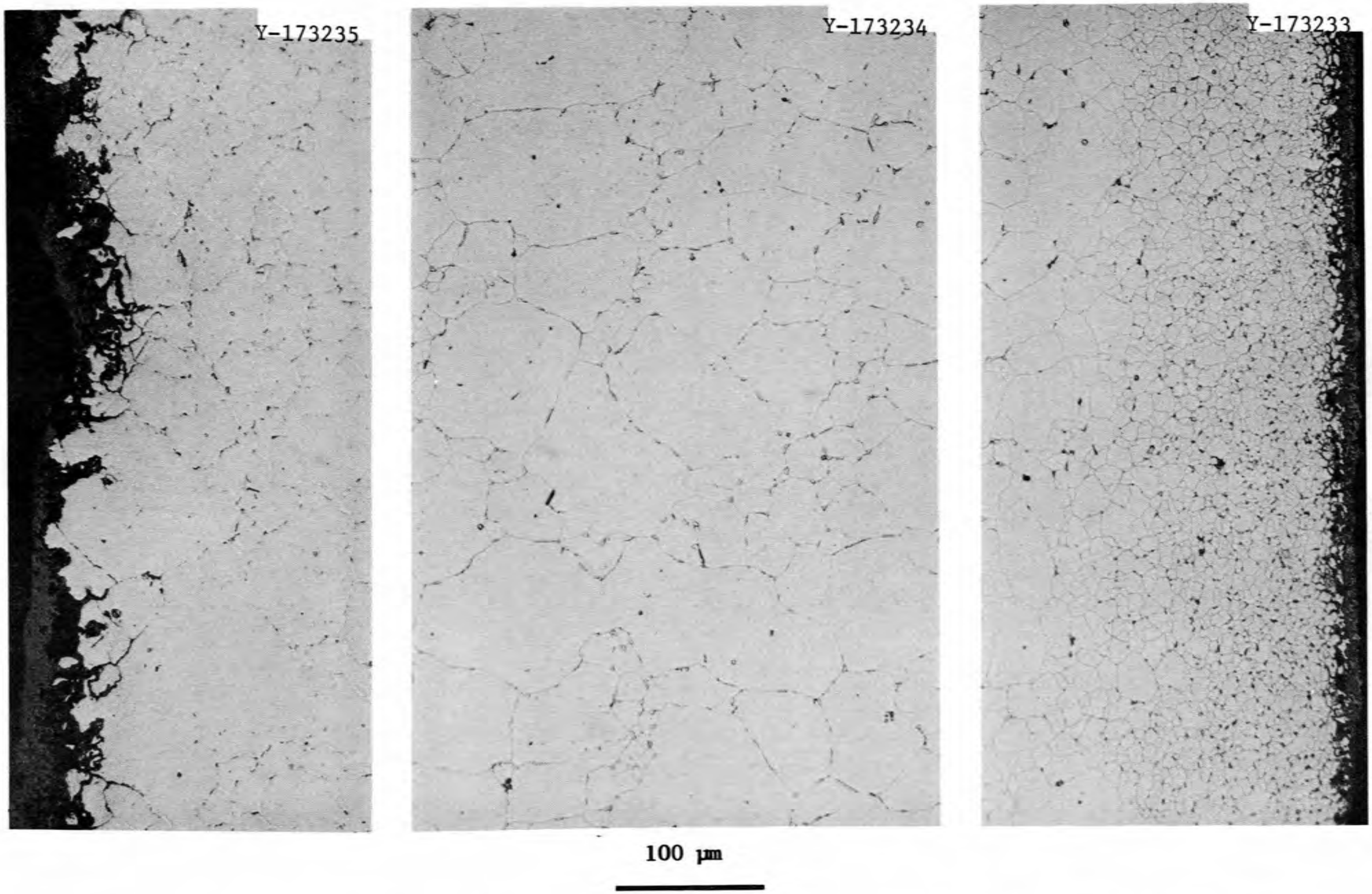

Fig. 21. Low magification of outside, midthickness, and inside of section A (Fig. 19) of type 321 stainless steel tube removed from the superheater section of the TVA Kingston power plant.

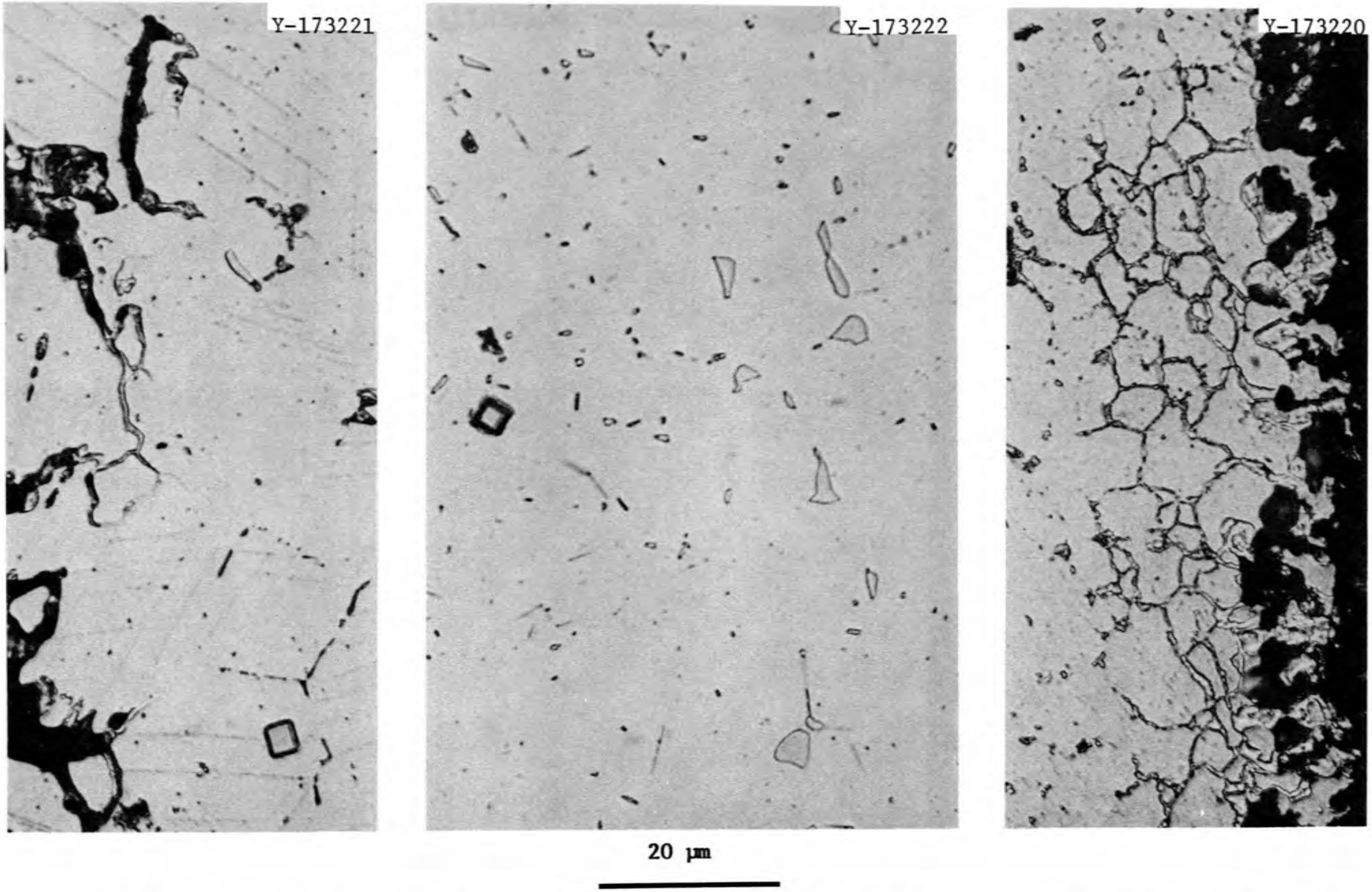

Fig. 22. High magification of outside, midthickness, and inside of section A (Fig. 19) of type 321 stainless steel tube removed from the superheater section of the TVA Kingston power plant.

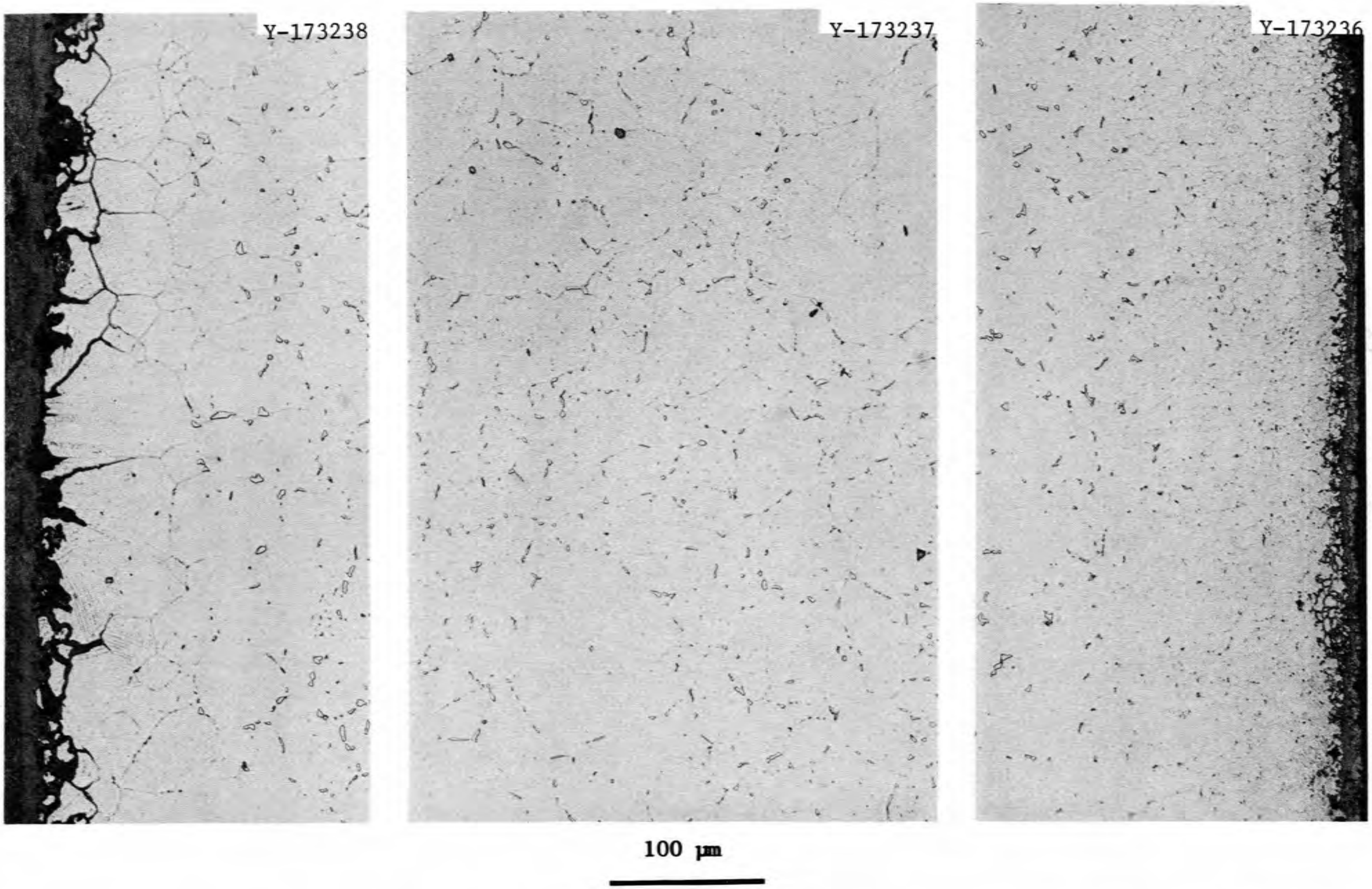

Fig. 23. Low magification of outside, midthickness, and inside of section B (Fig. 19) of type 321 stainless steel tube removed from the superheater section of the TVA Kingston power plant.

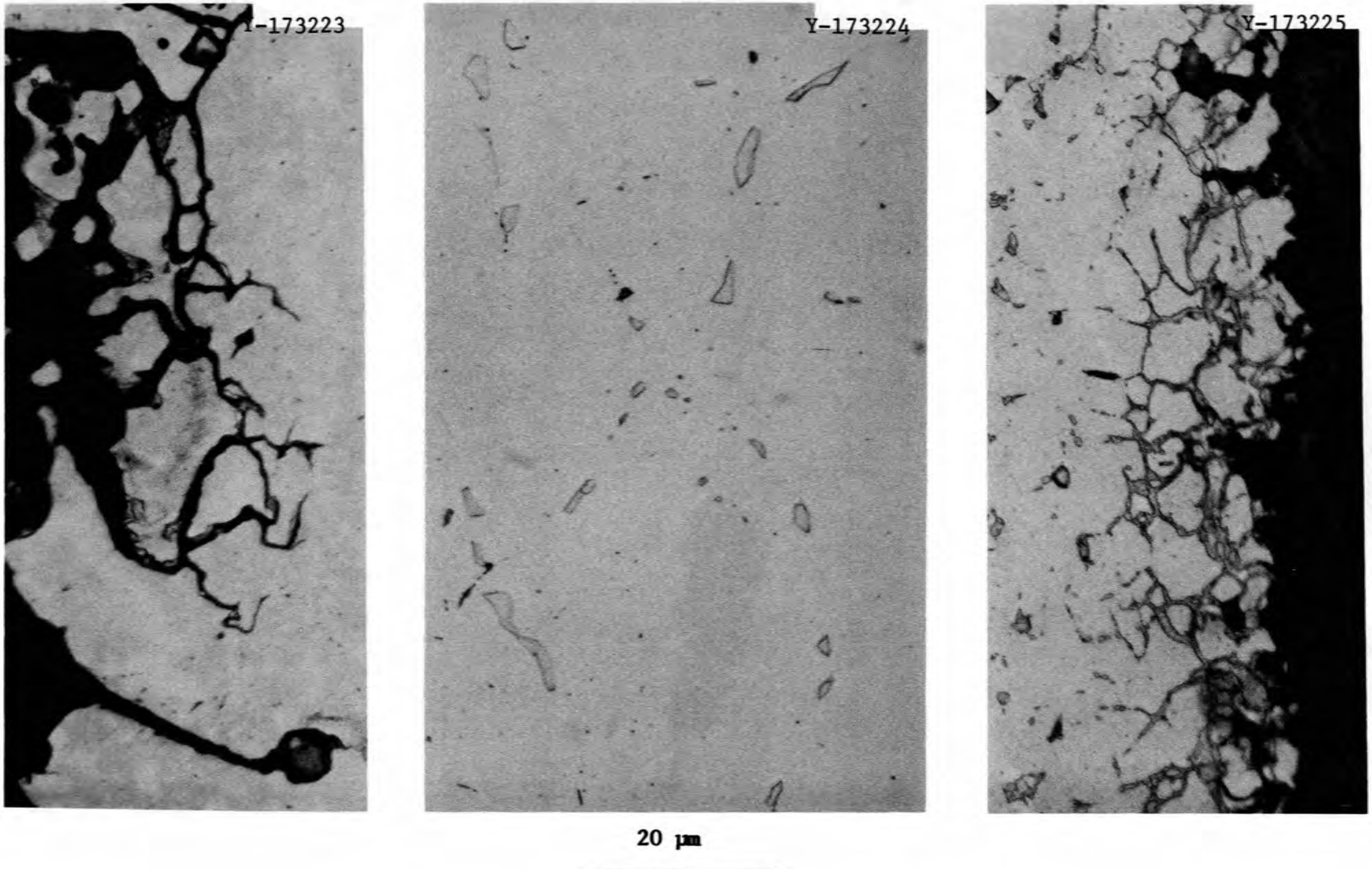

Fig. 24. High magification of outside, midthickness, and inside of section B (Fig. 19) of type 321 stainless steel tube removed from the superheater section of the TVA Kingston power plant.

The cracking of the as-removed tubes of type 321 stainless steel during flattening is probably the result of propagation of the cracks present at grain boundaries near the tube outer surface along the sigma-phase-embrittled grain boundaries across the wall thickness. The absence of any cracking during flattening of the reannealed tubes is a result of dissolution of sigma phase and consequent elimination of embrittled boundaries.

The leak during service after transition joint repair is possibly a result of the same mechanism as suggested above except that cracks propagated as a result of thermal stresses from welding repair.

SUMMARY AND CONCLUSIONS

The performance of modified 9 Cr-1 Mo, HT9, type 316 stainless steel, and type 321 in the ASTM flattening test (A 530) is presented. The modified 9 Cr-1 Mo tubes tested were made by centrifugal casting and cold pilgering and by hot extrusion. The modified 9 Cr-1 Mo and HT9 were tested in the normalized and tempered condition and after aging for 3000 h at 482, 538, 593, 649, and 704°C. Both alloys were also tested in the welded and heat-treated condition. Type 316 was tested in the mill-annealed condition. Type 321 was tested as removed from the superheater section of the TVA Kingston power plant and after solution annealing.

The following conclusions can be drawn from this work:

1. Modified 9 Cr-1 Mo tubes flattened until the sides met without any cracking in the normalized and tempered condition (1038°C, 1 h; 760°C, 1 h) for tubes made by two different processes; after aging 3000 h at 482, 538, 593, 649, and 704°C; and after welding and heat-treating 1 h at 732°C. The tube flattening characteristics of this alloy are similar to those of type 316 stainless steel tested in the mill-annealed condition.

2. The HT9 tubes cracked before flattening for both heats in the normalized and tempered condition. Tubes from one heat also cracked after aging 3000 h at 482, 538, 593, and 649°C but did not crack after aging at 704°C. Tubes of HT9 also cracked while flattening after welding and heat-treating 1 h at 732°C. The cracking in the welded tube initiated in the base metal.

3. Microstructural observations showed only small changes in modified 9 Cr-1 Mo after aging 3000 h at 482, 538, 593, and 649°C. Aging at 704°C produced some cleaning of the matrix, but the grain boundary carbide was still very fine.

4. Carbide in HT9 coarsened significantly after aging for 3000 h at 704°C. Coarse carbide helped relieve strains during flattening by nucleating voids at the interfaces. Some strains were also relieved by deformation in the relatively cleaner matrix. Both these factors allowed complete flattening of HT9 tubes after aging for 3000 h at 704°C.

5. Type 321 stainless steel tubes removed from service in the Kingston power plant failed during flattening at a height that reflected limited residual ductility. Solution annealing allowed complete flattening without any cracking. The microstructure of the as-removed type 321 showed a very fine grain structure near the inner surface and a coarse grain structure in the rest of the tube thickness. A continuous layer of sigma phase was present at the grain boundaries on the tube inner surface. The grain boundaries near the outer surface were cracked, and sigma phase particles were present at grain boundaries throughout the wall thickness. The cracking during flattening in type 321 stainless steel is believed to occur as a result of crack propagation along the sigma-phase-embrittled boundaries.

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