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FACTORS AFFECTING THE DUCTILITY OF IRON-CHROMIUM-ALUMINUM ALLOY SHEET

by

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An evaluation of induction-melting and fabrication procedures for the iron-25 w/o chromium-5 w/o aluminum alloy and the use of yttrium, niobium, and titanium as grain refiners in the alloy was undertaken. Melts were prepared from different grades of iron and chromium under various conditions of furnace atmospheres, slags, and melt hold times.

Copper, nitrogen, and probably silicon, present in starting materials, were found to be detrimental to bend ductility. In vacuum-induction melting, a long hold time after all additions were made removed volatile elements, including copper, and nullified the harmful effects of nitrogen, thereby improving bend ductility. It was found that a vacuum-melting procedure involving a long hold time after additions allows the use of ferrochromium as a substitute for high-purity grades of chromium. Nitrogen introduced during melting or welding destroys the high-temperature oxidation resistance of the alloy. A thermal exposure in air at 2100 F for 100 hr cancelled any beneficial effects in bend ductility derived from a short-time 1500 F anneal. Grain size showed no relationship to bend ductility

Yttrium and combined niobium-carbon additives to the iron-chromium-aluminum alloy reduced both grain size and grain growth, but these additives did not improve ductility. Titanium acted only as an embrittling contaminant.

INTRODUCTION

Alloys composed of iron, chromium, and aluminum possess properties of potential value as structural materials in high-temperature air or gas atmospheres. Of particular interest is the iron-25 w/o chromium-5 w/o aluminum alloy, which is characterized by excellent oxidation resistance at temperatures as high as 2100 F and by a high coefficient of expansion.(1) These qualities are potentially valuable in a structural and cladding material. However, the alloy must also possess reproducible characteristics of ductility and weldability. Ductility, in this case, refers to bend ductility since the material must be formable and retain a degree of toughness throughout a reasonable high-temperature exposure. A low rate of grain growth during prolonged exposures at high temperature would appear to be desirable to maintain ductility over the required service life.

These demands prompted a research program which had for its objectives (1) the evaluation of starting materials and processing procedures that might affect the reproducibility of characteristics in iron-chromium-aluminum alloys, and (2) the appraisal of a group of additives, including niobium, titanium, and yttrium, which were selected for their potential as grain refiners. In preparing materials, the operations evaluated were vacuum and inert-gas induction melting, fabrication, annealing, and welding. To simulate an exposure which might be encountered in service, specimens of sheet and weldments of all alloys were subjected to a 100-hr exposure in air at 2100 F. Evaluations were based upon the results of chemical analyses, hardness tests, weld-integrity (X-ray)

(1) References at end.

tests, metallographic examinations of specimens during the various processing stages, and room-temperature bend tests.

PREPARATION OF MATERIALS

Melting

Fifteen-pound ingots of the iron-25 w/o chromium-5 w/o aluminum alloy were prepared in an induction furnace using the following melting variations:

(1) Vacuum compared with an inert atmosphere of argon.

(2) No slag compared with a 1 w/o slag addition (composed of 60 w/o CaO-40 w/o Al_2O_3).

(3) Holding times at the pouring temperature of 1/4 or 3 hr before or after the aluminum addition.

(4) Charges of commercially available electrolytic iron and laboratory-grade electrolytic chromium compared with charges of Armco iron and low-carbon ferrochromium.

A fixed melting and pouring temperature of 2825 F (±25 F), measured by a dip-thermocouple technique, was maintained for all melts because past experience[2] had indicated that at higher temperatures reactions between the alumina crucible and some of the charge component (particularly yttrium) become rapid. Moreover, ingots cast at temperatures near the melting point have a finer grain structure than ingots poured at higher temperatures. Typical analyses of the starting materials are given in Table 1. Charge materials used in the grain-refiner investigation were again of two types: (1) electrolytic grades of iron and chromium, and (2) electrolytic iron and low-carbon ferrochromium. Armco iron was not used because of its copper content. The two grades of chromium were chosen in order to compare the use of relatively high-priced laboratory-grade electrolytic chromium with low-cost ferrochromium. Each quaternary addition was introduced (mixed with the aluminum) to produce a nominal 1 w/o alloy addition. Iron-25 w/o chromium-5 w/o aluminum-1/2 w/o niobium-1/2 w/o titanium alloys were also prepared. All melting operations of quaternary alloys were conducted in a vacuum of less than 10^{-3} mm of mercury. Melts were maintained at 2825 F for 1/4 hr before and after the aluminum addition.

TABLE 1. TYPICAL ANALYSES OF STARTING MATERIALS

Material	Chemical Analysis, ppm								
	C	Si	N	O	S	P	Cu	Mn	Other
Electrolytic iron	70	10	--	40	30	30	2	0.1	--
Armco iron	170	50	--	860	220	<30	2700	500	--
Iodide chromium	30	<20	<5	6	3-15	<5	1-2	<2	--
Laboratory grade electrolytic chromium	30	<10	20	5100	160	--	1-5	<2	--
Low-carbon ferrochromium	500	2500	1100	450	40	140	150	150	--
2S aluminum wire	--	800	<10	--	--	--	1100	500 (max)	1000 Zn (max)

Fabrication

In all cases, forging temperatures were selected on the basis of preliminary forging tests on pilot ingots that were prepared as a 1-lb appendage at the bottom of each 15-lb casting as shown in Figure 1. Ingots of the ternary alloys as well as those containing quaternary additions of niobium and titanium were forged at 2100 F to 1-in. plate and hot rolled at 2000 F to 90- or 60-mil sheet. The 90-mil sheet was then cold rolled to 80 mils and the 60-mil sheet was cold rolled to 20 mils. The only exception to the above procedure was that materials containing yttrium were forged at 2400 F to prevent cracking.

Annealing

Small sections of the cold-rolled alloys (80 and 20 mils thick) were annealed so that the physical characteristics of annealed sheet could be compared with those of cold-rolled sheet both before and after thermal-exposure tests. Based on preliminary tests, an anneal of 1/2 hr in air at 1500 F followed by air cooling was chosen.

Welding

Welding tests were performed on cold-rolled and on annealed 20-mil sheet, and consisted of butt welding by automatic Heliarc welding two sections of sheet having rolling directions oriented at right angles to each other. In order to be able to compare the effects of metal processing on welding, the welding operation was standardized as follows:

(1) Metal strips were ground flat on mating edges, wire brushed, and cleaned in acetone.

(2) These strips were butted together and clamped on an air-cooled copper jig.

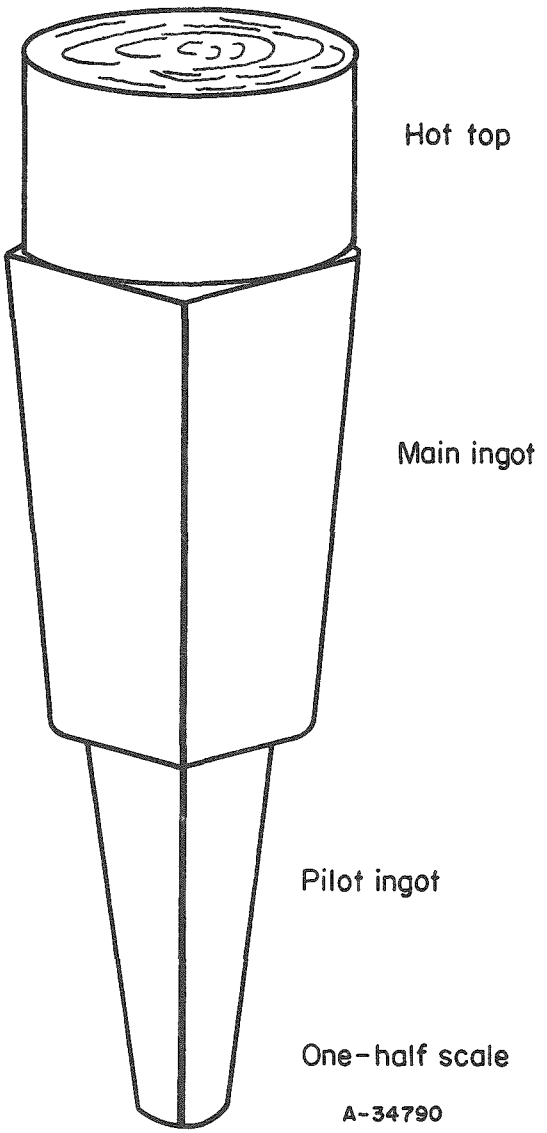


FIGURE 1. CONFIGURATION OF 15-LB EXPERIMENTAL INGOT

(3) Argon was used as an arc cover at a rate of 10 ft^3 per hr. (Initial experiments to determine the best argon flow indicated that higher flow rates led to poor arc control and poor protection due to turbulence of the gas.)

(4) The arc potential was 10 v and the arc current was 50 amp for sheet 20 to 23 mils in thickness.

(5) A welding speed of 4-1/4 in. per min was employed.

PROCESS OBSERVATIONS

Melting

Holding the melt for 3 hr in a vacuum in the order of 10^{-3} mm of mercury at a temperature of 2825 F, either before or after the aluminum addition, removed the more volatile constituents such as copper and manganese. Table 2 illustrates the effect of holding time in a vacuum on the removal of copper and manganese. As may also be seen in Table 2, removal of nitrogen during long hold periods in a vacuum was not clearly demonstrated, although this type of treatment of the melt evidently eliminated the deteterious effects of nitrogen. Further investigation of the role of nitrogen in the alloy appears to be warranted.

Melting conditions which hampered the removal of volatile contaminants, as illustrated in Table 2, were the use of an artificial slag and melting under a 1-atm pressure of argon. Admission of nitrogen to the molten alloy during pouring by way of an air leak to the furance destroyed the beneficial effect of a long hold period. These conditions resulted in very poor bend ductility of cold-rolled sheet, especially where contamination stemming from starting materials was high.

Fabrication

The effect of impurities in the iron-chromium-aluminum alloy usually manifests itself in the quality of fabricated sheet. Consequently, most of the metal evaluations were based on tests and examinations of sheet specimens of finished thickness. Chemical analyses were purposely restricted to the materials in the form of 20-mil sheet so that correlation might be made between the analyses and the effects of subsequent processing, e.g., welding and thermal exposure. The analyses and conditions of preparation of the various alloys are shown in Table 3. Included for purposes of comparison is the analysis of an iron-25 w/o chromium-5.5 w/o aluminum alloy, that was produced by a commercial vendor.

The maximum quantity of impurities found in any of the test sheets, viz., 800 ppm carbon, 800 ppm nitrogen, 6,000 ppm silicon, 1,100 ppm copper, 2,000 ppm manganese, 5,000 to 10,000 ppm nickel, 500 ppm cobalt, 150 ppm tin, and 2,000 ppm vanadium had no obvious effect on the hot-fabrication behavior of either the ternary iron-chromium-aluminum alloys or the quaternary alloys containing grain refiners. All ingots were

TABLE 2. THE EFFECT OF MELTING VARIATIONS ON RETAINED VOLATILES IN IRON-25 w/o CHROMIUM-5 w/o ALUMINUM ALLOYS PREPARED FROM ARMCO IRON, FERROCHROMIUM, AND 2S ALUMINUM

Heat	Melting and Casting Conditions				Analysis, ppm			Transverse Bend Radius Before Breaking[b], in.
	Holding Time, hr							
	Before Aluminum Addition	After Aluminum Addition	Artificial Slag	Atmosphere	Cu	Mn	N	
28	1/4	1/4	None	Vacuum	1000-2000	100	260	>1-1/2
29	3	1/4	None	Vacuum	100	<100	210	>1-1/2
32	0	3	None	Vacuum	30	<100	400	Sharp 180-deg bend without cracking
33	0	3	None	1-atm argon	1000-2000	2000	560	>1-1/2
34	1/4	1/4	1 w/o of charge[c]	Vacuum	1000-2000	2000	600	>1-1/2
50	0	3	None	Air leak during pouring, 500 μ	30	<100	800	>1-1/2

(a) The ferrochromium used contained 1100 ppm nitrogen which introduced about 400 ppm nitrogen into the alloy. The Armco iron and 2S aluminum contributed the copper and manganese.

(b) Materials were bent over a series of 75-deg, wedge-shaped mandrels the apexes of which were ground to various radii. Specimens 80 mils thick and all prepared under like fabricative conditions are compared.

(c) Slag composition: CaO - 40 w/o Al_2O_3.

forged and hot rolled without the development of edge or surface cracks. There was some evidence that hot-rolled 90-mil-thick sheet was more likely to crack during cold rolling than 60-mil-thick hot-rolled sheet.

A room-temperature bend test was used to compare the effect of the various process changes upon ductility. In this test, materials were bent over a series of 75-deg, wedge-shaped mandrels (105-deg bends) the apexes of which were ground to various radii. Results were recorded in terms of the least radius over which a specimen could be bent without cracking. Specimens were prepared so that the bend tests could be made both parallel (longitudinal specimen) and perpendicular (transverse specimen) to the direction of rolling. The bend test was more critical as a measure of bend ductility on transverse than on longitudinal specimens. Bend-test data for cold-rolled specimens are summarized in Table 4. Included are data for sheet prepared from alloys to which copper was deliberately added in two instances but substantially removed in one case by a 3-hr hold time at temperature. Also included are data for sheet prepared from an alloy which was deliberately exposed to air during pouring.

The tests indicate that bend ductility was impaired by copper, nitrogen, and probably silicon. The effect was especially evident in 80-mil sheet which could be bent in a sharp 180-deg bend only if these impurities were at a minimum. Tolerance levels of impurities were not determined, but there is reason to believe that embrittling effects may begin at levels as low as 400 ppm copper, 300 ppm nitrogen, and 5000 ppm silicon. A carbon content of 800 ppm appeared to have little effect.

Similar bend tests of quaternary alloys showed that titanium and, to a lesser extent, yttrium resulted in lower than normal bend ductility in cold-rolled 20-mil sheet (Table 5). Each of the quaternary elements (titanium, yttrium, and niobium) imparted extreme embrittlement, i.e., 1-1/2 in. bend radii, to the cold-rolled 80-mil sheet. Addition of 700 ppm carbon to the iron-chromium-aluminum-niobium alloy had no effect on bend ductility of cold-rolled sheet.

Of the elements added in an attempt to produce grain refinement, only yttrium was observed to reduce grain size substantially. Transverse grains of cold-rolled sheet of the ternary alloys averaged (calculated) about ASTM No. 3 in size; the quaternary alloys containing yttrium were about ASTM No. 5 in size. Niobium or titanium had no observable effect; however, the iron-chromium-aluminum-niobium-carbon alloy approached in grain size ASTM No. 4. Figure 2 shows the cold-rolled structures of 20-mil sheet (transverse sections) of each of the alloys prepared from electrolytic iron and chromium. A typical ternary is also shown in Figure 2 for comparison.

During this program it was observed that some of the materials exhibited brittleness as 80-mil cold-rolled sheet, but were relatively ductile as 20-mil cold-rolled sheet. In an attempt to improve ductility of sheet by increasing the amount of reduction, these materials were cold rolled from 90 to 60 mils (35 per cent reduction) instead of to 80 mils. Increasing the reduction did not improve bend ductility, however, but hot rolling to 60 mils thickness followed by as little as 10 per cent reduction produced sheet exhibiting good bend ductility. The occurrence of the embrittlement in the 80-mil sheet may be due to the cooling rate of the metal after hot rolling. The thicker stock cools slower, allowing time for a precipitation reaction to occur. In the thinner section, the cooling rate may have been sufficient to avoid precipitation.

TABLE 3. PREPARATIONAL AND ANALYTICAL DATA

Heat	Melting Data: Materials: Type of Iron	Melting Data: Materials: Type of Chromium	Melting Data: Holding Time, hr: Before Aluminum Addition	Melting Data: Holding Time, hr: After Aluminum Addition	Special Conditions	Chemi-: Cr, w/o	Chemi-: Al, w/o	Chemi-: C, ppm	Chemi-: N[b], ppm
Commercial	--	--	--	--	Process history unknown	24.3	5.46	800	60
21	Electrolytic	Iodide	1/4	1/12	Vacuum	25.2	5.20	300	330
22	Electrolytic	Electrolytic	1/4	1/4	Vacuum	24.2	4.88	400	170
25	Electrolytic	Electrolytic	3	1/4	Vacuum	22.1	5.50	300	170
23	Electrolytic	Electrolytic	0	1/4	Vacuum	24.3	4.94	400	140
26	Electrolytic	Electrolytic	0	3	Vacuum	21.4	4.57	300	100
24	Electrolytic	Electrolytic	0	1/4	Argon	23.8	4.87	400	120
27	Electrolytic	Electrolytic	0	3	Argon	25.0	5.05	300	220
37	Electrolytic	Electrolytic	1/4	1/4	Vacuum; slag	25.0	4.67	300	270
38	Electrolytic	Electrolytic	0	1/4	Vacuum; slag	25.1	4.54	200	100
39	Electrolytic	Electrolytic	0	1/4	Argon; slag	25.2	4.67	200	340
28	Armco	Ferro-chromium	1/4	1/4	Vacuum	25.2	5.13	300	260
31	Armco	Ferro-chromium	3	1/4	Vacuum	22.7	5.59	300	210
29	Armco	Ferro-chromium	0	1/4	Vacuum	25.3	4.70	300	280
32	Armco	Ferro-chromium	0	3	Vacuum	22.3	4.88	400	400
30	Armco	Ferro-chromium	0	1/4	Argon	25.6	5.09	300	400
33	Armco	Ferro-chromium	0	3	Argon	25.8	4.84	400	560
34	Armco	Ferro-chromium	1/4	1/4	Vacuum; slag	26.2	5.14	400	600
35	Armco	Ferro-chromium	0	1/4	Vacuum; slag	25.8	5.08	400	260
36	Armco	Ferro-chromium	0	1/4	Argon; slag	25.8	5.06	400	440
47	Electrolytic	Ferro-chromium	1/4	1/4	No copper added	25.3	5.1	--	420
48	Electrolytic	Electrolytic	0	3	0.16 w/o copper added	24.8	4.7	--	400
49	Electrolytic	Electrolytic	0	1/4	0.16 w/o copper added[d]	25.5	5.1	--	400
50	Armco	Ferro-chromium	0	3	Repeat of Heat 32	22.6	4.9	--	800
59	Armco	Ferro-chromium	0	3	Repeat of Heat 32[e]	23.5	4.6	--	120
51	Electrolytic	Electrolytic	1/4	1/4	1 w/o niobium added	24.9	4.6	300	20
52	Electrolytic	Electrolytic	1/4	1/4	1 w/o titanium added	25.5	4.7	200	20

FOR THE IRON-CHROMIUM ALUMINUM ALLOYS STUDIED

Analyses (Balance Nominally Iron) of 20-Mil Sheet

cal				Semiquantitative Spectrographic[a]										
S, ppm	P, ppm	O, ppm	H, ppm	Cu, ppm	Si, ppm	Ni, ppm	Mo, ppm	Co, ppm	V, ppm	B, ppm	Mn, ppm	Nb, w/o	Ti, w/o	Y, w/o
110	100	17	0.5	200-400	1000-2000	200-500	50	<100	<100	20	<100	<0.02	<0.005	--
20	30	67	0.4	200-400	1000-2000	200-500	50	<100	<100	<10	<100	<0.02	<0.005	--
40	30	21	<0.5	100-200	1000-2000	200-500	50	<100	<100	<10	<100	<0.02	<0.005	--
--	--	34	0.9	200-400	5000-6000	200-500	50	<100	<100	<10	<100	<0.02	<0.005	--
--	--	23	0.8	100-200	1000-2000	200-500	50	<100	<100	<10	<100	<0.02	<0.005	--
--	--	22	1.2	10-50	1000-2000	200-500	50	<100	<100	<10	<100	<0.02	<0.005	--
--	--	81	1.8	200-400	1000-2000	200-500	50	<100	<100	<10	<100	<0.02	<0.005	--
--	--	31	1.6	200-400	500-1000	200-500	50	<100	<100	<10	<100	<0.02	<0.005	--
--	--	28	1.3	100-200	500-1000	200-500	<50	<100	<100	10	<100	<0.02	<0.005	--
--	--	21	1.7	100-200	500-1000	200-500	<50	<100	<100	10	<100	<0.02	<0.005	--
--	--	40	3.2	100-200	500-1000	200-500	<50	<100	<100	10	<100	<0.02	<0.005	--
80	--	50	1.6	1000-2000	3000-4000	2,000-3,000	50-150	200-500	<10	<10	100	<0.02	<0.005	--
--	--	74	0.4	100[c]	1000-2000	2,000-3,000	50-150	200 500	10	10	<100	<0.02	<0.005	--
--	--	37	0.7	1000-2000	3000-4000	2,000-3,000	50-150	200-500	<10	<10	500	<0.02	<0.005	--
70	120	28	1.3	30[c]	1000-2000	2,000-3,000	50-150	200-500	10	10	<100	<0.02	<0.005	--
--	--	37	0.9	1500[c]	1000-2000	2,000-3,000	50-150	200-500	10	10	2000	<0.02	<0.005	--
--	--	16	0.6	1000-2000	1000-2000	2,000-3,000	50-150	200-500	10	10	2000	<0.02	<0.005	--
--	--	13	0.5	1000-2000	1000-2000	2,000-3,000	50	200-500	10	10	2000	<0.02	<0.005	--
--	--	11	0.4	1000-2000	1000-2000	2,000-3,000	50	200-500	10	10	2000	<0.02	<0.005	--
60	110	12	<0.4	1000-2000	1000-2000	2,000-3,000	50	200-500	10	10	2000	<0.02	<0.005	--
--	--	--	--	170[c]	2000	5,000	<50	200	1000	<10	500	<0.02	<0.005	--
--	--	--	--	100[c]	1000	5,000	<50	<100	<100	<10	<100	<0.02	<0.005	--
--	--	--	--	1100[c]	1000	5,000	<50	<100	<100	<10	<100	<0.02	<0.005	--
--	--	39	1.5	30[c]	2000	5,000	50	100	500	<10	<100	<0.02	<0.005	--
--	--	14	0.8	80[c]	2000	5,000 to 10,000	50	200	1000	<10	1000	<0.02	<0.005	--
--	--	--	--	100	1000	5,000	50	<100	<100	<10	<100	0.97	<0.005	--
--	--	--	--	150	4000	1,000	50	<100	<100	<10	<100	<0.02	0.79	--

TABLE 3.

Heat	Melting Data: Materials: Type of Iron	Melting Data: Materials: Type of Chromium	Melting Data: Holding Time, hr: Before Aluminum Addition	Melting Data: Holding Time, hr: After Aluminum Addition	Special Conditions	Chemi-: Cr, w/o	Chemi-: Al, w/o	Chemi-: C, ppm	Chemi-: N[b], ppm
53	Electrolytic	Electrolytic	1/4	1/4	1/2 w/o niobium + 1/2 w/o titanium added	24.6	4.8	200	10
54	Electrolytic	Electrolytic	1/4	1/4	1 w/o niobium + 0.08 w/o carbon added	25.6	4.9	700	10
55	Electrolytic	Electrolytic	1/4	1/4	1 w/o yttrium added	23.1	5.4	--	20
56	Electrolytic	Ferro-chromium	1/4	1/4	1 w/o niobium added	25.1	4.6	200	210
57	Electrolytic	Ferro-chromium	1/4	1/4	1 w/o titanium added	25.0	5.0	200	120
58	Electrolytic	Ferro-chromium	1/4	1/4	1/2 w/o niobium + 1/2 w/o titanium added	25.5	4.8	200	180
60	Electrolytic	Ferro-chromium	1/4	1/4	1 w/o yttrium added	26.0	5.1	--	30

(a) In all cases: lead, <20 ppm; tungsten, <200 ppm; zirconium, <300 ppm; tin, <100.
(b) Kjeldahl method.
(c) Rechecked by chemical analysis.
(d) Simulated air leak.
(e) Good vacuum (<1 x 10^{-3} mm mercury).

(Continued)

Analyses (Balance Nominally Iron) of 20-Mil Sheet

cal				Semiquantitative Spectrographic[a]										
S, ppm	P, ppm	O, ppm	H, ppm	Cu, ppm	Si, ppm	Ni, ppm	Mo, ppm	Co, ppm	V, ppm	B, ppm	Mn, ppm	Nb, w/o	Ti, w/o	Y, w/o
--	--	--	--	150	4000	1,000	<50	<100	<100	<10	<100	0.38	0.46	--
--	--	--	--	150	1000-2000	1,000	50	<100	<100	<10	<100	0.88	<0.005	--
--	--	--	--	150	1000-2000	1,000	<50	<100	<100	<10	<100	<0.02	<0.005	0.38
--	--	30	0.1	70[c]	1000-2000	5,000	50	200	500	<10	<100	0.97	<0.005	--
--	--	21	0.9	110[c]	3000	3,000	50	200	2000	10	100	<0.02	0.78	--
--	--	--	--	130[c]	2000	5,000 to 10,000	50	200	1000	10	2000	0.42	0.45	--
--	--	--	--	150	2000	5,000 to 10,000	50	200	1000	<10	2000	<0.02	<0.005	0.54

TABLE 4. EFFECT OF PROCESS VARIABLES ON ROOM-TEMPERATURE BEND DUCTILITY OF THE IRON-CHROMIUM-ALUMINUM ALLOYS STUDIED

Heat	Melting Data: Materials: Type of Iron	Melting Data: Materials: Type of Chromium	Melting Data: Holding Time, hr: Before Aluminum Addition	Melting Data: Holding Time, hr: After Aluminum Addition	Special Conditions	Minimum Bend Radius[a], in.: 80-Mil Cold-Rolled Sheet: Transverse	80-Mil Cold-Rolled Sheet: Longitudinal	20-Mil Cold-Rolled Sheet: Transverse	20-Mil Cold-Rolled Sheet: Longitudinal	Chemical Analysis, ppm: Cu	Chemical Analysis, ppm: N	Chemical Analysis, ppm: Si
21	Electrolytic	Iodide	1/4	1/12	Vacuum	180 deg	180 deg	180 deg	180 deg	200-400	330	1000-2000
22	Electrolytic	Electrolytic	1/4	1/4	Vacuum	180 deg	180 deg	180 deg	180 deg	100-200	170	1000-2000
25	Electrolytic	Electrolytic	3	1/4	Vacuum	3/4	180 deg	180 deg	180 deg	200-400	170	5000-6000
23	Electrolytic	Electrolytic	0	1/4	Vacuum	180 deg	180 deg	180 deg	180 deg	100-200	140	1000-2000
26	Electrolytic	Electrolytic	0	3	Vacuum	180 deg	180 deg	180 deg	180 deg	10-50	100	1000-2000
24	Electrolytic	Electrolytic	0	1/4	1 atm of argon	180 deg	180 deg	180 deg	180 deg	200-400	120	1000-2000
27	Electrolytic	Electrolytic	0	3	1 atm of argon	1/4	180 deg	180 deg	180 deg	200-400	220	500-1000
37	Electrolytic	Electrolytic	1/4	1/4	Vacuum; slag	180 deg	1/2	180 deg	180 deg	100-200	270	500-1000
38	Electrolytic	Electrolytic	0	1/4	Vacuum; slag	180 deg	180 deg	180 deg	180 deg	100-200	100	500-1000
39	Electrolytic	Electrolytic	0	1/4	1 atm of argon; slag	180 deg	3/64	180 deg	180 deg	100-200	340	500-1000
28	Armco	Ferrochromium	1/4	1/4	Vacuum	>1-1/2	105 deg	1/64	180 deg	1000-2000	260	3000-4000
31	Armco	Ferrochromium	3	1/4	Vacuum	1-1/2	1/2	180 deg	180 deg	100	210	1000-2000
29	Armco	Ferrochromium	0	1/4	Vacuum	>1-1/2	3/16	1/64	180 deg	1000-2000	280	3000-4000
32	Armco	Ferrochromium	0	3	Vacuum	180 deg	180 deg	180 deg	180 deg	30	400	1000-2000
30	Armco	Ferrochromium	0	1/4	1 atm of argon	>1-1/2	>1-1/2	3/4	105 deg	1500	400	1000-2000
33	Armco	Ferrochromium	0	3	1 atm of argon	>1-1/2	1-1/2	1/4	105 deg	1000-2000	560	1000-2000
34	Armco	Ferrochromium	1/4	1/4	Vacuum; slag	>1-1/2	1/4	1-1/2	105 deg	1000-2000	600	1000-2000
35	Armco	Ferrochromium	0	1/4	Vacuum; slag	>1-1/2	>1-1/2	3/16	180 deg	1000-2000	260	1000-2000
36	Armco	Ferrochromium	0	1/4	1 atm of argon; slag	>1-1/2	>1-1/2	1-1/2	105 deg	1000-2000	440	1000-2000
Commercial	Unknown		Unknown		Unknown	-	-	1/2	180 deg	200-400	60	1000-2000
47	Electrolytic	Ferrochromium	1/4	1/4	Vacuum, no addition	105 deg	180 deg	105 deg	180 deg	170	420	2000
48	Electrolytic	Electrolytic	0	3	Vacuum, 1600 ppm of copper added	180 deg	180 deg	180 deg	180 deg	100	400	1000
49	Electrolytic	Electrolytic	1/4	1/4	Vacuum, 1600 ppm of copper added	>1-1/2	180 deg	105 deg	180 deg	1100	400	1000
50	Armco	Ferrochromium	0	3	500-μ air leak during pouring	>1-1/2	105 deg	1/8	180 deg	30	800	2000
59	Armco	Ferrochromium	0	3	Pressure of $<10^{-3}$ mm of mercury during pouring	105 deg	180 deg	180 deg	180 deg	80	120	2000

(a) Given as the minimum radius over which the specimen could be bent without rupturing; where a sharp bend was possible the value of the included angle is provided in place of the bend radius.

TABLE 5. EFFECT OF ADDITIONS ON THE ROOM-TEMPERATURE BEND DUCTILITY OF SOME NOMINAL IRON-25 w/o CHROMIUM-5 w/o ALUMINUM ALLOY[a]

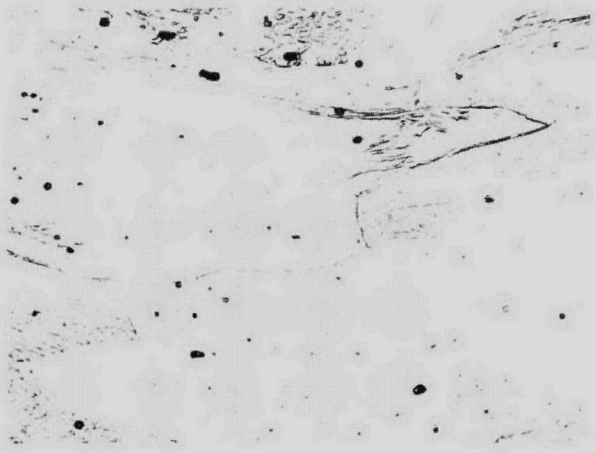
Heat	Materials: Type of Iron	Materials: Type of Chromium	Alloy Addition	Minimum Bend Radius of 20-Mil Cold-Rolled Sheet[b], in.: Transverse	Minimum Bend Radius of 20-Mil Cold-Rolled Sheet[b], in.: Longitudinal	Chemical Analysis: Nb, w/o	Ti, w/o	Y, w/o	C, ppm	N, ppm	Cu, ppm
51	Electrolytic	Electrolytic	1 w/o niobium	105 deg	180 deg	0.97	--	--	300	20	100
52	Electrolytic	Electrolytic	1 w/o titanium	>1-1/2	180 deg	--	0.79	--	200	20	150
53	Electrolytic	Electrolytic	1/2 w/o niobium + 1/2 w/o titanium	105 deg	180 deg	0.38	0.46	--	200	10	150
54	Electrolytic	Electrolytic	1 w/o niobium + 0.07 w/o carbon	105 deg	180 deg	0.88	--	--	700	10	150
55	Electrolytic	Electrolytic	1 w/o yttrium	1/8	105 deg	--	--	0.38	--	20	150
56	Electrolytic	Ferrochromium	1 w/o niobium	105 deg	180 deg	0.97	--	--	200	210	70
57	Electrolytic	Ferrochromium	1 w/o titanium	105 deg	180 deg	--	0.79		200	120	110
58	Electrolytic	Ferrochromium	1/2 w/o niobium + 1/2 w/o titanium	105 deg	180 deg	0.42	0.45		200	180	130
60	Electrolytic	Ferrochromium	1 w/o yttrium	1/4	105 deg	--	--	0.54	--	30	150

(a) All heats were held at temperature in vacuum 1/4 hr before and after the aluminum addition.

(b) Given as the minimum radius over which the specimen could be bent without breaking; where a sharp bend was possible, the value of the included angle of the bend is provided in place of the bend radius. Bend radii of 80-mil materials were greater than 1-1/2 in. in all instances.

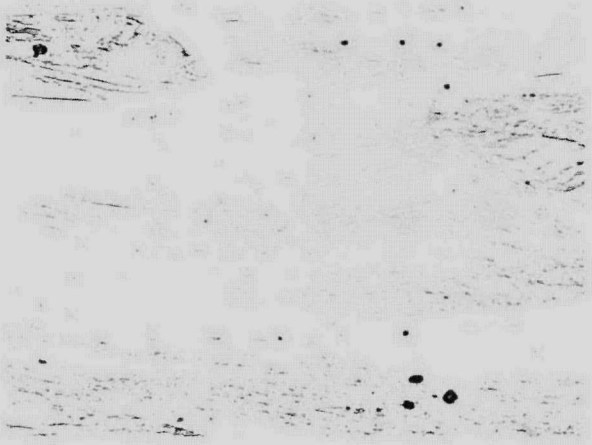
250X RM13328

a. Nominal Iron-25 w/o Chromium-5 w/o Aluminum Alloy (Heat 22)



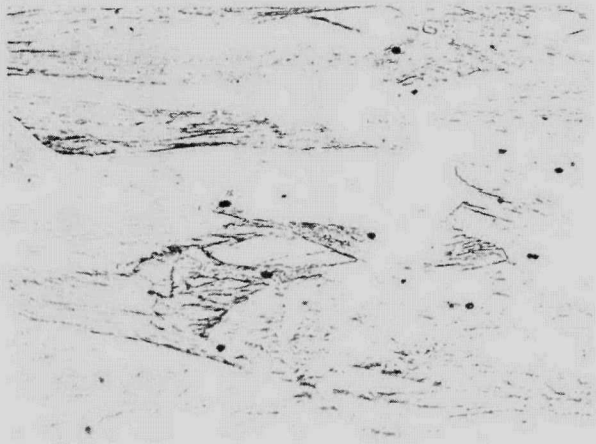
250X RM13771

b. Nominal Iron-25 w/o Chromium-5 w/o Aluminum-1 w/o Niobium Alloy (Heat 51)



250X RM13772

c. Nominal Iron-25 w/o Chromium-5 w/o Aluminum-1 w/o Titanium Alloy (Heat 52)



250X RM13774

d. Nominal Iron-25 w/o Chromium-5 w/o Aluminum-1/2 w/o Niobium-1/2 w/o Titanium Alloy (Heat 53)

250X RM13777

e. Nominal Iron-25 w/o Chromium-5 w/o Aluminum-1 w/o Niobium-0.08 w/o Carbon Alloy (Heat 54)

250X RM13778

f. Nominal Iron-25 w/o Chromium-5 w/o Aluminum-1 w/o Yttrium Alloy (Heat 55)

FIGURE 2. TYPICAL STRUCTURES OF TRANSVERSE SECTIONS FROM 20-MIL COLD-ROLLED SHEET SPECIMENS OF THE IRON-CHROMIUM-ALUMINUM ALLOYS STUDIED

All alloys shown were prepared with electrolytic iron and chromium. All sections were eteched with oxalic acid.

Annealing

Annealing at 1500 F for 1/2 hr in most cases improved room-temperature bend ductility as shown in Table 6. In some cases, materials that became glass brittle during cold working were made ductile enough by the anneal to allow a sharp 180-deg bend. Where copper and nitrogen contamination were both significant annealing was less effective, as shown in Table 7. Moreover, the beneficial effects gained by annealing materials containing significant amounts of copper and nitrogen were lost after the 100-hr thermal-exposure test conducted at 2100 F. Alloys containing titanium as an additive acted in much the same manner. It is interesting to note, however, that alloys containing yttrium retained a high degree of bend ductility after annealing and after the thermal exposure.

Welding

Only sheet containing titanium caused any serious welding difficulties. The presence of 0.4 w/o titanium caused gross cracking in the weld area. Radiographs of ternary-alloy specimens as well as specimens of the alloys with quaternary additions showed some tiny isolated voids which did not appear to be a function of previous metal treatment. Visual inspection showed some evidence of copper contamination on weld surfaces from the welding jig, but there were no weld failures that could be directly attributed to this source of contamination.

The analyses of weldments of alloy sheet, summarized in Table 8, showed: (1) that there was no significant change in chromium composition between weld metal and base metal, (2) that aluminum losses varied from no apparent loss to as much as 1.73 w/o, and (3) that the carbon content dropped appreciably in every instance.

Thermal Exposure

Thermal exposure of the alloy materials for 100 hr in air at 2100 F had little effect on the room-temperature bend ductility of materials containing small amounts of contaminants, i.e., the materials made from high-purity, electrolytic iron and chromium under conditions of good vacuum and minimum pouring temperatures. Materials containing appreciable amounts of copper or nitrogen had poor ductility after exposure (Table 7). All but one of the materials showed a variable increase in nitrogen after the thermal exposure, as can be seen in Table 9. However, bend ductility appeared relatively unaffected by nitrogen increases caused by the exposure alone. On the other hand, a large amount of nitrogen in material that had not been conditioned by a long holding time during melting was highly detrimental to both bend ductility and oxidation resistance. No explanation is given for this apparent anomaly. This was especially illustrated by specimens from Heats 50 and 59. Heat 50 was momentarily exposed to a simulated air leak during pouring (the pressure was allowed to rise to 0.5 mm of mercury and then was allowed to recover to 0.01 mm of mercury before the pouring was complete). Heat 59 was a rerun of Heat 32 to determine whether metal quality could be duplicated if procedures and materials were duplicated. Table 9 shows the comparative nitrogen content of these specimens before and after the thermal-exposure test. Note that the nitrogen content of Heat 50 was about seven times greater than that of Heat 59 before the thermal exposure, but was more than 100 times greater than the nitrogen content of Heat 59 after both had been exposed.

TABLE 6. EFFECT OF ANNEALING AND THERMAL EXPOSURE ON THE ROOM-TEMPERATURE BEND DUCTILITY OF SOME COLD-ROLLED 20-MIL IRON-CHROMIUM-ALUMINUM ALLOY SHEET SPECIMENS[a]

Heat	Materials: Type of Iron	Materials: Type of Chromium	Alloy Addition	Minimum Bend Radius[b], in.: Cold Rolled: Transverse	Cold Rolled: Longitudinal	Annealed: Transverse	Annealed: Longitudinal	Annealed and Exposed 100 Hr in Air at 2100 F: Transverse	Annealed and Exposed 100 Hr in Air at 2100 F: Longitudinal
22	Electrolytic	Electrolytic	--	180 deg	180 deg	180 deg	180 deg	180 deg	180 deg
28	Armco	Ferrochromium	--	1/64	180 deg	180 deg	180 deg	180 deg	180 deg
34	Armco	Ferrochromium	Slag cover	1-1/2	105 deg	105 deg	180 deg	105 deg	180 deg
51	Electrolytic	Electrolytic	1 w/o niobium	105 deg	180 deg	105 deg	105 deg	105 deg	180 deg
52	Electrolytic	Electrolytic	1 w/o titanium	>1-1/2	180 deg	1/16	105 deg	105 deg	105 deg
55	Electrolytic	Electrolytic	1 w/o yttrium	1/8	105 deg	180 deg	180 deg	105 deg	105 deg
56	Electrolytic	Ferrochromium	1 w/o niobium	105 deg	180 deg	105 deg	105 deg	105 deg	105 deg
57	Electrolytic	Ferrochromium	1 w/o titanium	105 deg	180 deg	105 deg	180 deg	>1-1/2	>1-1/2
60	Electrolytic	Ferrochromium	1 w/o yttrium	1/4	105 deg	105 deg	180 deg	1/64	180 deg

(a) All heats were held at temperature in vacuum 1/4 hr before and after the aluminum addition. Specimens of 80-mil sheet of the quaternary alloys (Heats 51 through 60), whether annealed or annealed and thermally exposed, all had bend radii greater than 1-1/2 in.

(b) Given as the minimum radius over which the specimen could be bent without rupturing; where a sharp bend was possible, the value of the included angle of the bend is shown in place of the bend radius.

TABLE 7. RELATION OF COPPER AND NITROGEN CONTENT TO THE EFFECTIVENESS OF ANNEALING IN IMPROVING THE ROOM-TEMPERATURE DUCTILITY OF SOME COLD-ROLLED 80-MIL IRON-CHROMIUM-ALUMINUM ALLOY SHEET SPECIMENS

			Minimum Bend Radius[a], in.						
	Analysis, ppm		Cold Rolled		Annealed		Annealed and Exposed 100 Hr in Air at 2100 F		
Heat	Copper	Nitrogen	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Notes
22	100-200	170	180 deg	180 deg	180 deg	180 deg	180 deg	180 deg	--
30	1500	400	>1-1/2	>1-1/2	>1-1/2	3/4	1/4	3/32	--
33	1000-2000	560	>1-1/2	>1-1/2	3/64	1/32	3/4	1/4	--
34	1000-2000	600	>1-1/2	1/4	3/64	3/32	1-1/2	3/4	--
35	1000-2000	260	>1-1/2	>1-1/2	1/8	1/64	1-1/2	1-1/2	--
36	1000-2000	440	>1-1/2	>1-1/2	1-1/2	>1/2	1-1/2	1-1/2	--
50	30	800	>1-1/2	>1-1/2	105 deg	180 deg	105 deg	180 deg	Specimen badly oxidized after thermal exposure (see Figure 8)

(a) Given as the minimum radius over which the specimen could be bent without breaking; where a sharp bend was possible, the value of the included angle of the bend is given in place of the bend radius.

TABLE 8. ANALYSES OF WELDMENTS IN 20-MIL COLD ROLLED NOMINAL IRON-25 w/o CHROMIUM-5 w/o ALUMINUM ALLOY SHEET SPECIMENS

Heat	Melting Data					Chemical Analysis					
	Materials		Holding Time, hr			Weldment			Base Metal		
	Type of Iron	Type of Chromium	Before Aluminum Addition	After Aluminum Addition	Other Process Conditions	Cr, w/o	Al, w/o	C, ppm	Cr, w/o	Al, w/o	C, ppm
Commercial	--	--	--	--	Unknown	24.4	5.39	100	24.3	5.46	800
21	Electrolytic	Iodide	1/4	1/12	Vacuum	25.1	4.96	100	25.2	5.20	300
22	Electrolytic	Electrolytic	1/4	1/4	Vacuum	24.5	4.53	100	24.2	4.88	400
25	Electrolytic	Electrolytic	3	1/4	Vacuum	22.3	5.52	100	22.1	5.50	300
23	Electrolytic	Electrolytic	0	1/4	Vacuum	24.5	3.21	100	24.3	4.94	400
26	Electrolytic	Electrolytic	0	3	Vacuum	21.6	4.29	100	21.4	4.57	300
24	Electrolytic	Electrolytic	0	1/4	Argon	23.9	4.91	100	23.8	4.87	400
27	Electrolytic	Electrolytic	0	3	Argon	24.6	4.56	100	25.0	5.05	300
37	Electrolytic	Electrolytic	1/4	1/4	Vacuum; slag	24.6	4.78	100	25.0	4.67	300
38	Electrolytic	Electrolytic	0	1/4	Vacuum; slag	24.9	4.78	100	25.1	4.54	200
39	Electrolytic	Electrolytic	0	1/4	Argon; slag	25.2	4.83	100	25.2	4.67	200
28	Armco	Ferrochromium	1/4	1/4	Vacuum	25.3	4.77	100	25.2	5.13	300
31	Armco	Ferrochromium	3	1/4	Vacuum	22.6	4.75	100	22.7	5.59	300
29	Armco	Ferrochromium	0	1/4	Vacuum	25.4	4.86	100	25.3	4.70	300
32	Armco	Ferrochromium	0	3	Vacuum	21.9	4.45	100	22.3	4.88	400
30	Armco	Ferrochromium	0	1/4	Argon	25.7	4.70	200	25.6	5.09	300
33	Armco	Ferrochromium	0	3	Argon	25.4	4.03	100	25.8	4.84	400
34	Armco	Ferrochromium	1/4	1/4	Vacuum; slag	26.0	4.84	100	26.2	5.14	400
35	Armco	Ferrochromium	0	1/4	Vacuum; slag	25.6	4.79	100	25.8	5.08	400
36	Armco	Ferrochromium	0	1/4	Argon; slag	25.4	4.86	100	25.8	5.06	400

TABLE 9. EFFECT OF EXPOSURE IN 2100 F AIR FOR 100 HR ON THE NITROGEN CONTENT OF IRON-CHROMIUM-ALUMINUM ALLOY SPECIMENS

Heat	Materials		Alloy Addition	Holding Time, hr		Other Process Conditions	Nitrogen Content, ppm	
	Type of Iron	Type of Chromium		Before Aluminum Addition	After Aluminum Addition		Before Exposure	After Exposure
47	Electrolytic	Ferrochromium	--	1/4	1/4	Vacuum	420	21,000
48	Electrolytic	Electrolytic	1600 ppm copper	0	3	Vacuum	400	2,900
49	Electrolytic	Electrolytic	1600 ppm copper	1/4	1/4	Vacuum	400	6,200
50	Armco	Ferrochromium	--	0	3	Vacuum (air leak during pouring)	800	15,000
51	Electrolytic	Electrolytic	1 w/o niobium	1/4	1/4	Vacuum	20	40
54	Electrolytic	Electrolytic	1 w/o niobium + 0.07 w/o carbon	1/4	1/4	Vacuum	10	80
55	Electrolytic	Electrolytic	1 w/o yttrium	1/4	1/4	Vacuum	20	100
56	Electrolytic	Ferrochromium	1 w/o niobium	1/4	1/4	Vacuum	200	200
59	Armco	Ferrochromium	--	0	3	Vacuum	120	140
60	Electrolytic	Ferrochromium	1 w/o yttrium	1/4	1/4	Vacuum	30	140

Figure 3 compares surfaces of thermally exposed weld specimens of these materials with each other and with an exposed specimen of a quaternary alloy (Heat 55) containing yttrium. As expected, the materials containing yttrium had extraordinary resistance to oxidation.

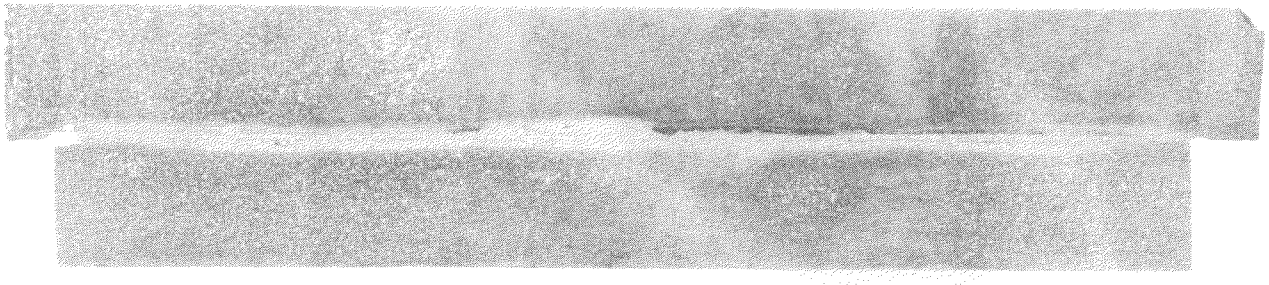
Although the grains of weldments and sheet specimens grew roughly twice in size during the thermal exposure, no correlation between grain growth or grain size could be made with bend ductility. Hardness of specimens, given in Table 10, could not be correlated with the ductility as indicated by bend tests, and the hardnesses of thermally exposed specimens were found to be essentially the same as in the annealed state prior to exposure. Radiographs of sheet and weldment specimens revealed no loss of weld integrity as a result of the thermal exposure.

It is of interest to note, as shown in Table 10, that annealing of sheet before welding had a definite effect on the hardness of welds. In the weld zone of annealed sheet the difference in hardness between nonexposed and thermally exposed specimens is significant. It is suspected that these differences are caused by changes in composition resulting from the welding process; subsequently, the base composition is in effect re-established by diffusion during the long (100 hr) high-temperature exposure. Apparently surface contamination produced by gases such as oxygen and nitrogen occurs during annealing and results in the loss of an alloy constituent. Variations in aluminum content would cause such changes in hardness, and the data show that hardnesses were generally low in sheet specimens that were low in aluminum content.

After the thermal exposure, visual examination of the specimens revealed that the surfaces of the quaternary alloys containing niobium had about as much scale as the ternary alloy materials. Materials containing titanium were more scaled, and any cracking that was evident before exposures continued to develop during the exposure in both weldment and sheet specimens. Materials containing yttrium showed the least scaling of all the alloys, and no cracking was discernible in radiographs. An examination of the microstructures of weldments and sheets after the thermal exposure revealed that the grain size of materials containing yttrium remained at about ASTM No. 4, roughly one-half the size of ternary-alloy specimens which were similarly exposed. A similar situation occurred in an alloy containing both 1 w/o niobium and 0.07 w/o carbon (Heat 54); however, additions of niobium (with no carbon additions) and titanium produced little grain refinement. Nitrogen pickup resulting from the thermal exposure was very low in all of the quaternaries.

Quaternary-alloy specimens of 80-mil sheet were not prepared for bend specimens because of brittleness, as noted earlier; however, specimens of 20-mil stock were prepared. The quaternary alloys prepared from ferrochromium and containing titanium which were subjected to the thermal exposure became embrittled, as shown in Table 6. Materials containing niobium and yttrium were fairly ductile after the thermal exposure; 20-mil specimens of the material containing both niobium and carbon were as ductile as any of the other materials similarly exposed.

a. Heat 50
This Armco iron-25 w/o ferrochromium-5 w/o 2S aluminum alloy was melted in vacuum and held 3 hr at 2825 F before pouring. A minor air leak was simulated at the time of pouring.



b. Heat 59
Conditions for this heat duplicated those of Heat 50 except that a good vacuum was maintained throughout. The surface shown is typical of most of the ternary alloys exposed.

c. Heat 55
This electrolytic iron-25 w/o electrolytic chromium-5 w/o aluminum-1 w/o yttrium alloy exhibited no surface scaling after the exposure.

N59955

FIGURE 3. IRON-CHROMIUM-ALUMINUM ALLOY 20-MIL WELD SPECIMENS AFTER EXPOSURE IN 2100 F AIR FOR 100 HR

TABLE 10. SUMMARY OF HARDNESS DATA FOR THE IRON-CHROMIUM-ALUMINUM ALLOYS STUDIED

Heat	Materials: Type of Iron	Materials: Type of Chromium	Alloy Addition	Holding Time, hr: Before Aluminum Addition	Holding Time, hr: After Aluminum Addition	Other Special Conditions	Vickers Hardness (5-Kg Load) of Indicated Material Before and After 100 Hr Exposure in 2100 F Air: 20-Mil Sheet, Before Exposure, As Cast	20-Mil Sheet, Before Exposure, Cold Rolled	20-Mil Sheet, Before Exposure, Annealed	20-Mil Sheet, Annealed, After Exposure	Weldments in 20-Mil Sheet, Before Exposure, Cold Rolled	Weldments in 20-Mil Sheet, Before Exposure, Annealed	Weldments in 20-Mil Sheet, Annealed, After Exposure
Commercial	--	--	--	--	--	--	--	360	239	223	260	187	244
21	Electrolytic	Iodide	--	1/4	1/12	Vacuum	220	313	232	225	214	165	227
22	Electrolytic	Electrolytic	--	1/4	1/4	Vacuum	213	325	203	234	216	165	225
25	Electrolytic	Electrolytic	--	3	1/4	Vacuum	216	341	234	244	221	172	271
23	Electrolytic	Electrolytic	--	0	1/4	Vacuum	210	332	254	223	201	167	234
26	Electrolytic	Electrolytic	--	0	3	Vacuum	197	277	204	227	195	152	257
24	Electrolytic	Electrolytic	--	0	1/4	Argon	205	310	234	251	206	157	241
27	Electrolytic	Electrolytic	--	0	3	Argon	206	283	223	303	212	160	262
37	Electrolytic	Electrolytic	--	1/4	1/4	Vacuum; slag	205	306	236	241	167	185	219
38	Electrolytic	Electrolytic	--	0	1/4	Vacuum; slag	201	289	232	221	178	152	229
39	Electrolytic	Electrolytic	--	0	1/4	Argon; slag	216	293	225	239	169	158	223
28	Armco	Ferrochromium	--	1/4	1/4	Vacuum	208	332	225	241	208	167	216
31	Armco	Ferrochromium	--	3	1/4	Vacuum	213	299	241	219	227	168	251
29	Armco	Ferrochromium	--	0	1/4	Vacuum	212	321	239	296	223	164	232
32	Armco	Ferrochromium	--	0	3	Vacuum	204	310	236	241	210	161	221
30	Armco	Ferrochromium	--	0	1/4	Argon	223	313	249	262	239	192	221
33	Armco	Ferrochromium	--	0	3	Argon	214	303	246	260	236	182	232
34	Armco	Ferrochromium	--	1/4	1/4	Vacuum; slag	212	296	229	244	192	193	234
35	Armco	Ferrochromium	--	0	1/4	Vacuum; slag	212	313	227	260	190	195	257
36	Armco	Ferrochromium	--	0	1/4	Argon; slag	212	345	239	257	188	190	241
50	Armco	Ferrochromium	--	0	3	Air leak	--	333	--	188	306	--	180
59	Armco	Ferrochromium	--	0	3	Good vacuum	--	350	--	218	251	--	218
51	Electrolytic	Electrolytic	1 w/o niobium	1/4	1/4	--	--	375	--	238	328	--	238
52	Electrolytic	Electrolytic	1 w/o titanium	1/4	1/4	--	--	374	--	198	246	--	208
53	Electrolytic	Electrolytic	1/2 w/o niobium + 1/2 w/o titanium	1/4	1/4	--	--	371	--	220	239	--	223
54	Electrolytic	Electrolytic	1 w/o niobium + 0.08 w/o carbon	1/4	1/4	--	--	322	--	209	297	--	207
55	Electrolytic	Electrolytic	1 w/o yttrium	1/4	1/4	--	--	332	--	216	345	--	220
56	Electrolytic	Ferrochromium	1 w/o niobium	1/4	1/4	--	--	370	--	235	357	--	238
57	Electrolytic	Ferrochromium	1 w/o titanium	1/4	1/4	--	--	369	--	218	377	--	218
58	Electrolytic	Ferrochromium	1/2 w/o niobium + 1/2 w/o titanium	1/4	1/4	--	--	396	--	232	247	--	232
60	Electrolytic	Ferrochromium	1 w/o yttrium	1/4	1/4	--	--	362	--	229	309	--	229

CONCLUSIONS

The findings in this study which relate directly to the ability to reproduce the qualities of ductility and weldability in the iron-25 w/o chromium-5 w/o aluminum alloy are as follows:

(1) Melting by the vacuum-induction technique especially demands a tight system and good vacuum and temperature control as a safeguard against nitrogen pickup.

(2) Starting materials should be low in copper, nitrogen, and silicon since each of these contaminants can result in poor bend ductility in both cold-rolled and heat-treated material. Nitrogen, introduced during melting or during welding, appears to destroy the oxidation resistance of the alloy.

(3) Long holding times during the melting procedure, particularly after the aluminum addition, are beneficial in removing volatile tramp impurities and in modifying the effect of nitrogen content; bend ductility is generally improved as a result. A long holding time before pouring permits the use of ferrochromium in place of more costly electrolytic chromium, and good metal quality can be reproduced. However, the increased cost of the necessarily long melting operation may overshadow the lower cost of ferrochromium.

(4) The dependence of ductility on metal purity was obvious in thicker sheet.

(5) Annealing at 1500 F for 1/2 hr improves bend ductility even though copper and nitrogen are present; however, after a long thermal exposure in air (2100 F for 100 hr) materials containing these contaminants again became embrittled.

(6) During the welding operation, contamination can result from improper use of an argon cover or from the copper welding jig.

(7) Some of the observations made on quaternary alloy additions would indicate that they contribute to the brittleness of the alloy. However, an important distinction should be made at this point. With the exception of the titanium, the alloy additions did not result in poorer bend ductility after thermal exposure. The effect observed in the alloy in the cold-rolled condition was due to the change effected in cold working qualities. Therefore, losses in bend ductility of the cold-rolled material could be reduced by annealing. These would not reappear after thermal exposure like the losses of ductility attributed to the nitrogen, copper, and silicon contaminants and the titanium alloy addition.

Additions of yttrium and of the niobium-carbon combination both reduced grain size and grain growth.

(8) Large grain size in, or rapid grain growth of, sheet material bore no relationship to poor bend ductility.

The most important conclusions of the alloy study center about the purity of charge materials and the imposition of proper melting and welding techniques. This investigation has shown that nitrogen plays an important role in both the ductility and the oxidation resistance of the iron-25 w/o chromium-5 w/o aluminum alloy. Further research is recommended to explain how nitrogen effects the deterioration of oxidation resistance of the alloy. In addition, a determination of the tolerance levels of some of the common impurities, such as copper, silicon, and nitrogen, which are associated with the starting materials appears warranted.

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