Report No. BMI-1420

UC-25 Metallurgy and Ceramics
(TID-4500, 15th Ed.)

Contract No. W-7405-eng-92

EFFECTS OF YTTRIUM ON THE FABRICATION
AND TENSILE PROPERTIES OF TWO
MODIFIED STAINLESS ALLOYS

by

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February 24, 1960

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EFFECTS OF YTTRIUM ON THE FABRICATION AND TENSILE PROPERTIES OF TWO MODIFIED STAINLESS ALLOYS

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and Ronald F. Dickerson

Alloys containing 55 w/o iron-22 u/o nickel-17 u/o chromium-2.5 w/o molybdenum-1.0 u/o niobium-0.03 w/o carbon-0.5 u/o manganese-0.5 w/o silicon with nominal additions of from 0 to 1.5 w/o yttrium, and 36 u/o iron-37 u/o nickel-18 u/o chromium-2.5 u/o molybdenum-1.5 u/o niobium-1.0 u/o aluminum-0.05 w/o carbon-0.5 w/o manganese-0.5 u/o silicon with nominal additions of from 0 to 2.0 u/o yttrium, were prepared by vacuum-induction melting.

Alloys containing 55 u/o iron were successfully forged in air at 1900 F, rolled at 1850 F to 0.060-in. sheet and cold rolled to 0.015-in. sheet. Fabrication of alloys containing 36 w/o iron with more than 0.5 u/o yttrium was unsuccessful.

Addition of yttrium had relatively no effect on the yield and ultimate strength from room temperature to 1850 F. The ductility of fabricable alloys studied was increased at elevated temperatures by increasing yttrium contents. The greatest increase in ductility occurred at 1.5 u/o yttrium.

INTRODUCTION

Alloys with higher tensile strength, better oxidation resistance, and resistance to carburization and nitriding at temperatures as high as 1850 F are needed for cladding application in the GCRE (Gas-Cooled Reactor Experiment). Present commercial alloys do not meet all of these specifications; however, a survey of the compositions of a number of superalloys has produced general information which can serve as a guide in the development of a cladding material to meet the requirements of the GCRE.

Oxidation resistance of present-day stainless steels is derived primarily from chromium additions, with 15 to 20 w/o chromium being the optimum concentration. Nickel is known to improve the adherence of the oxide films; however, its major contribution is as a stabilizer of the austenitic structure. Small additions of aluminum, niobium, and silicon have been shown to improve resistance to oxidation, carburization, and nitriding. The addition of silicon minimizes the diffusion of carbon and nitrogen. The creep strength of stainless steels is improved by the addition of molybdenum, but the amount must be limited to prevent the formation of sigma phase.

The information briefly discussed in the preceding paragraph has been obtained as a result of much research effort and is well known. In recent months yttrium metal has been receiving a great deal of study as an alloying addition. Unfortunately, the results of this study have been classified and are not widely known. However, recently declassified information⁽¹⁾ shows that the addition of yttrium to some alloys results in

(1) Reference at end.

improved oxidation resistance and in grain refinement at elevated temperatures. The alloys investigated did not contain chromium. On the basis of this information, it was reasonable to believe that additions of yttrium might increase the high-temperature strength and the oxidation resistance of some of the better qualified alloys.

In the present study, two alloy compositions were selected in an attempt to incorporate the best effects of each alloying addition. To these base alloys, varying amounts of yttrium were added in an attempt to improve the oxidation resistance at elevated temperatures. This report discusses the study concerned with the effects of various yttrium additions on the fabrication and mechanical properties of these alloys. The effect of yttrium on the oxidation resistance of the base alloys is being determined by another laboratory.

ALLOY PREPARATION

Ingots weighing 1000 g were prepared by melting in an induction furnace under a vacuum of less than 1×10^{-2} mm of mercury. Commercial-grade material was used in all heats. The nominal compositions are listed in Table 1. Alloys containing nominally 55 w/o iron were prepared with nominal additions of 0, 0.5, 1.0, and 1.5 w/o yttrium. Alloys with nominal 36 w/o iron contained nominally 0, 0.5, 1.0, 1.5, and 2.0 w/o yttrium additions. A loss in yttrium during melting had been expected, and the yttrium was overcharged in anticipation of this loss. The amount of overcharge was 0.5 g; however, subsequent chemical analysis showed that about a 0.35-g overcharge would have been sufficient. The yttrium metal was added just before pouring the melt to minimize the loss.

TABLE 1. NOMINAL COMPOSITIONS OF ALLOYS STUDIED

Alloying Elements	Nominal Composition, w/o	
	55 w/o Iron-Base Alloy	36 w/o Iron-Base Alloy
Iron	55	36
Nickel	20-23	35-39
Chromium	16.5-17.5	17-19
Molybdenum	2.5-3.0	2.5-3.0
Yttrium	0, 0.5, 1.0, and 1.5	0, 0.5, 1.0, 1.5, and 2.0
Niobium	1.0-1.5	1.5-2.0
Carbon	0.03 maximum	0.05 maximum
Manganese	0.5 maximum	0.5 maximum
Silicon	0.5 maximum	0.5 maximum
Aluminum	--	0.8-1.2

After melting, the top and bottom of each ingot were cropped, and machine turnings were removed for chemical analysis. No other preparation was made prior to fabrication.

CHEMICAL ANALYSIS

Complete chemical analyses were necessary to thoroughly evaluate the fabrication and mechanical properties. Analyses of the yttrium content were essential to determine yttrium losses during melting. Two ingots were prepared for each yttrium addition. One ingot with each nominal yttrium addition was analyzed for all alloying constituents.

There was not as great a loss of yttrium during melting as was anticipated; therefore, the majority of alloys have a slightly higher yttrium content than was originally planned. The analyzed compositions were within the nominal composition ranges except for the aluminum content of the 36 w/o iron-base alloys. The aluminum was overcharged in expectation of losses; however, these losses did not occur. Tables 2 and 3 list the analyzed compositions of the alloys with 55 and 36 w/o iron, respectively.

ALLOY FABRICATION

Ingot of both base alloys (55 and 36 w/o iron), nominally containing from 0 to 2 w/o yttrium, were forged with no prior heat treatment at 1900 F in air.

55 w/o Iron-Base Alloys

All alloys containing 55 w/o iron were forged to sound 5/8-in.-thick plate. These plates were then rolled to sheet 2 in. wide and 0.060 in. thick at 1850 F in air. After rolling this sheet was grit blasted to remove a light oxide film, and a piece 3 in. long was sheared from the end. This piece was annealed at 1850 F for 15 min, water quenched, and then rolled at room temperature to sound 0.015-in. sheet. Reductions were about 10 per cent per pass. The cold-rolled sheet had bright unblemished surfaces and smooth edges with no evidence of edge cracking. Yttrium did not appear to change the fabrication behavior of these alloys.

36 w/o Iron-Base Alloys

The same fabrication methods were employed for the 36 w/o iron-base alloys as were used for the 55 w/o iron-base alloys. Alloys containing 36 w/o iron with 0, 0.10, and 0.55 w/o yttrium were successfully fabricated into both 0.060- and 0.015-in.-thick sheet. Alloys containing more than 0.55 w/o yttrium exhibited edge and slight surface cracking during forging. During rolling these cracks opened up extensively, causing fracture of all of the alloys after only a 10 per cent reduction of the 5/8-in. slabs.

TABLE 2. CHEMICAL ANALYSES OF ALLOYS CONTAINING 55 w/o IRON

Alloying Addition	Alloy Composition (Balance Iron), w/o					
	Nominal	Analyzed for Indicated Alloy				
		1	2	3	4	5
Yttrium	0, 0.5, 1.0, and 1.5	0	0.67	1.2	1.5	1.97
Nickel	20-23	22.7	22.5	20.6	22.6	--
Chromium	16.5-17.5	17.0	16.4	17.4	16.7	--
Molybdenum	2.5-3.0	2.48	2.57	2.40	2.44	--
Niobium	1.0-1.5	1.21	1.26	1.36	1.29	--
Carbon	0.03 maximum	0.04	0.02	0.03	0.03	--
Silicon	0.5 maximum	0.06	0.10	0.10	0.11	--
Manganese	0.5 maximum	0.09	0.11	0.05	0.13	--

TABLE 3. CHEMICAL ANALYSES OF ALLOYS CONTAINING 36 w/o IRON

Alloying Addition	Alloy Composition (Balance Iron), w/o						
	Nominal	Analyzed for Indicated Alloy					
		6	7	8	9	10	11
Yttrium	0, 0.5, 1.0, 1.5, and 2.0	0	0.10	0.55	1.25	1.40	2.0
Nickel	35-39	37.2	37.4	--	37.8	37.8	37.4
Chromium	17-19	18.0	17.1	--	17.8	17.6	17.9
Molybdenum	2.5-3.0	2.48	2.38	--	2.50	2.41	2.58
Niobium	0.5-2.0	1.86	1.88	--	1.83	1.81	1.70
Aluminum	0.8-1.2	1.83	1.53	--	1.57	1.55	1.52
Carbon	0.05 maximum	0.04	0.03	--	0.04	0.03	0.03
Silicon	0.5 maximum	0.19	0.04	--	0.05	0.05	0.07
Manganese	0.5 maximum	0.09	0.09	--	0.08	0.09	0.07

METALLOGRAPHIC EXAMINATION

Selected microstructures of both the 36 and 55 w/o iron-base alloys were examined in the as-cast and as-forged conditions. Figure 1 shows the as-cast and as-forged microstructures of the 55 w/o iron-base alloy. In 55 w/o iron alloys containing yttrium, there is evidence that a low-melting second phase forms at the grain boundaries during solidification, a portion of which is a yttrium compound, probably YFe_5 . This compound is probably formed by a low-melting eutectic reaction, which would account for its location.

Figures 2, 3, and 4 show this YFe_5 compound and the effects of increasing yttrium content on the amount of formation of the compound in the 55 w/o iron alloys. The compound is shown as dark patches along what appear to be the as-cast grain boundaries. The as-forged microstructures of these alloys, also shown in these figures, indicate that complete breakdown of the original as-cast structure was obtained.

The microstructure of the 36 w/o iron alloy containing no yttrium shows what is probably aluminum in the grain boundaries in the as-cast microstructure. The as-forged structure of this alloy appears to be broken down. Figure 5 shows these microstructures. When 1.25 w/o yttrium is added to the 36 w/o iron-base alloy a different type of microstructure is obtained. There appears to be a mixed compound present at the grain boundaries of these alloys, probably YFe_5 and an aluminum-yttrium compound (possibly YAl). Increasing yttrium contents result in increased amounts of grain-boundary compounds. Examples of these structures are shown in Figures 6, 7, and 8 in the as-cast and as-forged conditions. No successful breaking down of the as-cast structure is evident from these photomicrographs. During fabrication the 36 w/o iron alloys containing more than 0.55 w/o yttrium appeared to be hot short. The existence of a YAl compound at the grain boundaries could result in hot shortness at the 1900 F forging temperature.

Yttrium up to 1.97 w/o did not appear to affect the fabrication of the 55 w/o iron-base alloy, while 36 w/o iron-base alloys containing more than 0.55 w/o yttrium failed to fabricate under the same condition. The presence of a YAl compound is suspected to be responsible for the lack of fabricability.

TENSILE PROPERTIES

The tensile properties were determined at 75, 1000, 1300, 1750, and 1850 F in air for all alloys which were fabricated. These tests were performed on a Baldwin-Southwark tensile testing machine at strain rate of 0.003 in. per in. per min in the elastic region and a crosshead speed in the plastic region of 0.12 in. per in. Specimens with 2-in. gage lengths were prepared from the 0.060-in. sheet stock. The stress-strain curves for the room temperature, 1000 F, and 1300 F groups of alloys were obtained by means of an extensometer mounted on the specimens. Curves for the 1750 and 1850 F groups were obtained by measuring crosshead movement.

100X

RM11255

a. As Cast

100X

RM11277

b. Forged at 1900 F

FIGURE 1. MICROSTRUCTURES OF THE 55 w/o IRON-BASE ALLOY WITHOUT ADDITION OF YTTRIUM

100X

RM11258

a. As Cast

100X

RM11280

b. Forged at 1900 F

Note low-melting second phase at grain boundaries believed to be, in part, YFe_5 . The compound occurs as dark patches along what appear to be the cast grain boundaries.

The as-cast structure appears to be completely broken down. YFe_5 appears as dark patches.

FIGURE 2. MICROSTRUCTURES OF 55 w/o IRON-BASE ALLOY CONTAINING 0.67 w/o YTTRIUM

100X

RM11265

a. As Cast

Low-melting second phase and YFe_5 occur along the probable grain boundaries. More YFe_5 , visible as dark patches, is apparent than in Figure 2.

100X

RM11281

b. Forged at 1900 F

As-cast structure is completely broken down. Dark patches are YFe_5 compound.

FIGURE 3. MICROSTRUCTURES OF 55 w/o IRON-BASE ALLOY CONTAINING 1.26 w/o YTTRIUM

100X

RM11267

a. As Cast

This structure is similar to that shown in Figure 3a.

100X

RM11281

b. Forged at 1900 F

This structure is similar to that shown in Figure 3b.

FIGURE 4. MICROSTRUCTURES OF 55 w/o IRON-BASE ALLOY CONTAINING 1.43 w/o YTTRIUM

100X

RM11285

a. As Cast

The substance at the apparent grain boundaries is probably aluminum.

100X

RM11288

b. Forged at 1900 F

As-cast structure is broken down.

FIGURE 5. MICROSTRUCTURES OF 36 w/o IRON-BASE ALLOY WITHOUT YTTRIUM ADDITION

100X

RM11252

a. As Cast

There appears to be a mixed compound at the grain boundaries, probably YFe_5 and YAl .

100X

RM11291

b. Forged at 1900 F

As-cast structure is still present after forging.
The alloy appeared to be hot short.

FIGURE 6. MICROSTRUCTURES OF 36 w/o IRON-BASE ALLOY CONTAINING 1.25 w/o YTTRIUM

100X

RM11250

a. As Cast

Note slight increase in mixed YFe_5 - YAl compound over that exhibited by alloy in Figure 6a.

100X

RM11294

b. Forged at 1900 F

The as-cast structure is still present after forging. The alloy appeared to be hot short.

FIGURE 7. MICROSTRUCTURES OF 36 w/o IRON-BASE ALLOY CONTAINING 1.40 w/o YTTRIUM

100X

RM11262

a. As Cast

Note very large increase in probable YFe_5 - YAl mixed compound at grain boundaries over that shown by alloy in Figure 6a. The grain boundaries appear almost continuous.

100X

RM11296

b. Forged at 1900 F

The as-cast structure is still present after forging. Grain boundaries appear continuous. The alloy appeared to be hot short.

FIGURE 8. MICROSTRUCTURES OF 36 w/o IRON-BASE ALLOY CONTAINING 2.0 w/o YTTRIUM

FIGURE 9. EFFECT OF YTTRIUM ON YIELD AND TENSILE STRENGTH OF 55 w/o IRON ALLOYS AT ELEVATED TEMPERATURES

FIGURE 10. EFFECT OF YTTRIUM ON YIELD AND TENSILE STRENGTH AT 36 w/o IRON ALLOYS AT ELEVATED TEMPERATURES

FIGURE 11. EFFECTS OF YTTRIUM ON DUCTILITY OF 55 w/o IRON ALLOYS AT ELEVATED TEMPERATURES

FIGURE 12. EFFECTS OF YTTRIUM ON DUCTILITY OF 36 w/o IRON ALLOYS AT ELEVATED TEMPERATURES

TABLE 4. TENSILE PROPERTIES OF 55 w/o IRON-BASE ALLOYS CONTAINING FROM 0 TO 1.97 w/o YTTRIUM

Temperature, F	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation in 2 In., per cent	Reduction in Area, per cent
<u>No Yttrium</u>				
75	85,200	96,200	11	36
1000	67,400	73,700	6	16
1300	37,500	47,700	31	58
1750	7,680	12,000	36	39
1850	4,880	7,800	35	32
<u>0.67 w/o Yttrium</u>				
75	74,900	91,200	13	27
1000	6,220	70,400	7	18
1300	39,900	50,200	30	54
1750	7,930	12,200	51	54
1850	5,450	9,000	48	54
<u>1.2 w/o Yttrium</u>				
75	75,500	95,200	24	24
1000	68,600	77,800	5	12
1300	39,600	53,900	20	38
1750	6,790	12,400	51	62
1850	4,960	8,470	51	58
<u>1.5 w/o Yttrium</u>				
75	88,200	10,100	6	24
1000	71,700	82,800	3	7
1300	42,100	59,000	20	41
1750	6,140	10,400	64	60
1850	5,020	8,560	60	56
<u>1.97 w/o Yttrium</u>				
75	84,000	92,000	2	2
1000	72,700	84,100	4	8
1300	39,100	56,700	16	25
1750	6,920	11,900	62	64
1850	4,290	8,220	70	68

TABLE 5. TENSILE PROPERTIES OF 36 w/o IRON-BASE ALLOYS CONTAINING FROM 0 TO 0.55 w/o YTTRIUM

Temperature, F	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation in 2 In., per cent	Reduction in Area, per cent
<u>No Yttrium</u>				
75	90,600	107,000	12	22
1000	74,600	92,200	14	20
1300	55,600	75,000	32	51
1750	9,130	12,500	50	55
1850	5,240	9,630	40	49
<u>0.10 w/o Yttrium</u>				
75	83,800	109,000	14	21
1000	71,800	91,600	9	18
1300	58,000	76,000	20	32
1750	9,260	13,300	59	58
1850	5,620	8,970	36	41
<u>0.55 w/o Yttrium</u>				
75	101,000	116,000	10	23
1000	84,200	101,000	7	17
1300	54,900	75,900	30	51
1750	8,040	13,000	69	71
1850	--	--	--	--

Evaluation of the tensile data indicates that the addition of yttrium did not result in extensive strengthening of the alloys above 1000 F. Below 1000 F there was quite a spread in values, but it does not appear that any effect on tensile strength can be assigned to the different levels of yttrium content. Figures 9 and 10 show graphically the effect of yttrium and increasing temperature on the yield and tensile strengths.

The ductility of alloys containing 36 and 55 w/o iron at 1750 and 1850 F was greater for those alloys having the higher yttrium content; while below 1750 F the inverse was true. The total elongation at failure and the reduction in area at 1850 F appear to have been increased by a factor of 2 due to the addition of approximately 2 w/o yttrium to the 55 w/o iron-base alloy. In alloys containing 36 w/o iron the addition of only 0.55 w/o yttrium increased the total elongation from 50 per cent to 69 per cent and the reduction in area from 55 per cent to 71 per cent at 1750 F. Figures 11 and 12 show graphically the effect of yttrium on ductility. Tables 4 and 5 summarize the tensile data.

CONCLUSIONS

The following may be concluded from this study of the effects of yttrium additions on the fabrication and mechanical properties of two modified stainless steels:

- (1) The ductility expressed in terms of per cent elongation and reduction in area at 1750 and 1850 F was improved by the addition of yttrium. It appears that 1.5 w/o yttrium is the optimum nominal addition of yttrium to the 55 w/o iron alloy.
- (2) Yttrium in nominal concentrations up to 2 w/o does not have any effects on the fabrication of the alloys having 55 w/o iron as a base material.
- (3) The 36 w/o iron alloys containing more than 0.55 w/o yttrium could not be fabricated at 1900 F. The poor fabricability is probably due to the formation of a compound, YAl , in the grain boundaries.
- (4) No improvements in yield or tensile strengths were obtained due to the addition of yttrium.
- (5) Neither the 36 or 55 w/o iron alloy has increased strength over that of the ASTM Type 300 series stainless steels.

REFERENCE

- (1) Collins, J. F., Calkins, V. P., McGurty, J. A., "Applications of Rare Earths to Ferrous and Nonferrous Alloys", AECU-4424 (November 2, 1959).