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INFLUENCE OF VARIOUS ALLOYING ADDITIONS ON THE STRENGTH OF NICKEL-BASE ALLOYS

H. E. McCoy

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METALS AND CERAMICS DIVISION

INFLUENCE OF VARIOUS ALLOYING ADDITIONS ON THE STRENGTH OF NICKEL-BASE ALLOYS

H. E. McCoy

DECEMBER 1972

OAK RIDGE NATIONAL LABORATORY
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INFLUENCE OF VARIOUS ALLOYING ADDITIONS ON THE STRENGTH OF NICKEL-BASE ALLOYS

H. E. McCoy

ABSTRACT

The effects of Mo, Cr, Fe, Si, and Mn on the strength of nickel-base alloys at 25 and 650°C were studied. The strength at 25°C was enhanced by Mo and Cr but not significantly affected by Fe, Si, and Mn in the concentrations studied. At 650°C the yield stress and the creep strength were improved by additions of Mo, Cr, and Si, while Fe and Mn had no measurable effect. These changes are thought to be a result primarily of solid-solution hardening, although Mo, Cr, and Si influence the type of carbide that is formed.

INTRODUCTION

Hastelloy N is a nickel-base alloy developed specifically for use with fluoride salts.[1] The alloy contains 16% Mo, 7% Cr, 4% Fe, 0.5% Si, and 0.5% Mn as solid-solution alloying additions. Roche[2] investigated the influence of some of these alloying additions on the strength and concluded that molybdenum is the principal strengthener.

More recently, changes in melting practice and a desire to produce a certain type of microstructure have led us to look again[3] at the role of the alloying additions in Hastelloy N. In the present study the alloys were of the nominal composition of Hastelloy N listed above except for the element being varied. Thus, the alloying effects being studied are for an

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[1]W. D. Manly, J. H. Coobs, J. H. DeVan, D. A. Douglas, H. Inouye, P. Patriarca, T. K. Roche, and J. L. Scott, "Metallurgical Problems in Molten Fluoride Systems," *Progr. Nucl. Energy Ser. IV*, 2: 164–79 (1960).

[2]T. K. Roche, *The Influence of Composition Upon the 1500°F Creep-Rupture Strength and Microstructure of Molybdenum-Chromium-Iron-Nickel-Base Alloys*, ORNL-2524 (June 24, 1958).

[3]M. W. Rosenthal, P. N. Haubenreich, H. E. McCoy, and L. E. McNeese, "Recent Progress in Molten-Salt Reactor Development," *At. Energy Rev.* 9: 601–50 (September 1971).

alloy base that varies slightly from series to series. The bulk of the work is concerned with the creep and tensile properties at 650°C.

EXPERIMENTAL DETAILS

The alloys were all prepared from virgin melting stock of 99.9% purity or better. The alloy charges were about 2 lb each and were arc-melted in an inert environment. The alloys were melted several times for consolidation. The solid hearth was replaced with one having a small opening and a mold in the bottom. By concentrating the arc on this hole, the melt was cast into the mold. The usable part of the casting was 1 in. diam × 6 in. long. The ingot was fabricated by swaging in the following sequence:

1 in. diam to 0.750 in. diam, worked at 1180°C,
0.750 in. diam to 0.437 in. diam, worked at 870°C,
0.437 in. diam to 0.250 in. diam, worked at 25°C.

The nominal chemical compositions are used throughout this report, but the actual chemical analyses of the alloys are given in Table 1. All of the alloys contained a nominal 0.05% C. Typical microstructures following a 1-hr anneal at 1180°C are shown in Figs. 1 through 5. Molybdenum has a significant effect upon the microstructure, as seen in Fig. 1. The grain size is refined, with the largest changes taking place in the range 10 to 14% Mo. Through 12% Mo the alloys appear to be primarily solid solutions. At 14% a finely dispersed second phase begins to appear. At 20% Mo the precipitate is concentrated along dendrites from the original casting.

The photomicrographs of the chromium series in Fig. 2 show that the addition of 2% Cr refines the grain size and increases the amount of precipitate. Further additions of chromium have no appreciable effect on the microstructure. For the silicon series, Fig. 3 shows that increasing silicon favors retention of the cast structure. The photomicrographs in Fig. 4 of the iron series do not show an effect of iron on the microsturcture, but are all typified by the retained cast structure due to the presence of the 0.4% Si. Figure 5 shows no apparent variation with manganese concentration. These alloys are low in silicon, and the cast structure was not retained.

Table 1. Chemical Compositions of Nickel-Base Alloys

Alloy	Content, wt %					
	Mo	Cr	Fe	Mn	C	Si
118	9.85	6.92		0.21	0.052	
119	0.005	6.52	0.042	0.21	0.056	<0.01
120	5.35	7.0		0.21	0.057	
121	8.44	6.90		0.21	0.055	
122	12.1	5.96		0.20	0.058	
123	14.5	7.01		0.21	0.057	
124	16.2	6.90		0.21	0.056	
125	18.9	7.04	0.073	0.23	0.056	0.02
113	16.2	0.0009	0.07	0.21	0.057	0.020
114	16.1	2.01	0.07	0.20	0.062	0.016
115	15.6	4.97	0.06	0.21	0.053	0.019
116	15.7	7.23	0.08	0.22	0.063	0.027
117	16.2	9.12	0.08	0.22	0.057	0.035
38	16.0	7.9	3.9	0.48	0.066	0.40
40	16.2	7.9	0.02	0.39	0.068	0.40
41	15.7	7.8	1.87	0.48	0.070	0.40
42	16.6	7.6	4.2	0.003	0.066	0.02
43	15.2	7.5	4.0	0.19	0.063	0.01
44	16.0	7.5	4.0	0.50	0.065	0.01
45	14.6	7.6	3.7	0.96	0.066	0.01
46	15.4	7.5	3.9	0.003	0.067	0.20
47	16.2	7.8	3.8	0.003	0.061	0.50
48	15.0	7.5	3.7	0.002	0.062	1.05

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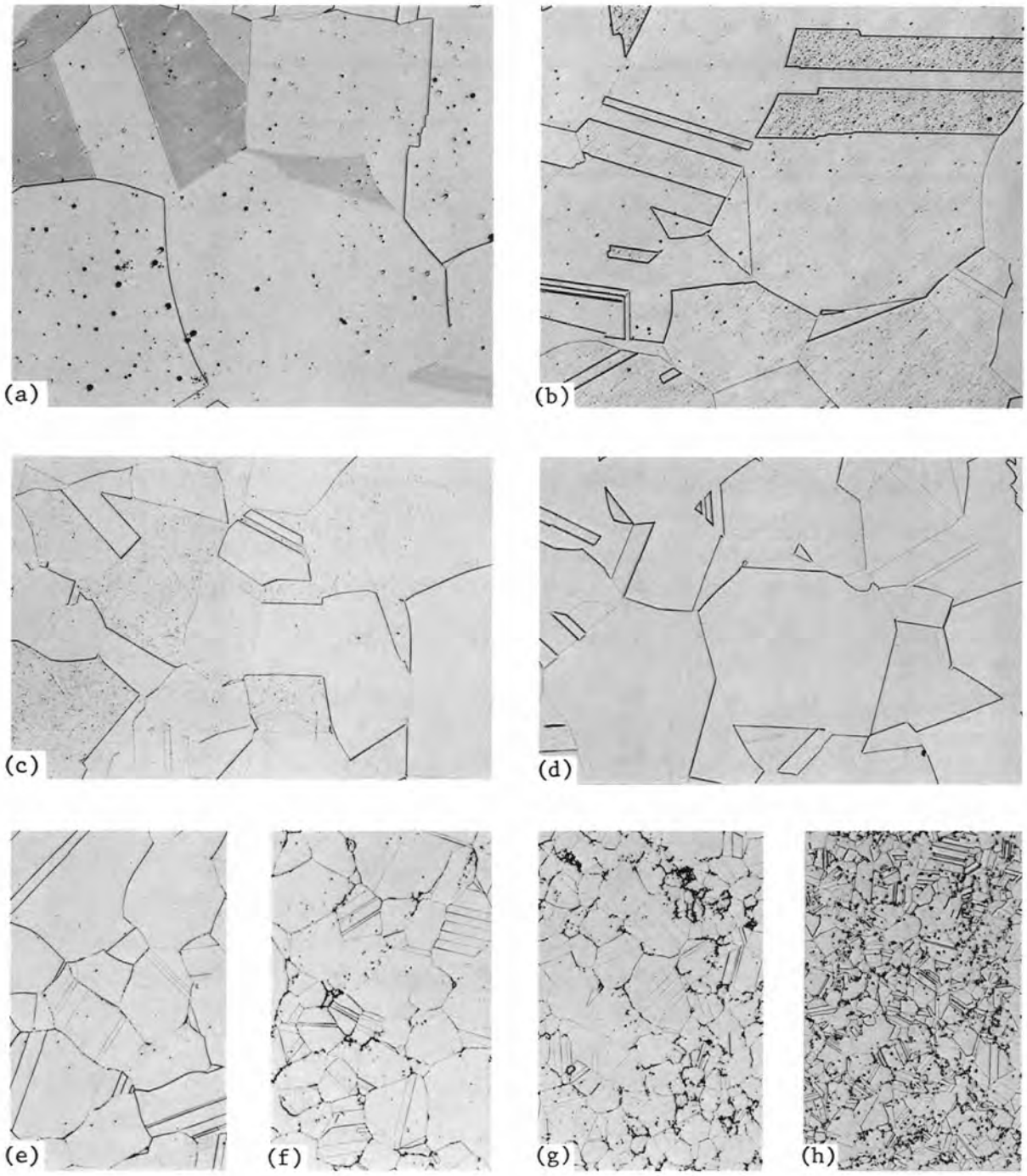

Fig. 1. Typical Photomicrographs of Alloys with Varying Molybdenum Content. Base composition: Ni—7% Cr—0.2% Mn—0.05% C. Annealed 1 hr at 1180°C. Etched with glyceria regia, 100×. (a) Alloy 119, no Mo. (b) 120, 5%. (c) 121, 8%. (d) 118, 10%. (e) 122, 12%. (f) 123, 14%. (g) 124, 16%. (h) 125, 20%.

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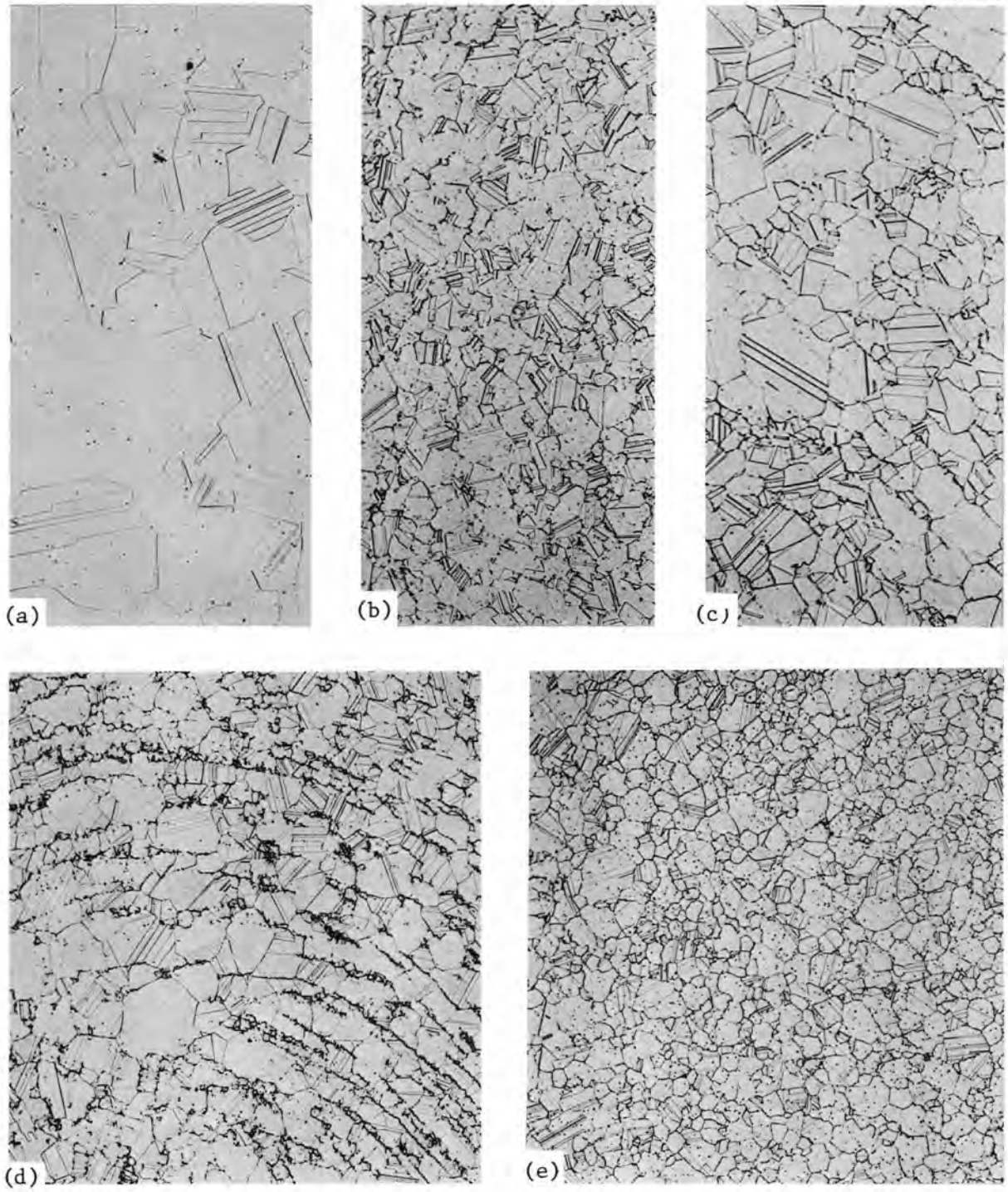

Fig. 2. Typical Photomicrographs of Alloys with Varying Chromium Content. Base composition: Ni—16% Mo—0.2% Mn—0.05% C. Annealed 1 hr at 1180°C. Etched with glyceria regia, 100×. (a) Alloy 113, no Cr. (b) 114, 2%. (c) 115, 5%. (d) 116, 7%. (e) 117, 9%.

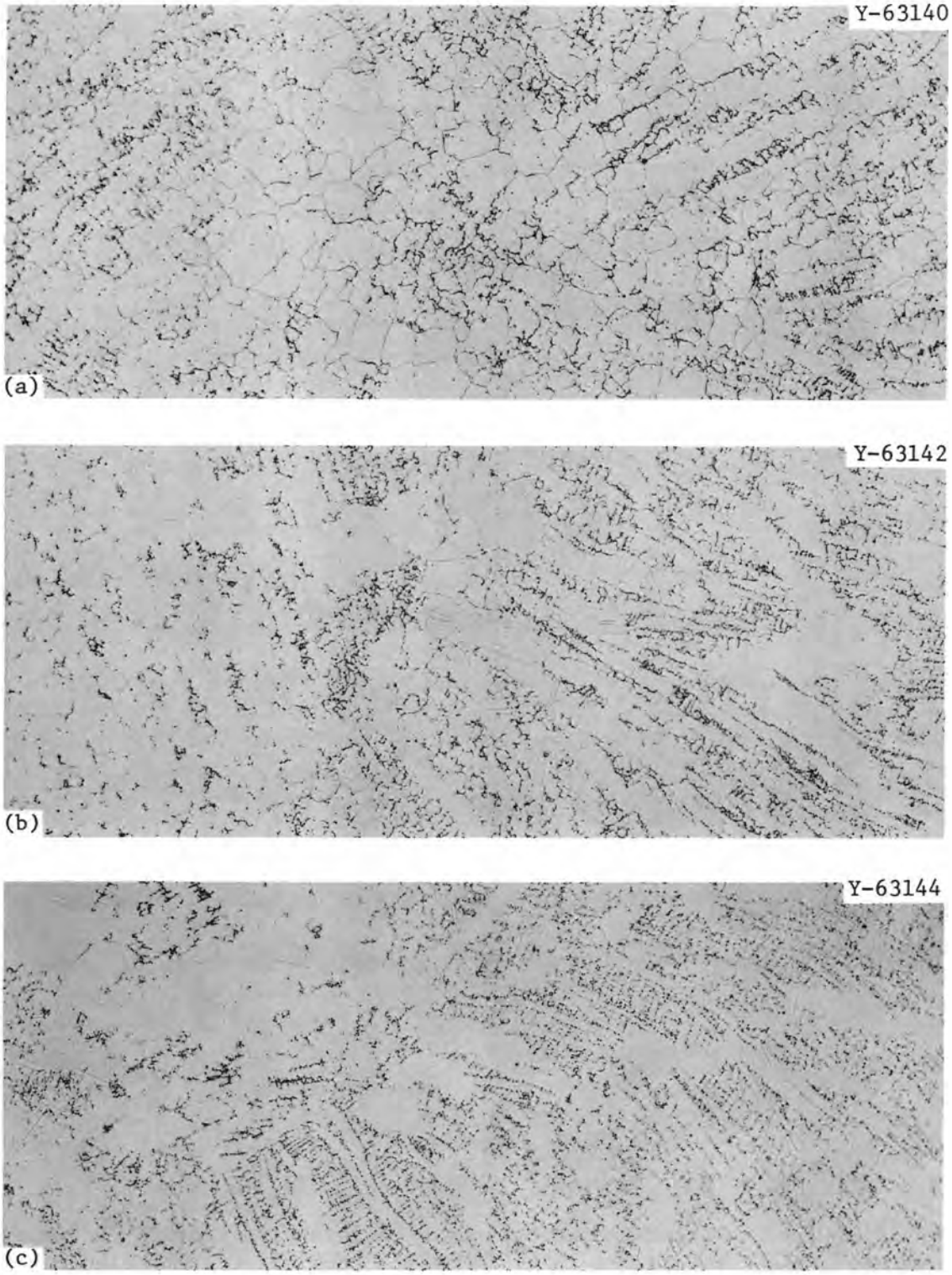

Fig. 3. Typical Photomicrographs of Alloys with Varying Silicon Content. Base Composition: Ni—16% Mo—7% Cr—4% Fe—0.05% C. Annealed 1 hr at 1180°C. Etched with glyceria regia, 100×. (a) Alloy 46, 0.20% Si. (b) 47, 0.50%. (c) 48, 1.0%.

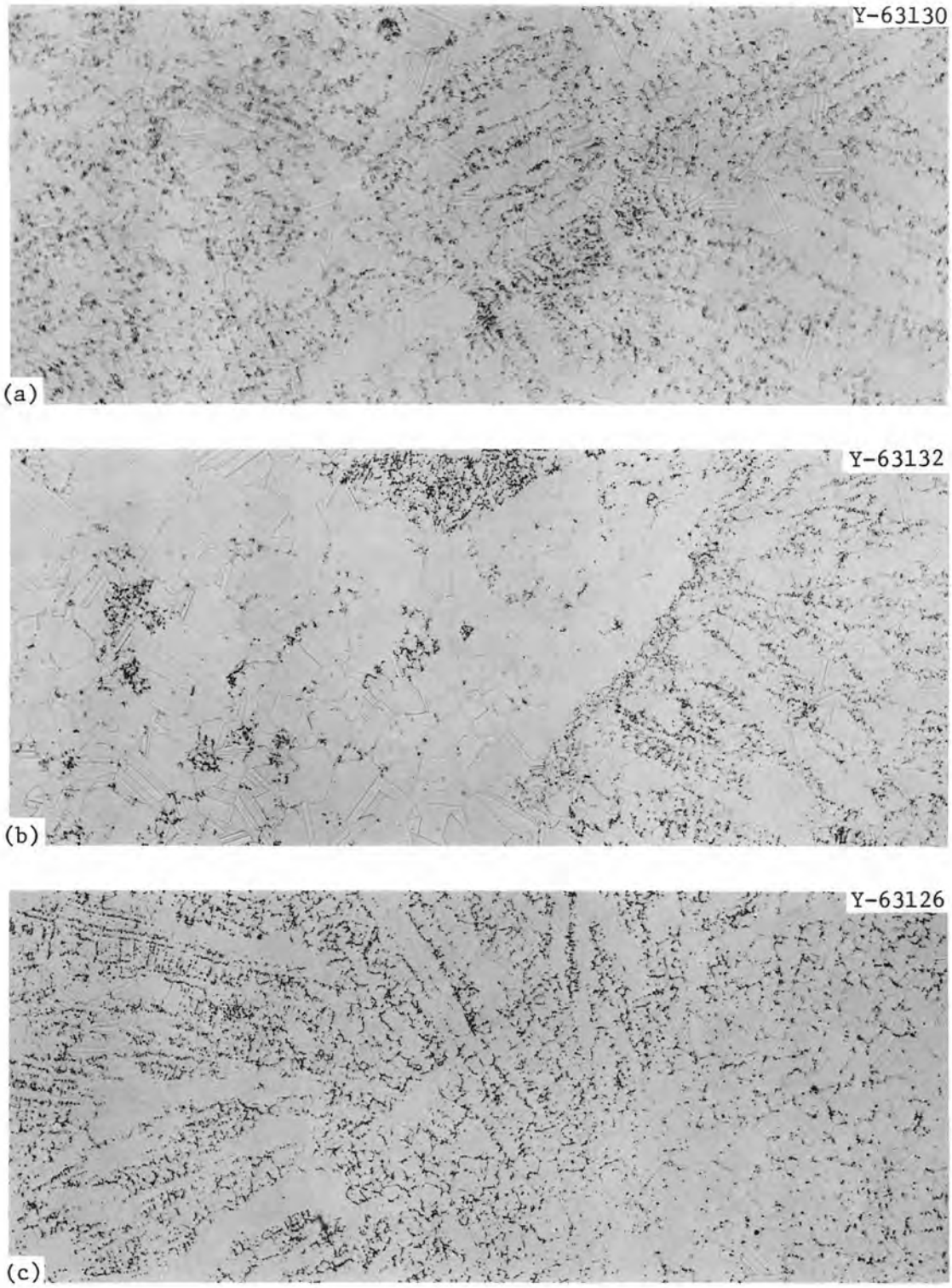

Fig. 4. Typical Photomicrographs of Alloys with Varying Iron Content. Base composition: Ni—16% Mo—7% Cr—0.5% Mn—0.5% Si—0.05% C. Annealed 1 hr at 1180°C. Etched with glyceria regia, 100×. (a) Alloy 40, no Fe. (b) 41, 2%. (c) 38, 4%.

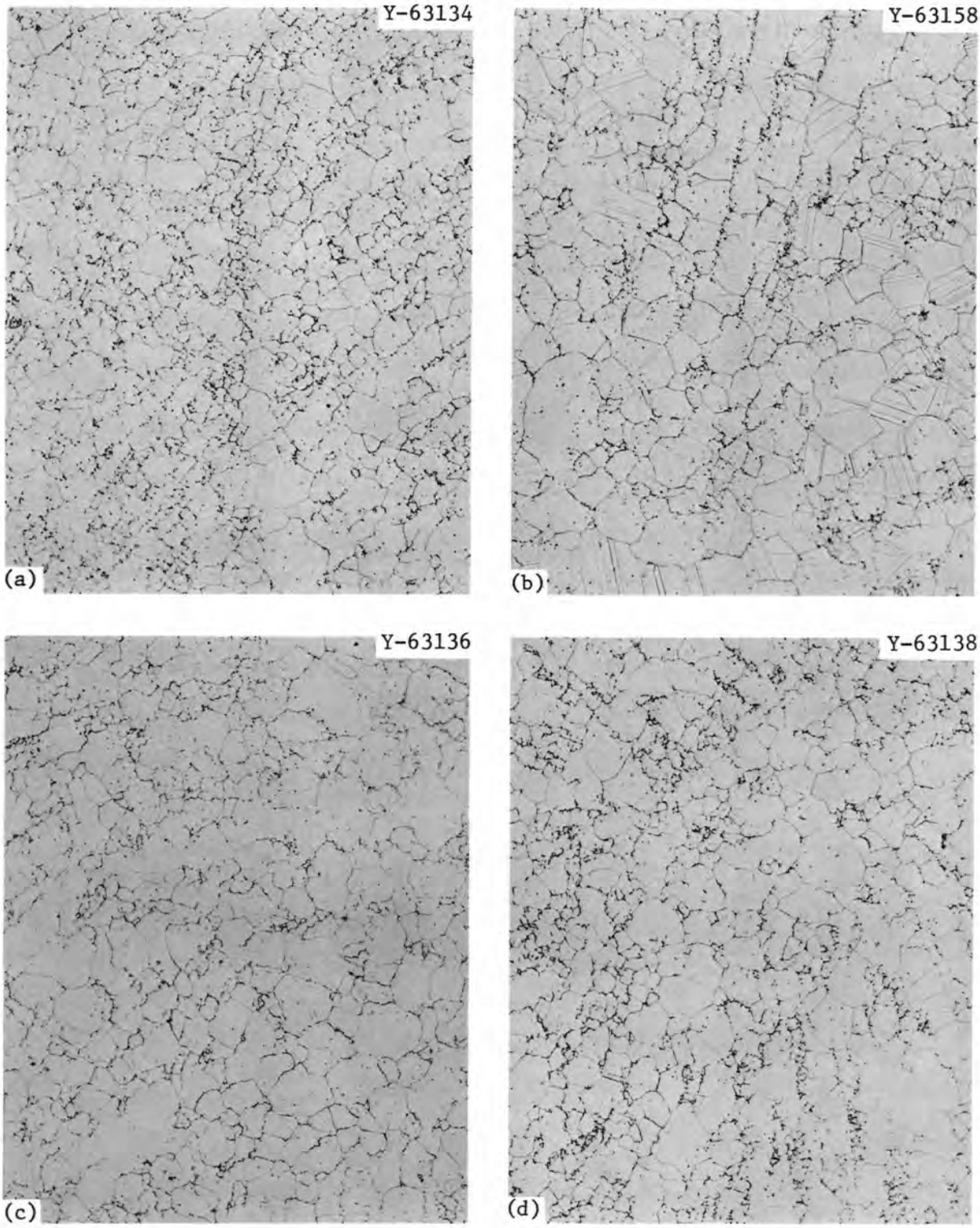

Fig. 5. Typical Photomicrographs of Alloys with Varing Manganese Content. Base Composition: Ni—16% Mo—7% Cr—4% Fe—0.05% C. Annealed 1 hr at 1180°C. Etched with glyceria regia. 100×. (a) Alloy 42, no Mn. (b) 43, 0.2%. (c) 44, 0.5%. (d) 45, 1.0%.

Mechanical property samples were of the design shown in Fig. 6. This small size gave maximum utilization of the small quantity of material, but likely led to some scatter in the test results. Tensile tests were run in a universal testing machine, and strain measurements were taken from the crosshead movement. The creep tests were run in air in standard dead-load machines, and the strain measurements were taken from a dial indicator attached to the load train.

EXPERIMENTAL OBSERVATIONS

Molybdenum Series

The stress-rupture properties at 650°C of the alloys with various concentrations of molybdenum are shown in Fig. 7. The alloy with no molybdenum was extremely weak. The stress-rupture properties increased markedly with the first 5% addition of molybdenum and continued to increase up to 20%, the highest level that was investigated. The minimum creep rates of these same alloys are shown in Fig. 8, and molybdenum has a very definite strengthening effect. The effects of molybdenum concentration on the rupture life and minimum creep rate at 650°C at a stress level of 32,400 psi are shown in Fig. 9. The rupture life is increased at a decreasing rate with molybdenum additions above 14%. The minimum creep rate decreases systematically with increasing molybdenum content. The fracture strains of these alloys generally decrease as the minimum creep rate decreases, as shown in Fig. 10. Increasing molybdenum content does not have an adverse effect on the fracture strain; in fact, a fair case can be made from the results in Fig. 10 for the reverse trend. This could be due to the finer grain size that results from increasing molybdenum concentration.

Tensile tests were run at 25 and 650°C. The uniform strains are shown in Fig. 11 as a function of molybdenum content. At 25°C the uniform strain is a maximum for the alloy containing 12% Mo. At 650°C the maximum shifts to the alloy containing 14% Mo. After aging for 1000 hr at 650°C and then testing at 650°C, all alloys increased in uniform strain except the one containing no molybdenum. The shape of the curve is somewhat

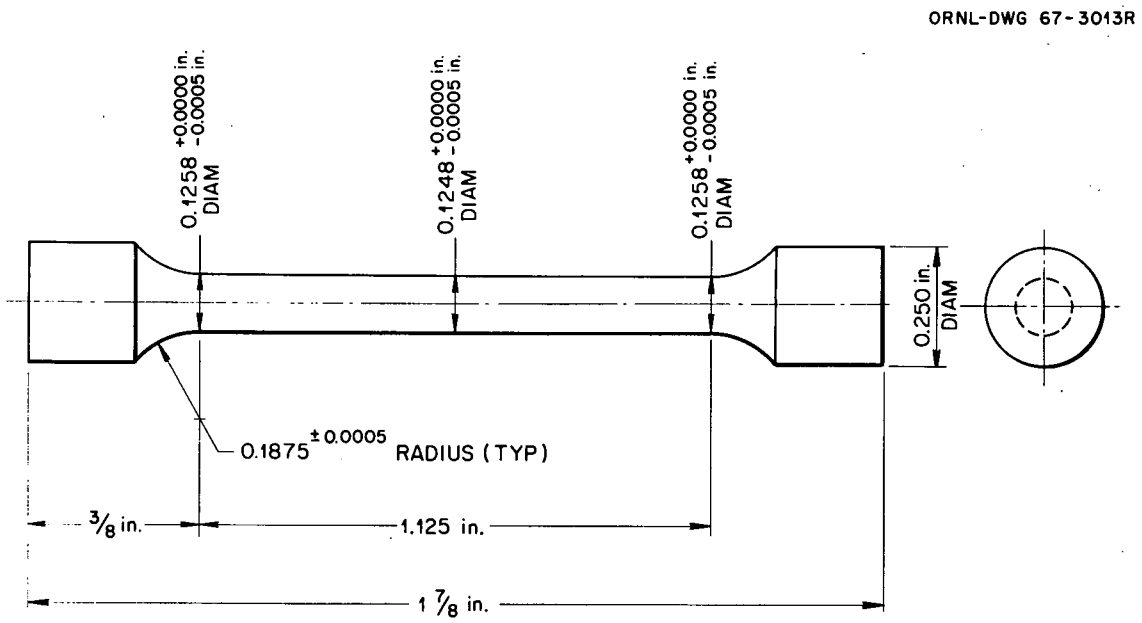

Fig. 6. Mechanical Property Sample.

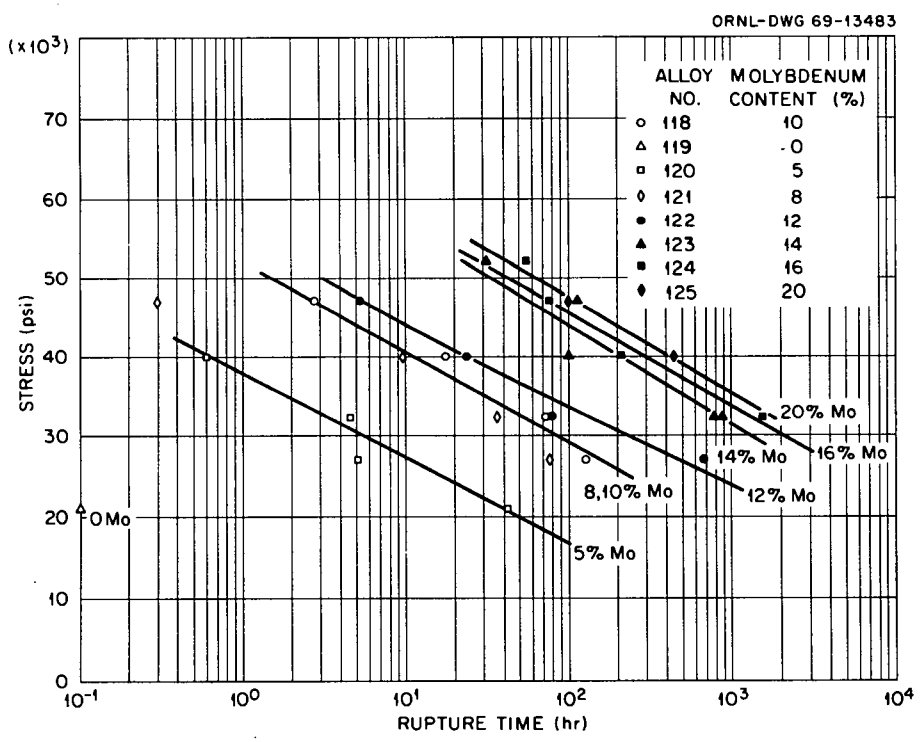

Fig. 7. Stress-Rupture Properties at 650°C for Alloys with Varying Molybdenum Concentration. Base composition: Ni—7% Cr—0.2% Mn—0.05% C.

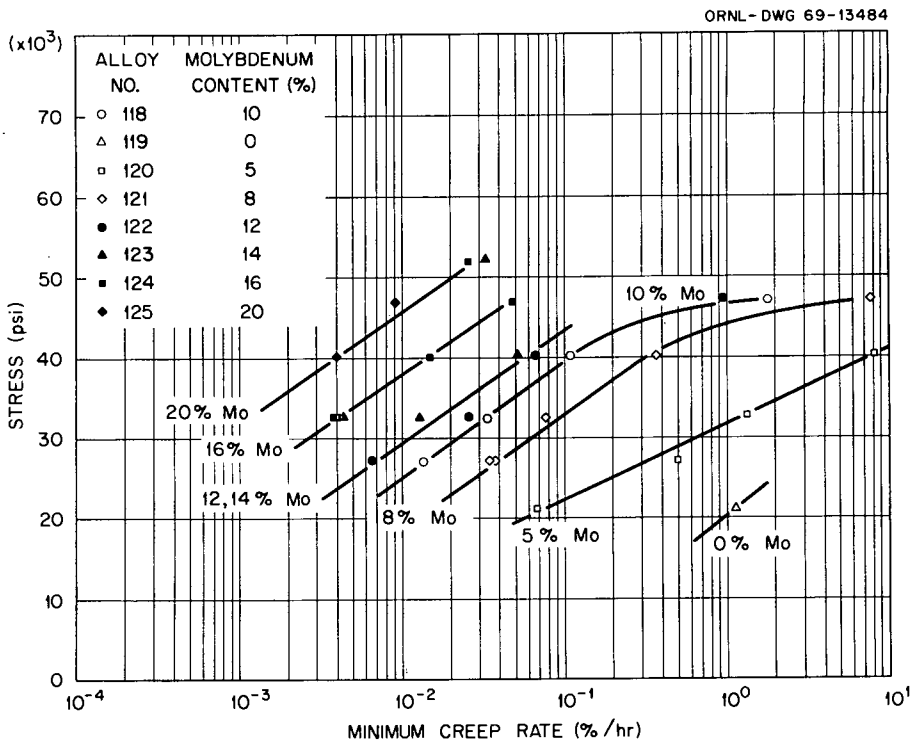

Fig. 8. Minimum Creep Rates at 650°C for Alloys with Varying Molybdenum Concentrations. Base composition: Ni—7% Cr—0.2% Mn—0.05% C.

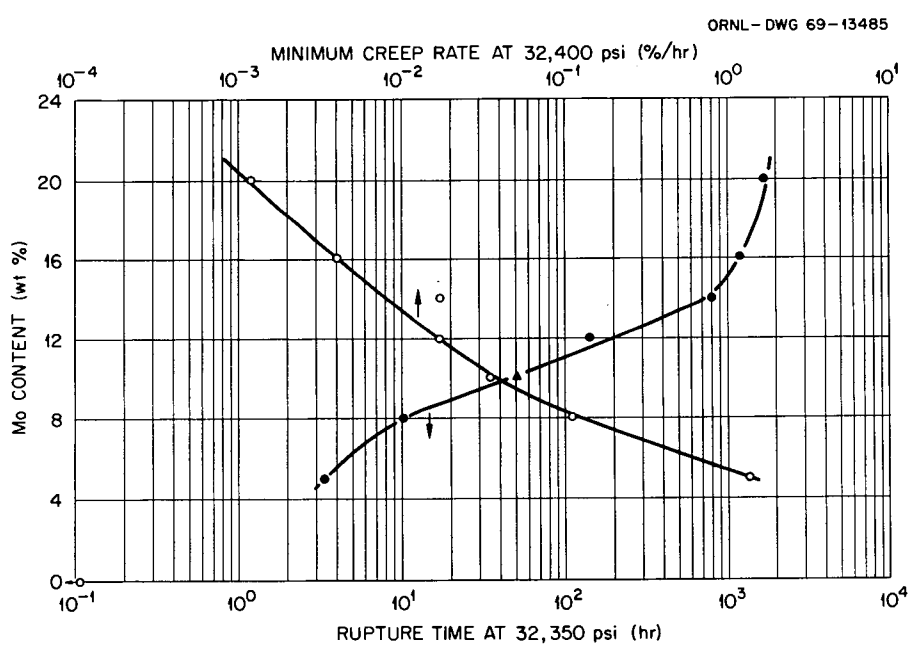

Fig. 9. Variation of the Rupture Life and the Creep Rate with Molybdenum Content for a Stress Level of 32,400 psi at 650°C.

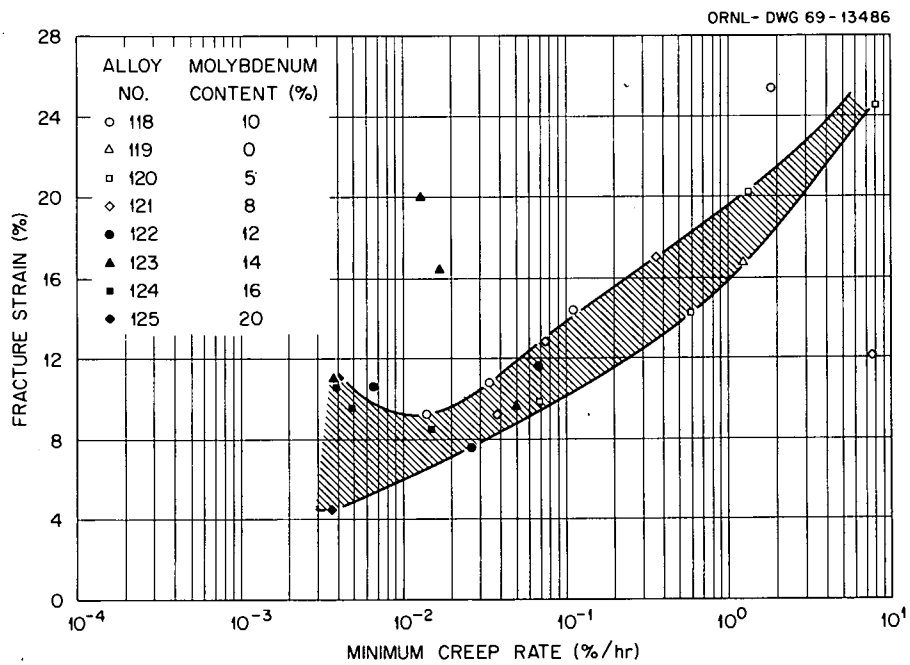

Fig. 10. Variation of the Fracture Strain at 650°C with the Creep Rate for Alloys Containing Various Amounts of Molybdenum. Base composition: Ni–7% Cr–0.2% Mn–0.05% C.

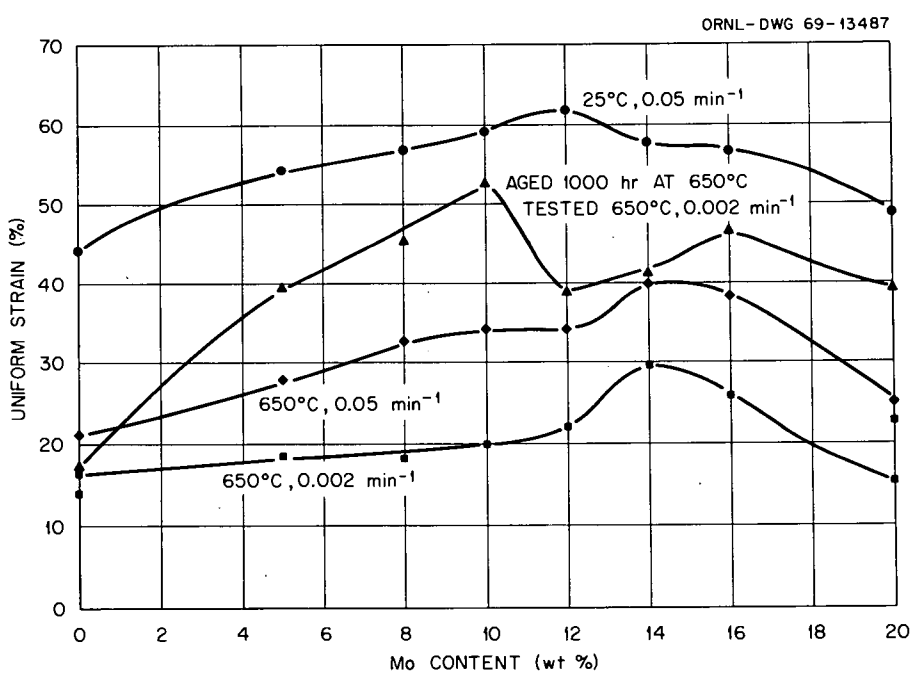

Fig. 11. Variation of the Uniform Strain with Molybdenum Content During Tensile Tests at 25 and 650°C. Base composition: Ni–7% Cr–0.2% Mn–0.05% C.

different from that of the unaged material. The fracture strains paralleled the trends just discussed for the uniform strains, as shown in Fig. 12.

The yield and tensile strengths at 25°C are shown in Fig. 13. These quantities generally increase linearly with increasing molybdenum content. The potency of the molybdenum addition for strengthening can be appreciated by the fact that the yield stress at 25°C was increased from 12,000 to 57,000 psi by the addition of 20% Mo. At 650°C, molybdenum continues to increase the yield and tensile strengths, as shown in Fig. 14. Very little improvement in strength is gained with the addition of more than 14% Mo. After the alloy is aged, the yield strength is unchanged but the ultimate strength increases, as shown in Fig. 15. The strength seems to change at a lower rate for molybdenum additions above 14%.

The fractures of the alloys with nominal molybdenum concentrations of 12, 14, 16 and 20% after testing at 650°C at a strain rate of 0.002/min are shown in Fig. 16. The dominant features are the intergranular cracks and the intergranular fracture. The fracture strains for these alloys varied from 16 to 30% (Fig. 12). The fractures of these same alloys after aging 1000 hr at 650°C and testing at 650°C are shown in Fig. 17, and those for alloys with lower molybdenum content in Fig. 18. All of the alloys except the one containing a nominal 20% Mo have a very fine precipitate. There seems to be some variation in the amount of precipitate, but some of this is due to variations in etching. The precipitates that formed in all of these alloys were not studied in detail, but the probable carbide type can be inferred from our work on these and other alloys.[4] Alloy 119 with only 0.005% Mo likely has an $M_{23}C_6$-type carbide, where "M" is primarily chromium. We have observed the precipitation of M_2C carbide [approximately $(Mo_{0.8}Cr_{0.2})_2C$, a = 2.98 Å, c = 4.68 Å, c/a = 1.57] in alloys containing 12 to 16% Mo and no more than 0.2% Si. This carbide is likely to be present in alloy 120, which contains as little as 5% Mo. Alloy 125 with 20% Mo has a high-parameter (11.13-Å) M_6C carbide. The

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[4]H. E. McCoy and R. E. Gehlbach, "Influence of Irradiation Temperature on the Creep-Rupture Properties of Hastelloy N," *Nucl. Technol.* 11: 45–60 (1971).

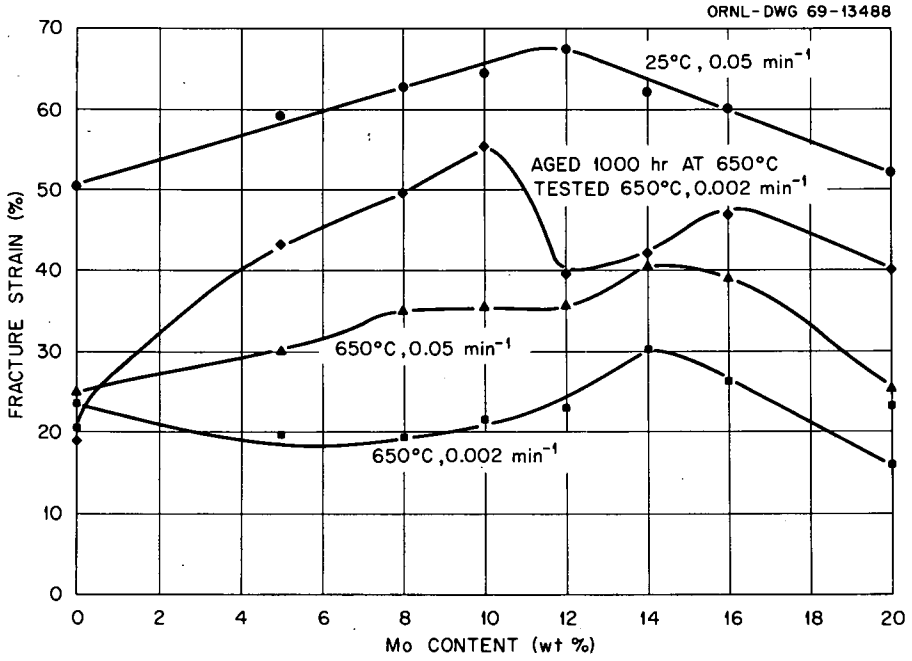

Fig. 12. Variation of the Fracture Strain with Molybdenum Content During Tensile Tests at 25 and 650°C. Base composition: Ni—7% Cr—0.2% Mn—0.05% C.

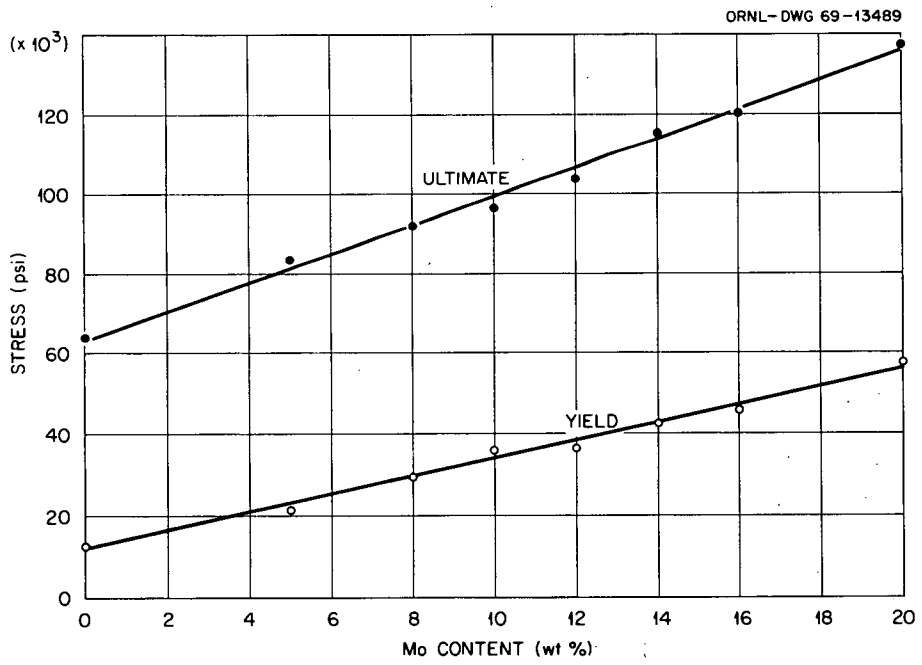

Fig. 13. The Yield and Ultimate Tensile Stresses for Alloys Containing Various Amounts of Molybdenum Measured at 25°C and a Strain Rate of 0.05/min. Base composition: Ni—7% Cr—0.2% Mn—0.05% C.

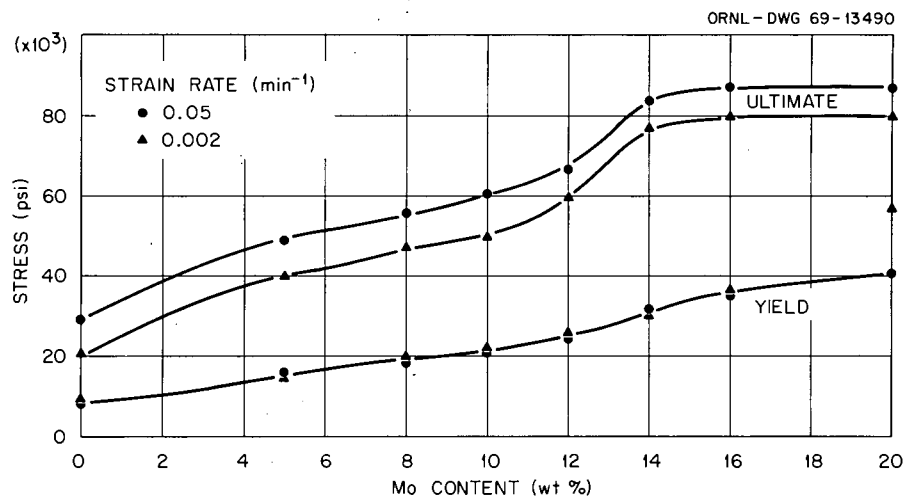

Fig. 14. The Yield and Ultimate Tensile Stresses for Alloys Containing Various Amounts of Molybdenum, Measured at 650°C and Strain Rates of 0.05 and 0.002/min. Base composition: Ni–7% Cr–0.2% Mn–0.05% C.

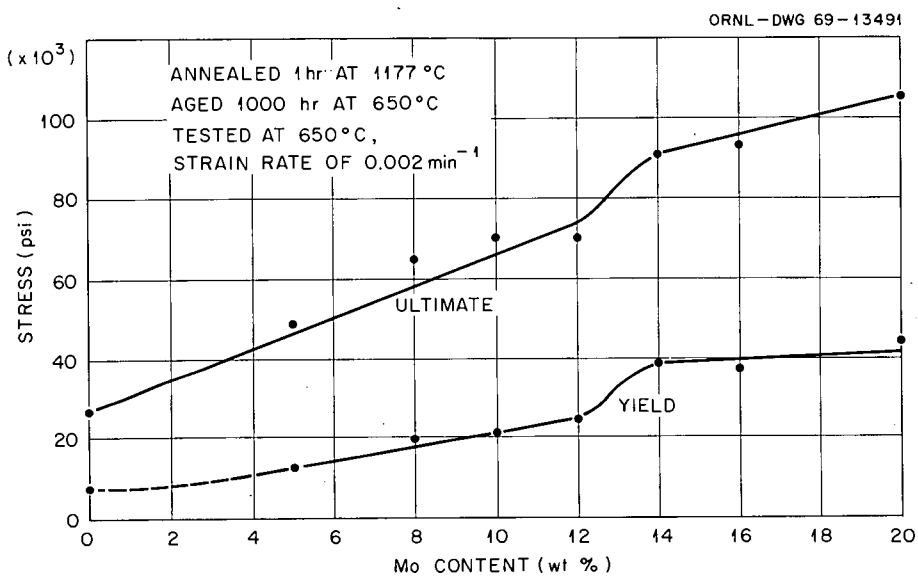

Fig. 15. The Yield and Ultimate Tensile Stresses for Alloys Containing Various Amounts of Molybdenum, Measured at 650°C and a Strain Rate of 0.002/min. These samples were aged before testing. Base composition: Ni–7% Cr–0.2% Mn–0.05% C.

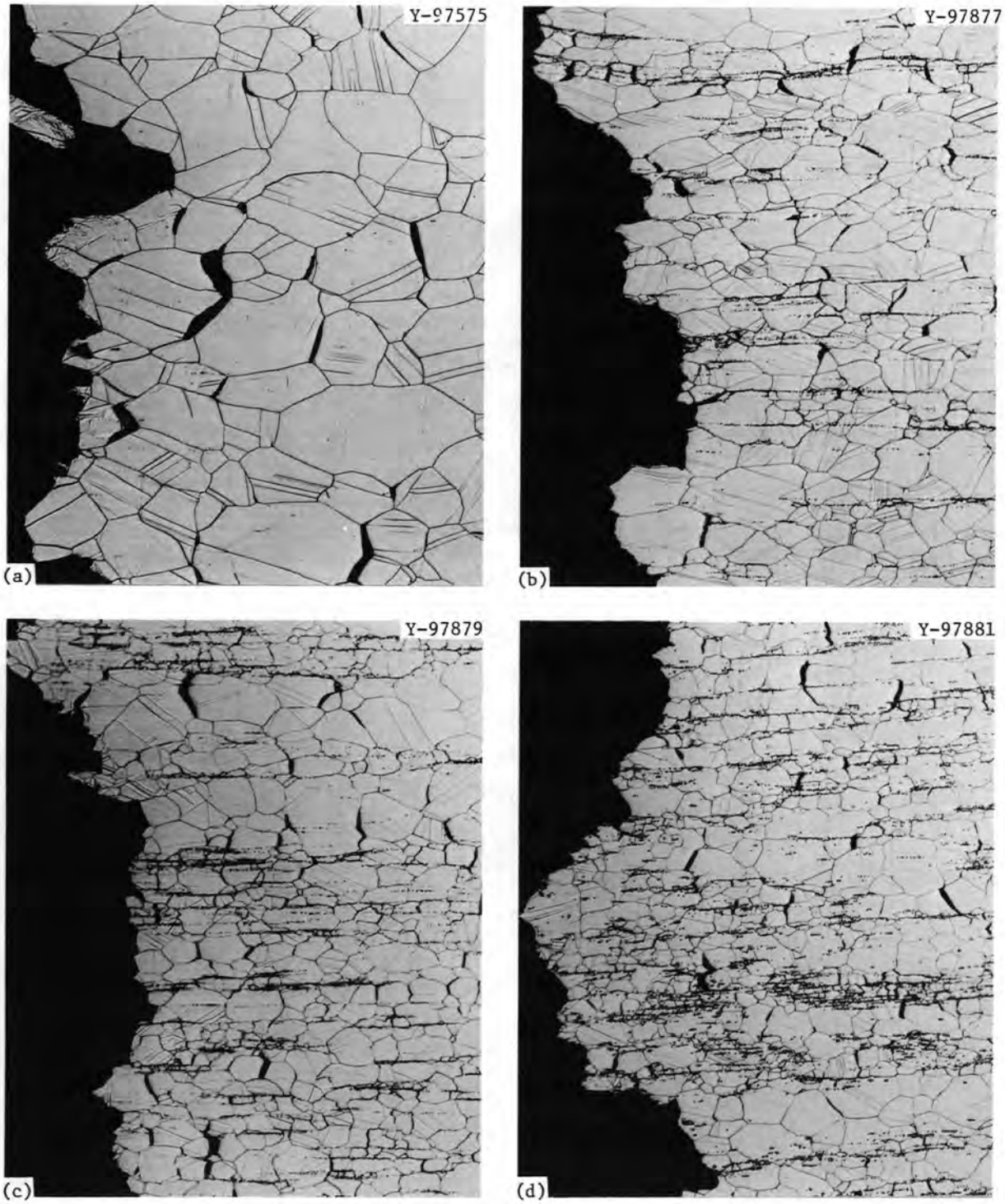

Fig. 16. Photomicrographs of the Fractures of Alloys Containing Various Concentrations of Molybdenum After Annealing 1 hr at 1180°C and Testing at 650°C at a Strain Rate of 0.002/min. Etched with glyceria regia, 100×, reduced 15%. (a) Alloy 122, 12% Mo. (b) 123, 14%. (c) 124, 16%. (d) 125, 20%.

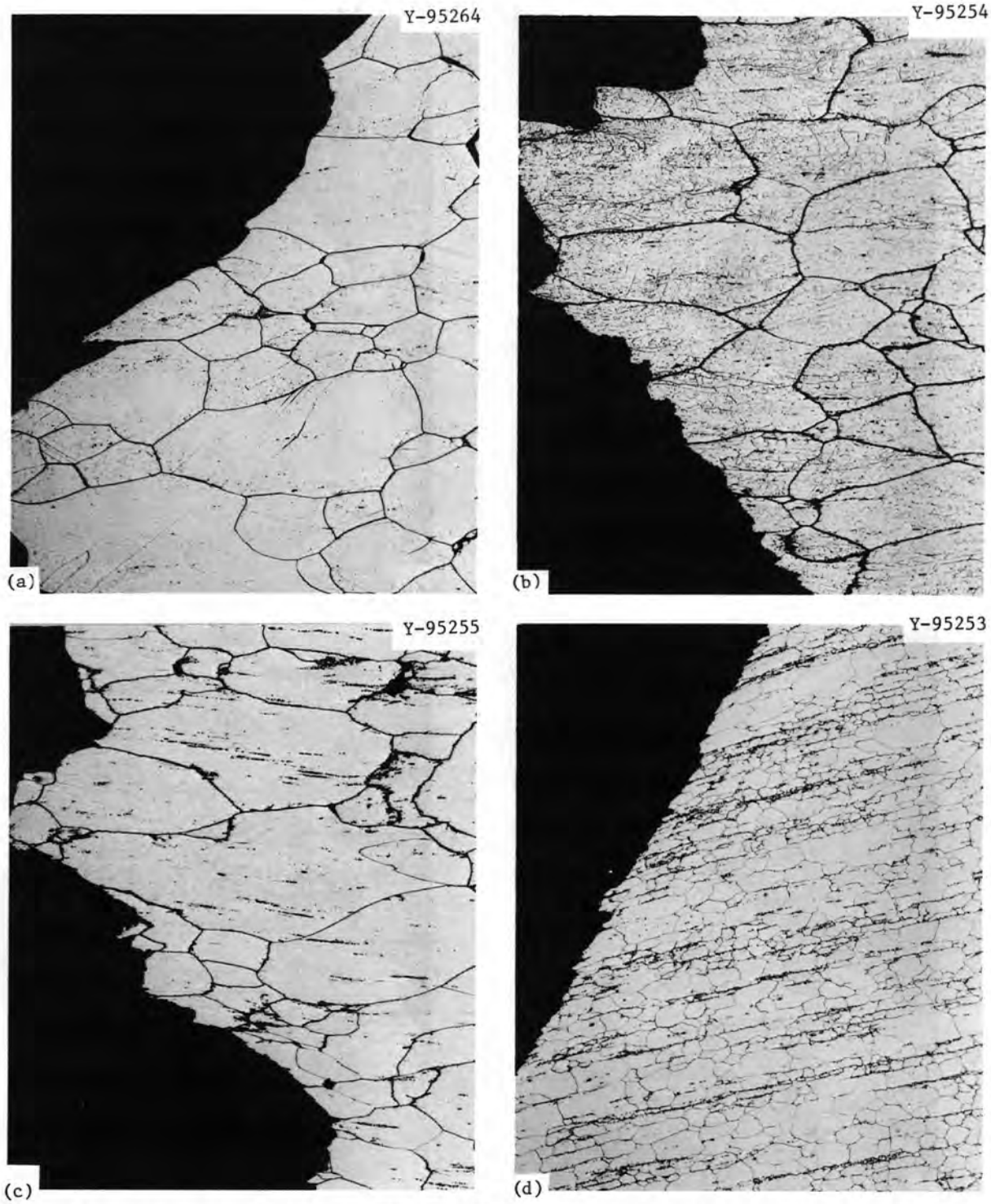

Fig. 17. Photomicrographs of the Fractures of Alloys Containing Higher Concentrations of Molybdenum After Annealing 1 hr at 1180°C, Aging 1000 hr at 650°C, and Testing at 650°C at a Strain Rate of 0.05/min. Etched with glyceria regia, 100×, reduced 15%. (a) Alloy 122, 12% Mo. (b) 123, 14%. (c) 124, 16%. (d) 125, 20%.

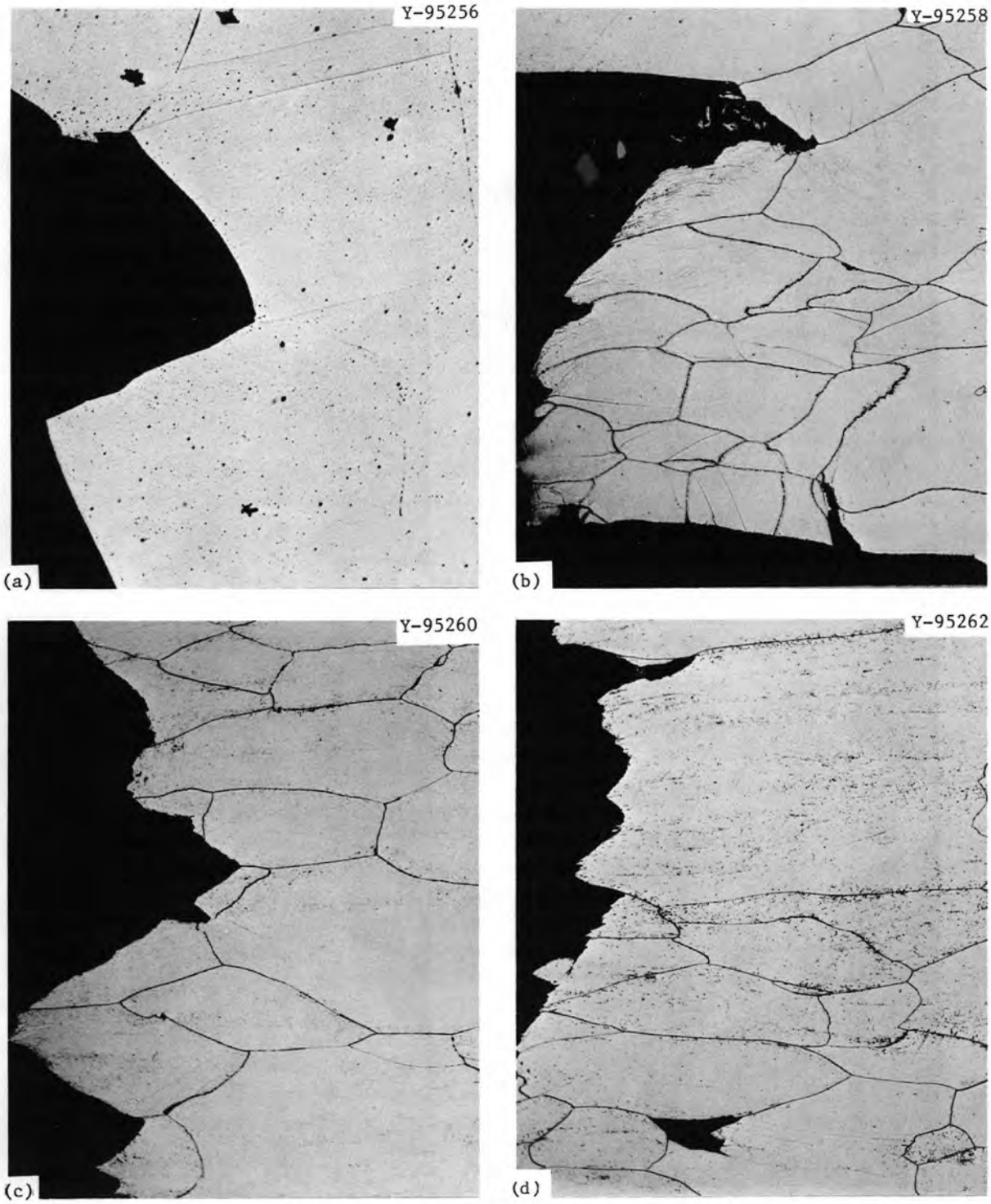

Fig. 18. Photomicrographs of the Fractures of Alloys Containing Lower Concentrations of Molybdenum After Annealing 1 hr at 1180°C, Aging 1000 hr at 650°C, and Testing at 650°C at a Strain Rate of 0.05/min. Etched with glyceria regia, 100×, reduced 15%. (a) Alloy 119, no Mo. (b) 120, 5% Mo. (c) 121, 8% Mo. (d) 118, 10% Mo.

M_6C carbide seems to remain rather coarse and is not very susceptible to solution annealing and reprecipitation. This supports the apparent lack of a fine precipitate in alloy 125 [Fig. 17(d)] after aging.

Chromium Series

The results of stress-rupture tests at 650°C on several chromium-bearing alloys are shown in Fig. 19. All of these alloys contain 16% Mo. The rupture life increases with increasing chromium content up to 7%, where the effect seems to saturate. The improvement in rupture life covers about 2 orders of magnitude. The minimum creep rates for these same samples are shown in Fig. 20. The creep rate is reduced by additions of 2 and 5% Cr, but similar creep rates were observed for alloys containing 5, 7, and 9% Cr. The fracture strains for these tests at 650°C are shown in Fig. 21 as a function of minimum creep rate. The fracture strains generally decrease with decreasing creep rate, but there is no detectable effect of chromium content on the fracture strain.

Tensile tests at 25°C show a maximum in fracture strain for an alloy containing 2% Cr; however, the total range of fracture strains observed is quite small, as seen in Fig. 22. At 650°C the fracture strains range from 25 to 45%. The fracture strain increases systematically with additions up to 5% Cr and then remains constant for further additions. The yield and tensile strengths increase with increasing chromium up to 7% Cr, where the strengthening saturates, as shown in Fig. 23. The strength changes are reasonably parallel at 25 and 650°C.

Iron Series

Three alloys were studied that contained from 0 to 4% Fe. The stress-rupture properties of these alloys at 650°C are shown in Fig. 24. Iron additions decreased the rupture life at a given stress level. The creep strength was not influenced detectably by the range of iron concentrations studied, as seen in Fig. 25. The fracture strains exhibited such a large amount of scatter, shown in Fig. 26, that conclusions are difficult.

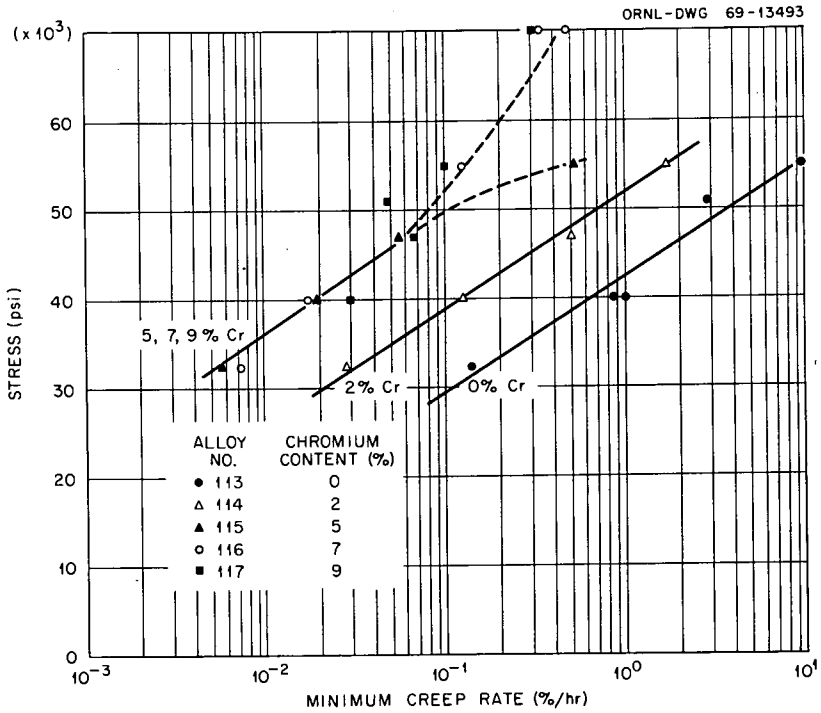

Fig. 19. Stress-Rupture Properties at 650°C for Alloys with Varying Chromium Concentration. Base composition: Ni—16% Mo—0.2% Mn—0.05% C.

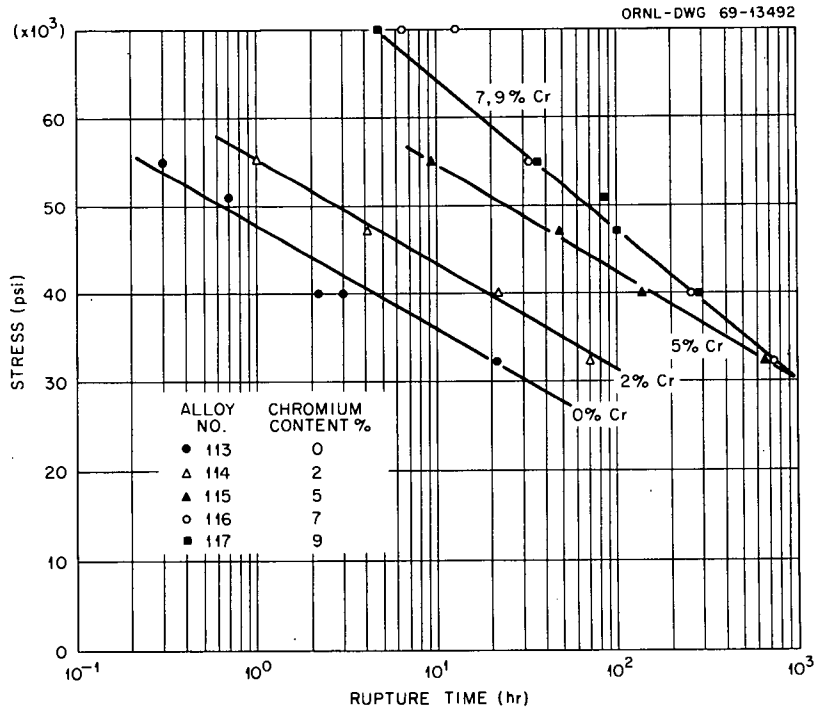

Fig. 20. Creep Properties at 650°C for Alloys with Varying Chromium Concentrations. Base composition: Ni—16% Mo—0.2% Mn—0.05% C.

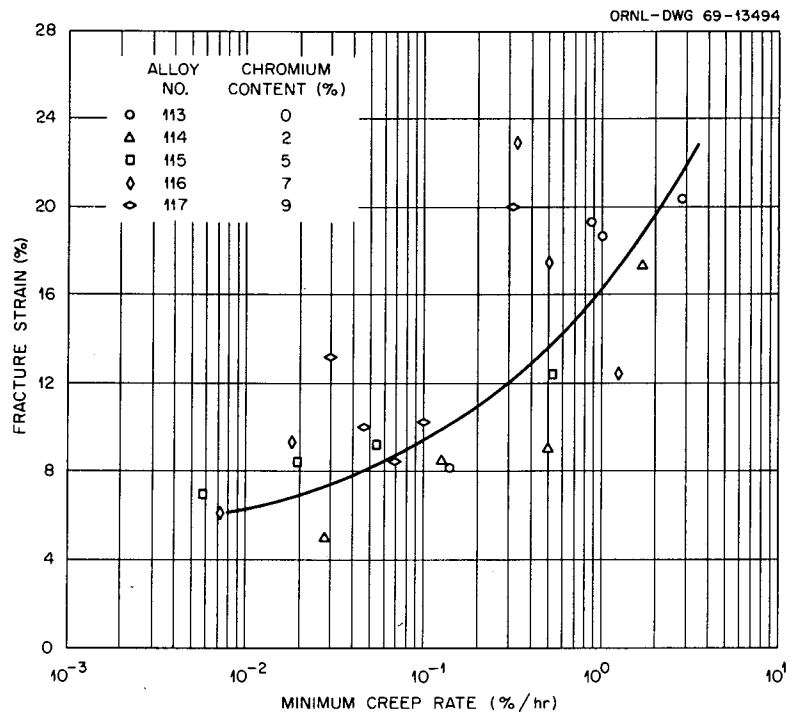

Fig. 21. Variation of the Fracture Strain at 650°C with the Creep Rate for Alloys Containing Various Amounts of Chromium. Base composition: Ni–16% Mo–0.2% Mn–0.05% C.

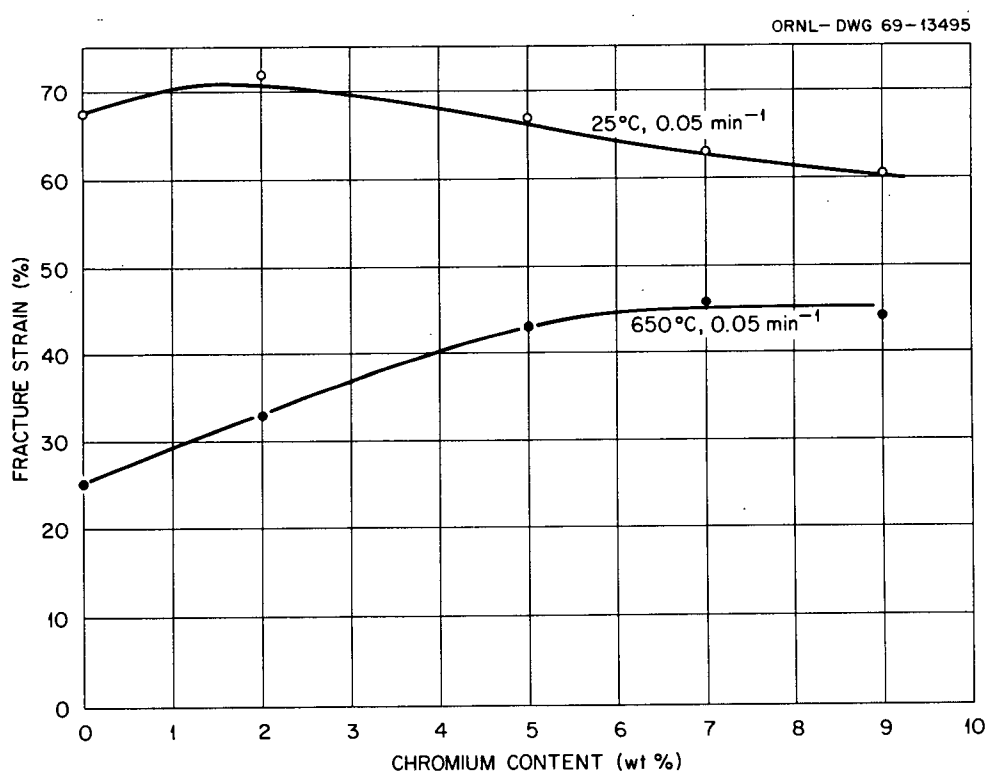

Fig. 22. Variation of the Fracture Strain with Chromium Content During Tensile Tests at 25 and 650°C. Base composition: Ni–16% Mo–0.2% Mn–0.05% C.

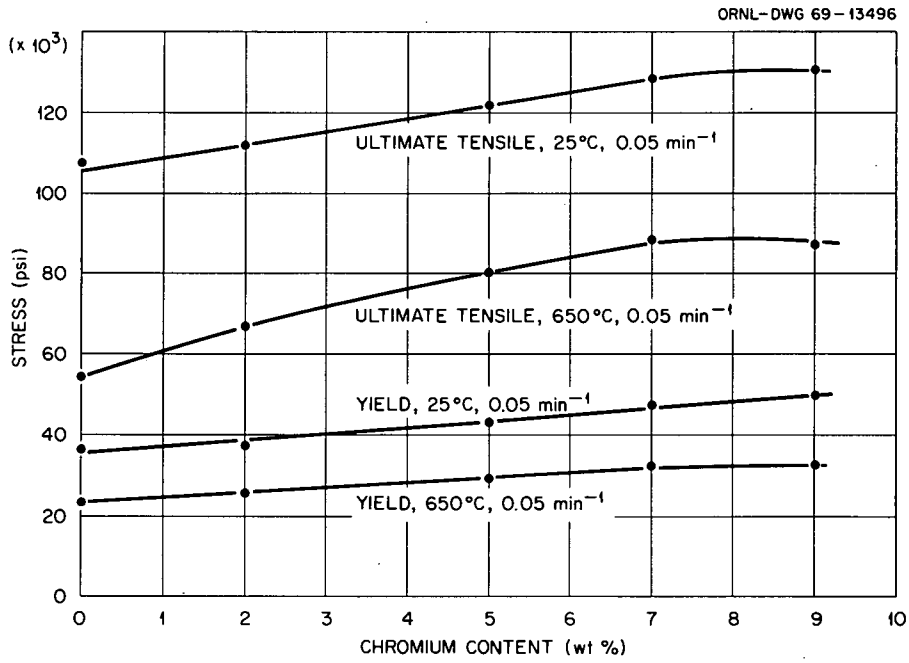

Fig. 23. The Yield and Ultimate Tensile Stresses for Alloys Containing Various Amounts of Chromium, Measured at 25 and 650°C at a Strain Rate of 0.05/min. Base composition: Ni–16% Mo–0.2% Mn–0.05% C.

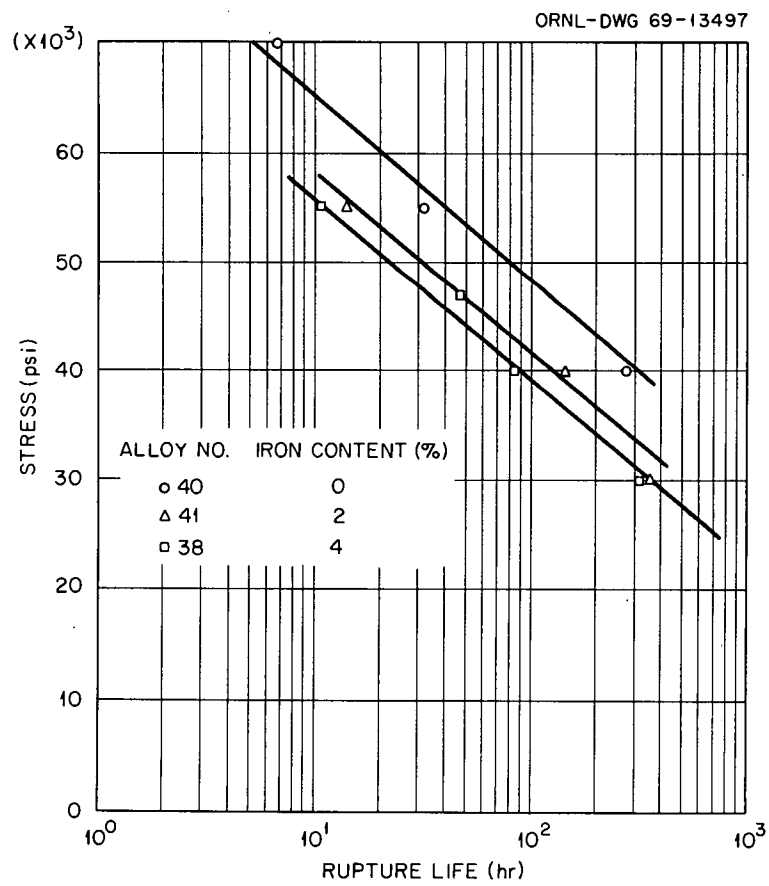

Fig. 24. Stress-Rupture Properties at 650°C for Alloys with Varying Iron Concentration. Base composition: Ni–16% Mo–7% Cr–0.5% Mn–0.5% Si–0.05% C.

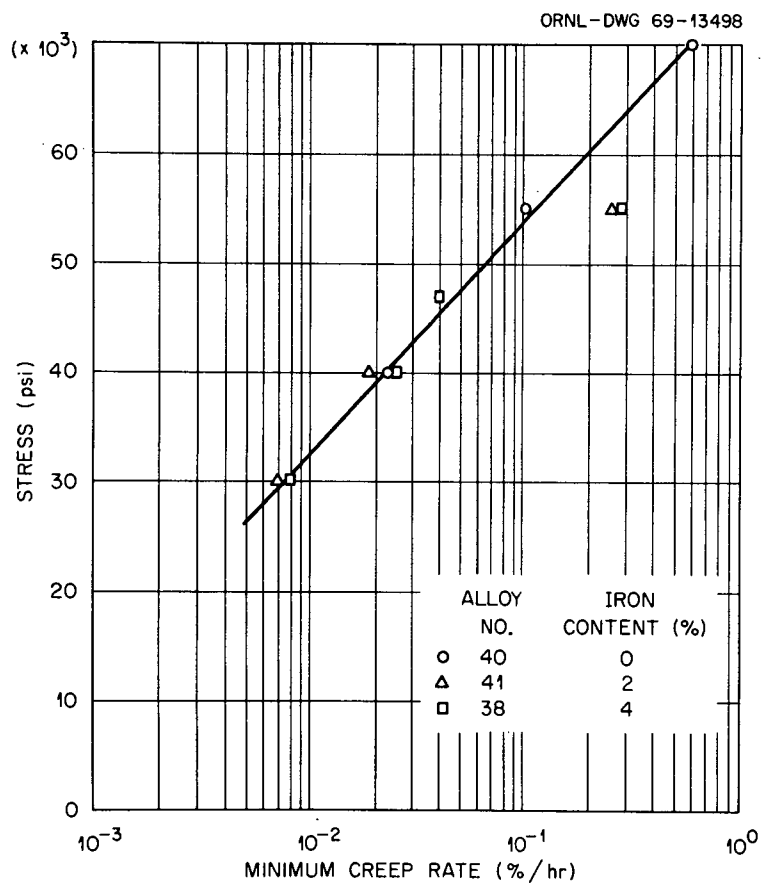

Fig. 25. Minimum Creep Rate at 650°C for Alloys with Varying Iron Concentrations. Base composition: Ni–16% Mo–7% Cr–0.5% Mn–0.5% Si–0.05% C.

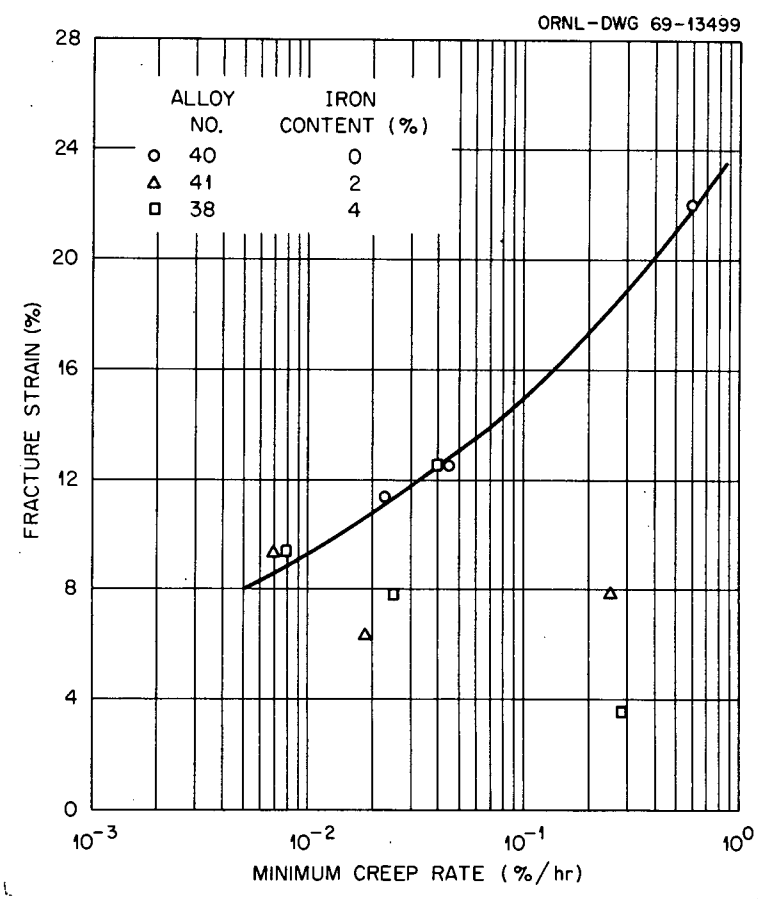

Fig. 26. Variation of the Fracture Strain at 650°C with the Creep Rate for Alloys Containing Various Amounts of Iron. Base composition: Ni–16% Mo–7% Cr–0.5% Mn–0.5% Si–0.05% C.

Tensile tests were run at 25 and 650°C. The fracture strain was not affected by the iron concentration at either test temperature, as seen in Fig. 27. The yield stresses at both temperatures were not influenced by iron concentration, but the ultimate tensile stresses were reduced about 3% at both test temperatures by the addition of iron, as seen in Fig. 28. These changes are quite small.

Silicon Series

The range of 0 to 1% Si was chosen because this covers the range normally encountered for this alloy when the melting practice varies from vacuum to air melting. The stress-rupture properties at 650°C are shown in Fig. 29. The rupture lives are about the same for the alloys containing from 0 to 0.5% Si, but decreased markedly when the silicon content was increased to 1%. The creep strength is shown in Fig. 30 for these same alloys. The creep strength is equivalent for alloys containing from 0 to 0.5% Si and then decreases when 1% Si is added. The fracture strains shown in Fig. 31 defy interpretation. There is a tendency for the fracture strains to be higher for the alloy containing 1% Si. Some of the samples were annealed at 1260°C before testing and these points are also shown in Figs. 29 through 31. The higher annealing temperature did not change the rupture life, reduced the minimum creep rate, and decreased the fracture strain.

The series was tensile tested at 25 and 650°C. The fracture strain at 25°C went through a slight minimum at 0.2% Si, as seen in Fig. 32. At 650°C the fracture strain decreased from 36% with no silicon present to 29% with 0.5 to 1% Si. The yield and ultimate strengths at 25°C were not changed measurably by silicon concentration, as shown by Fig. 33. At 650°C the yield stress increased and the ultimate stress decreased with increasing silicon content.

Silicon additions to the alloy exert a strong influence on the type of carbide that precipitates. A transition from all M_2C to all silicon-rich M_6C occurs as the silicon concentration is increased from trace levels to about 0.5% at a nominal carbon concentration of 0.05%. Both phases

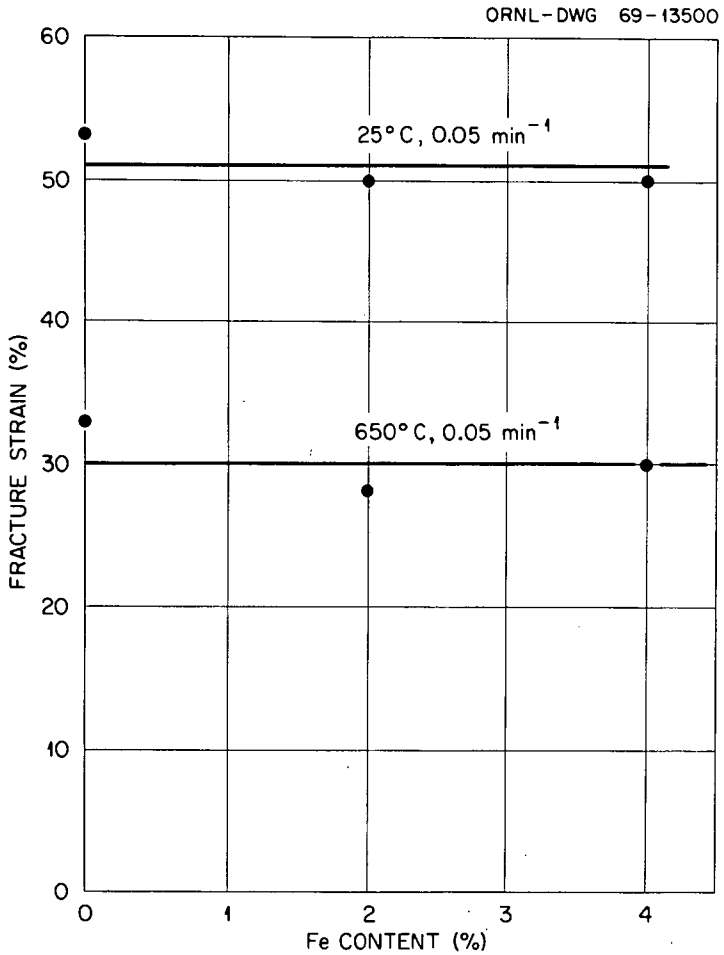

Fig. 27. Variation of the Fracture Strain with Iron Content During Tensile Tests at 25 and 650°C. Base composition: Ni—16% Mo—7% Cr—0.5% Mn—0.5% Si—0.05% C.

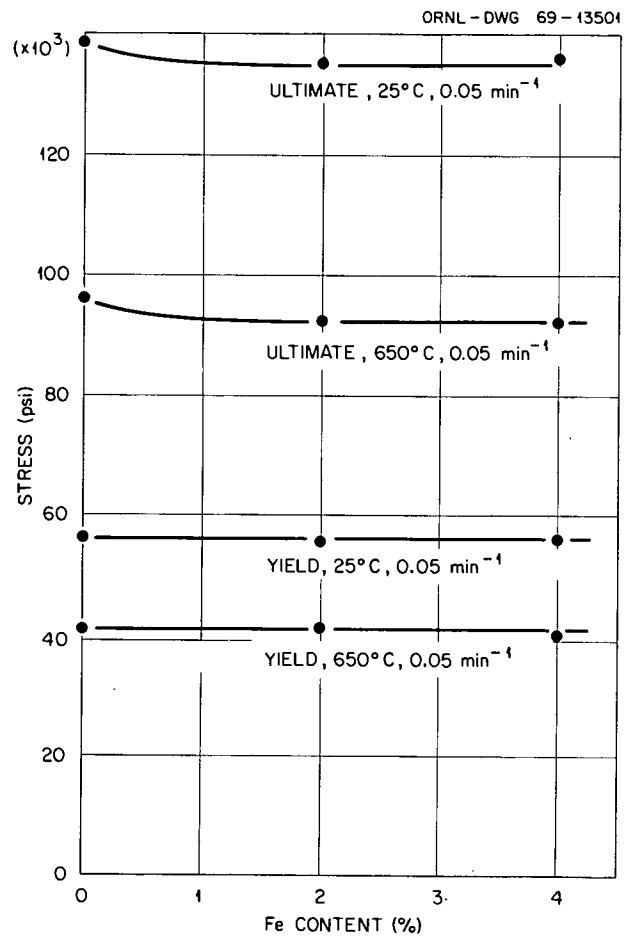

Fig. 28. The Yield and Ultimate Tensile Stresses for Alloys Containing Various Amounts of Iron, Measured at 25 and 650°C at a Strain Rate of 0.05/min. Base composition: Ni—16% Mo—7% Cr—0.5% Mn—0.5% Si—0.05% C.

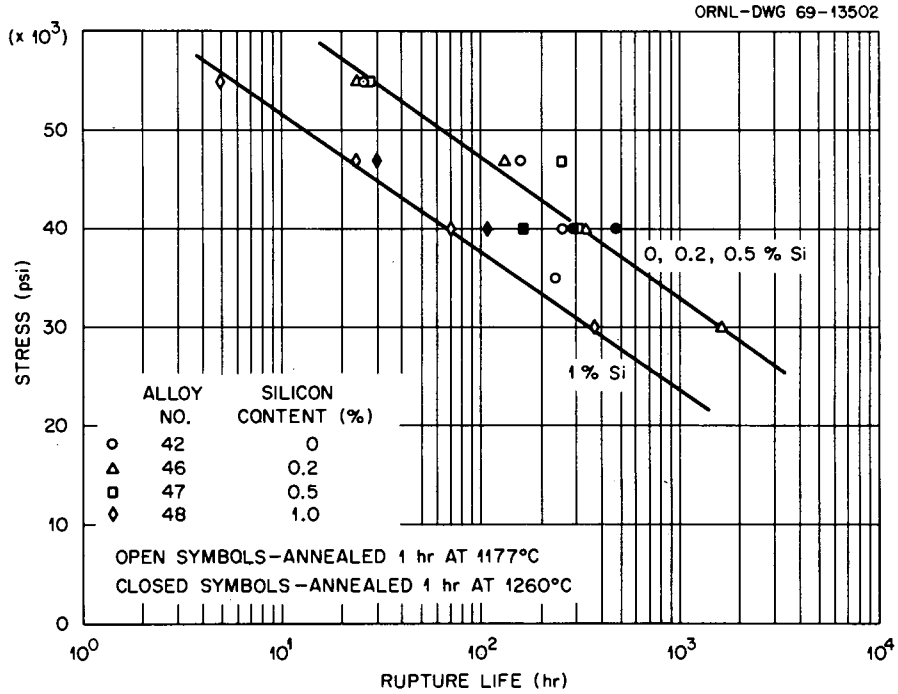

Fig. 29. Stress-Rupture Properties at 650°C for Alloys with Varying Silicon Concentration. Base composition: Ni—16% Mo—7% Cr—4% Fe—0.05% C.

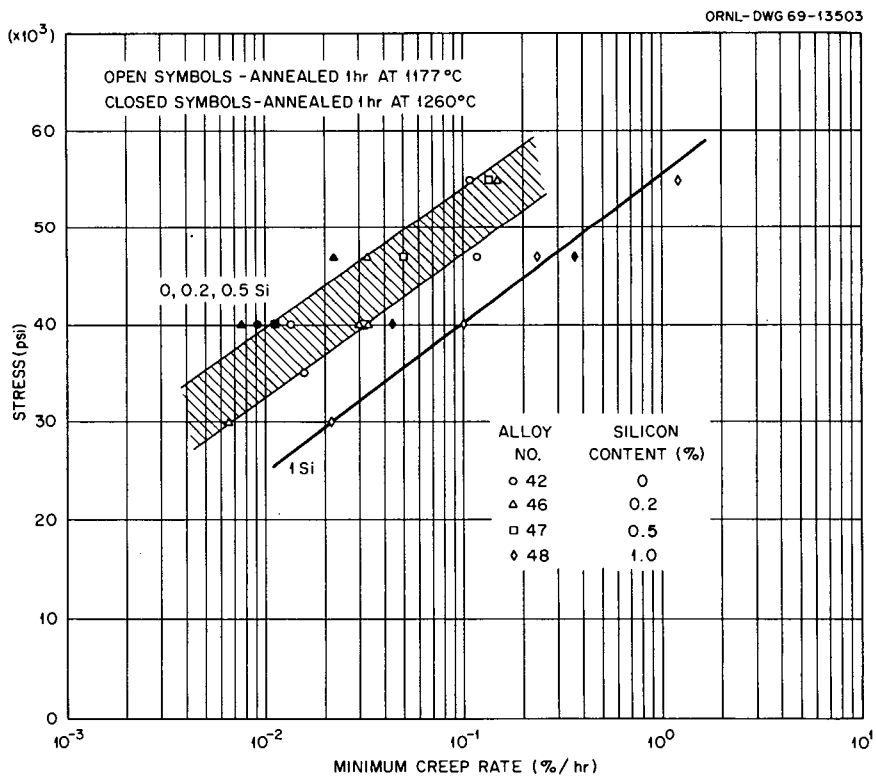

Fig. 30. Minimum Creep Rate at 650°C for Alloys with Varying Silicon Concentrations. Base composition: Ni—16% Mo—7% Cr—4% Fe—0.05% C.

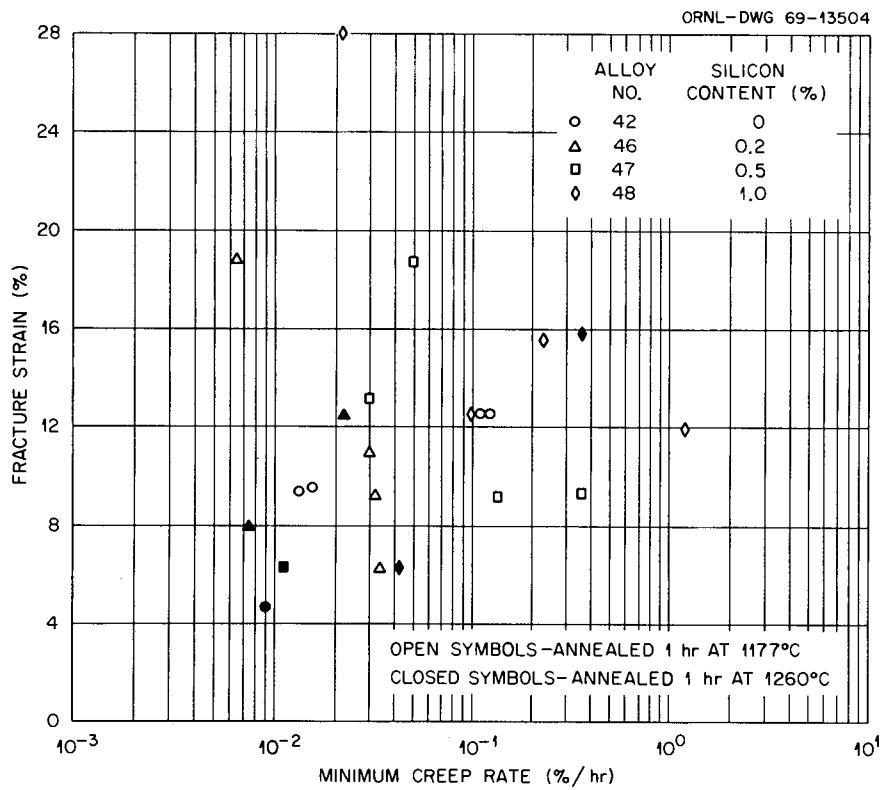

Fig. 31. Variation of the Fracture Strain at 650°C with the Creep Rate for Alloys Containing Various Amounts of Silicon. Base composition: Ni–16% Mo–7% Cr–4% Fe–0.05% C.

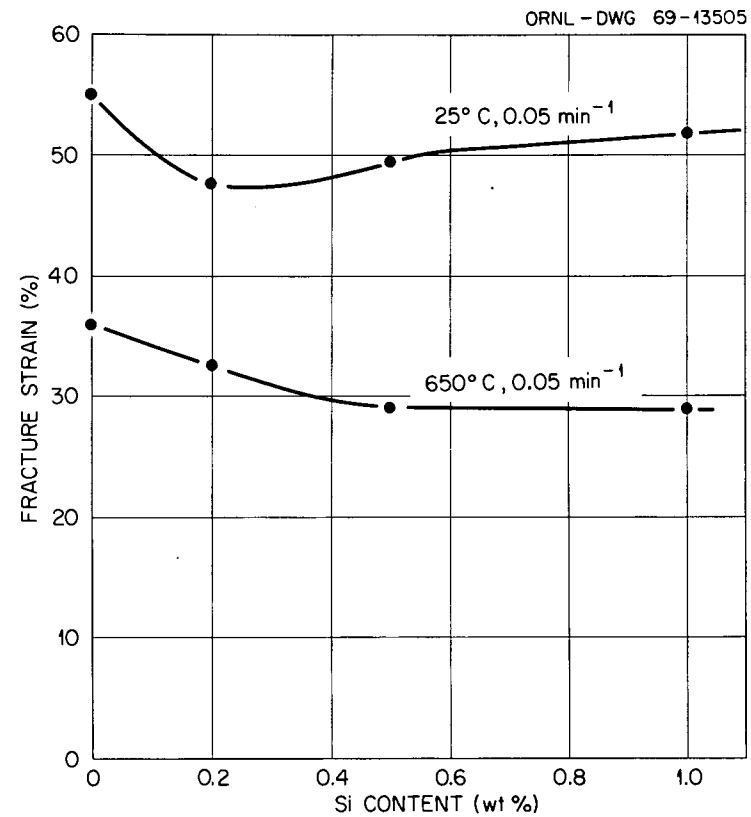

Fig. 32. Variation of the Fracture Strain with Silicon Content During Tensile Tests at 25 and 650°C. Base composition: Ni–16% Mo–7% Cr–4% Fe–0.05% C.

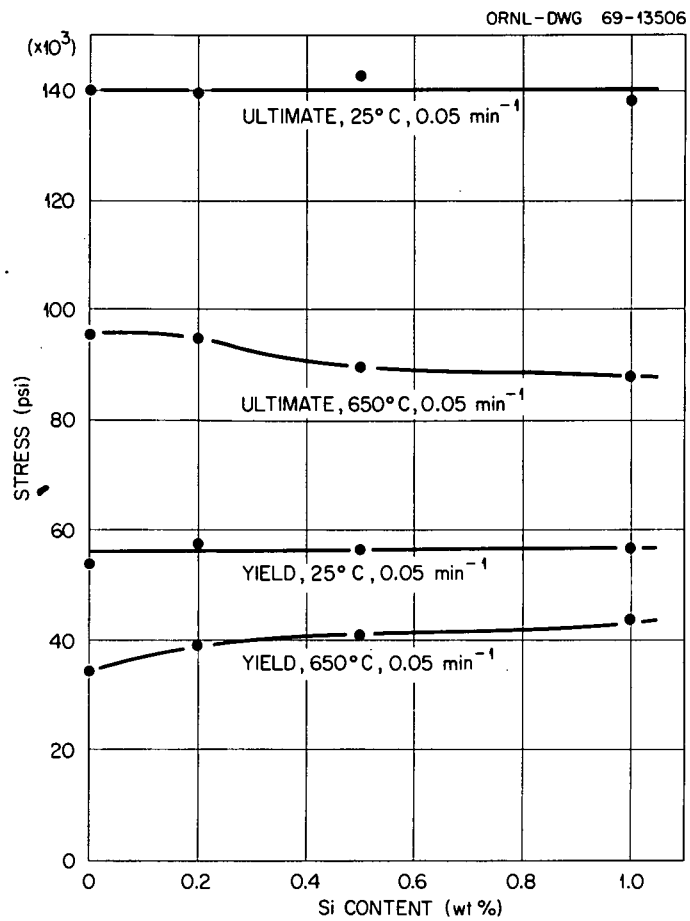

Fig. 33. The Yield and Ultimate Tensile Stresses for Alloys Containing Various Amounts of Silicon, Measured at 25 and 650°C at a Strain Rate of 0.05/min. Base composition: Ni—16% Mo—7% Cr—4% Fe—0.05% C.

coexist in the 0.1 to 0.3% Si range. Whereas the M_2C can be put into solid solution and its morphology varied by heat treatment, the silicon-rich M_6C occurs on grain boundaries and as stable blocky primary particles or stringers. This carbide has a lattice parameter of 11.02 Å, and the metallic elements consist of approximately 28% Ni, 3.3% Si, 0.7% Fe, 56% Mo, and 4% Cr.

Manganese Series

The stress-rupture properties of several alloys containing various amounts of manganese are shown in Fig. 34. The properties do not show any systematic variation with manganese content. The same observation applies

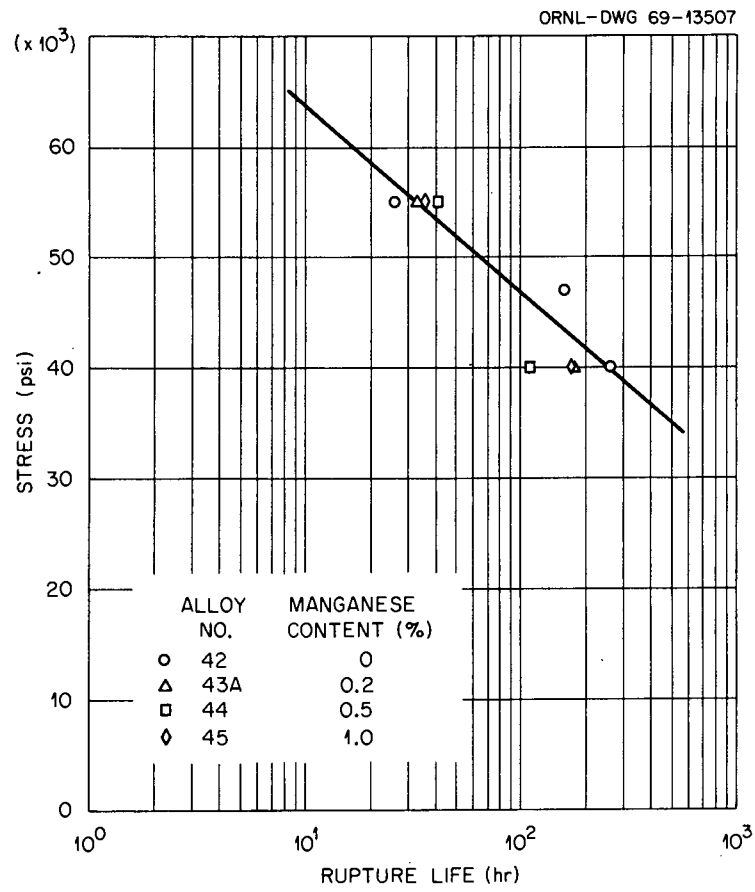

Fig. 34. Stress-Rupture Properties at 650°C for Alloys with Varying Manganese Concentration. Base composition: Ni—16% Mo—7% Cr—4% Fe—0.05% C.

to the minimum creep rate, shown in Fig. 35. The fracture strains observed in creep tests are shown in Fig. 36 as a function of creep rate. Again, there is no systematic variation of this property with manganese content.

Tensile tests at 25 and 650°C showed slight variations in properties with varying manganese concentration. The fracture strain at 25°C is optimum at 0.2% Mn, and at 650°C an improvement from 36 to 41% strain occurs with the first 0.2% Mn addition, as seen in Fig. 37. The yield and ultimate strengths generally show a minimum value at 0.2% Mn, as seen in Fig. 38.

DISCUSSION OF RESULTS

The effects of the various alloying additions on the creep strength at 650°C are summarized in Fig. 39. The actual chemical analyses in Table 1

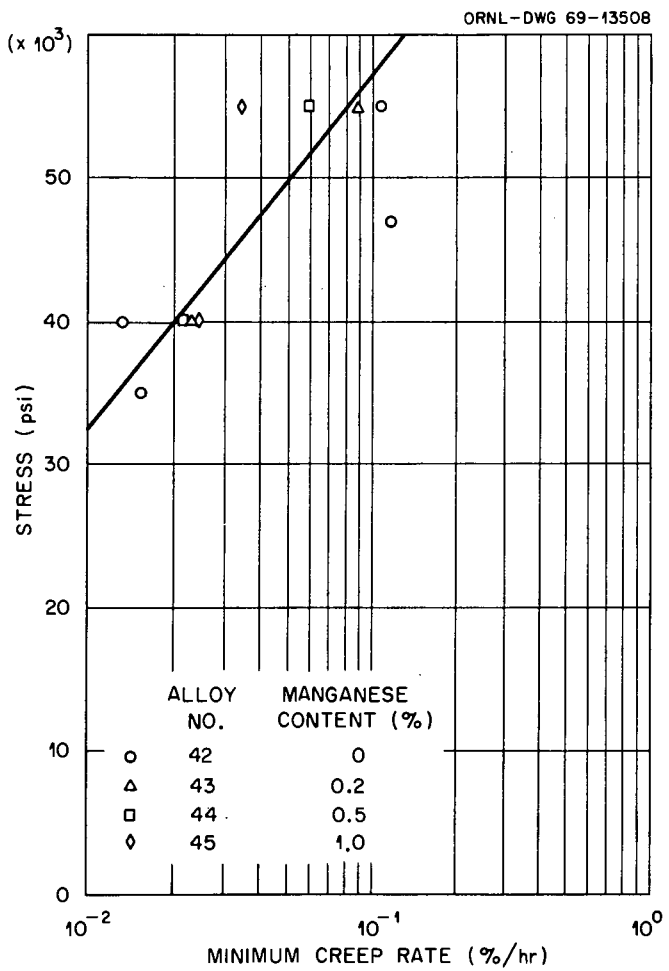

Fig. 35. Minimum Creep Rate at 650°C for Alloys with Varying Manganese Concentrations. Base composition: Ni–16% Mo–7% Cr–4% Fe–0.05% C.

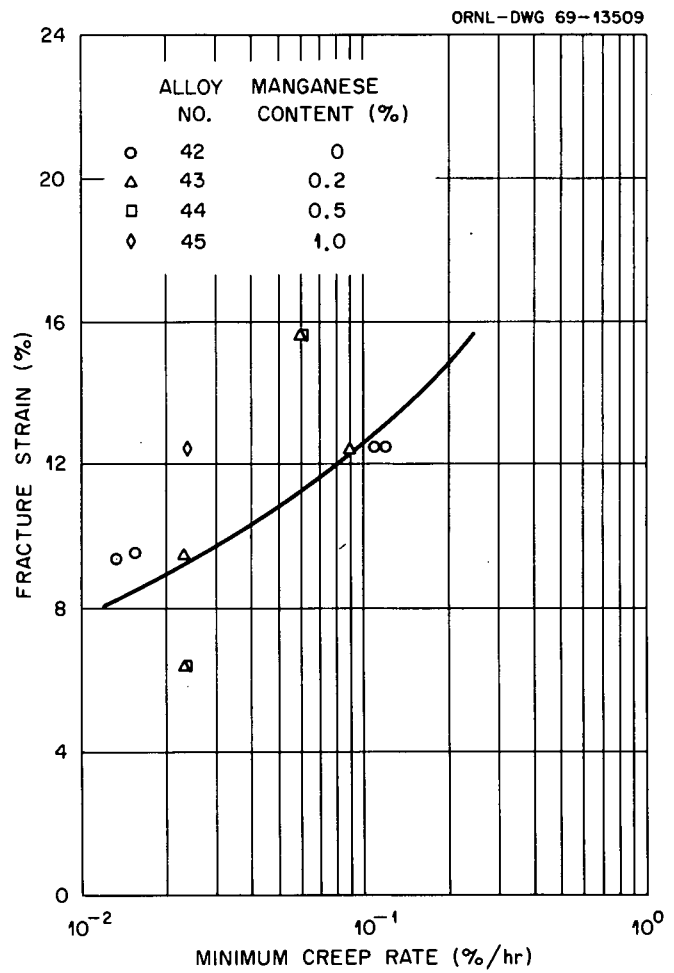

Fig. 36. Variation of the Fracture Strain at 650°C with the Creep Rate for Alloys Containing Various Amounts of Manganese. Base composition: Ni–16% Mo–7% Cr–4% Fe–0.05% C.

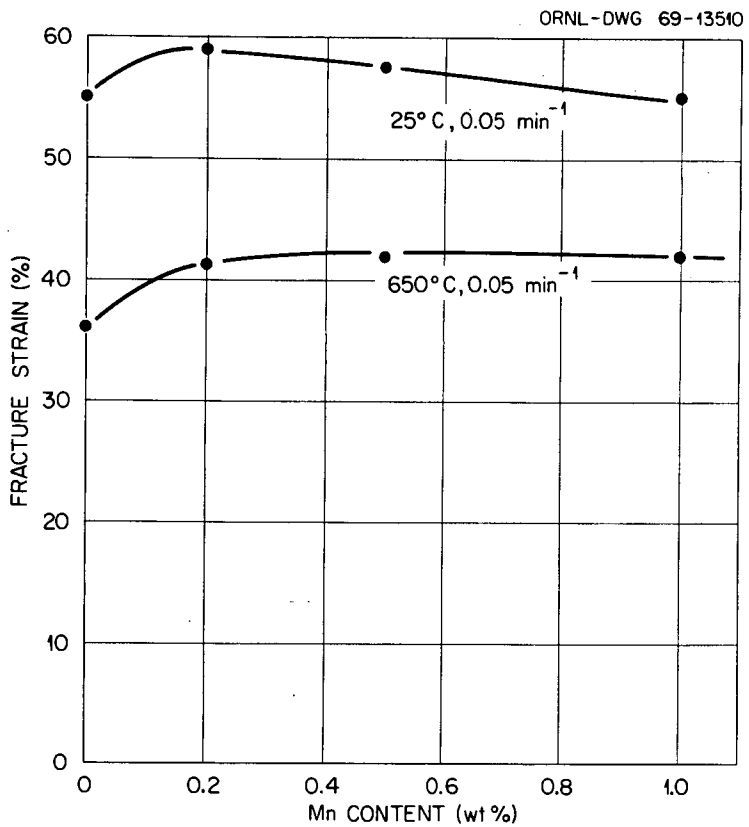

Fig. 37. Variation of the Fracture Strain with Manganese Content During Tensile Tests at 25 and 650°C. Base composition: Ni–16% Mo–7% Cr–4% Fe–0.05% C.

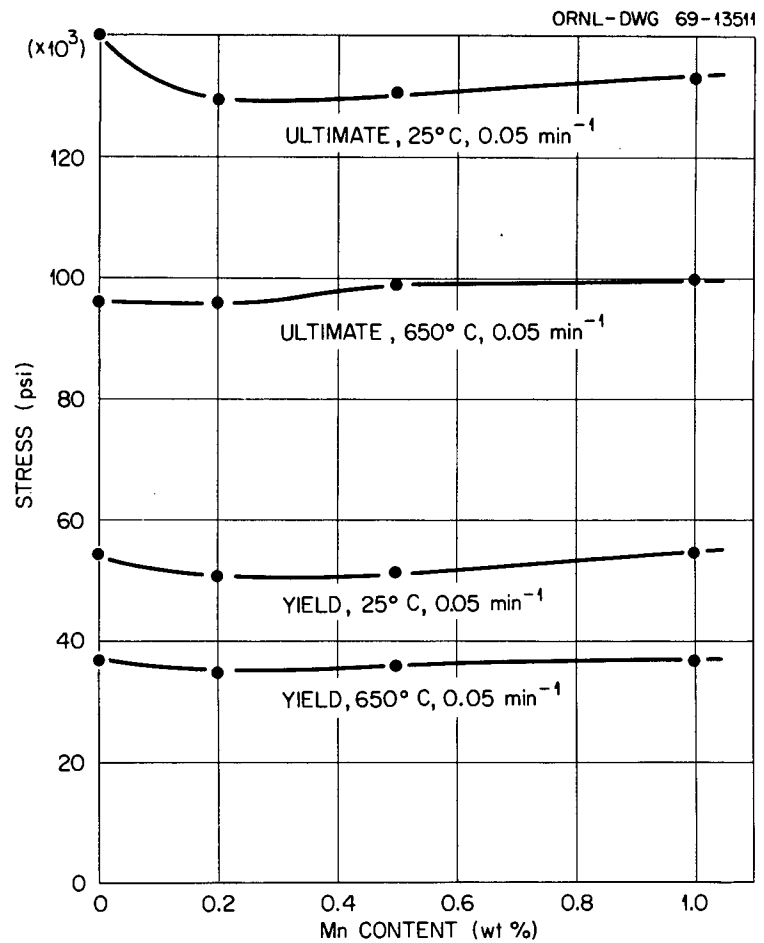

Fig. 38. The Yield and Ultimate Tensile Stresses for Alloys Containing Various Amounts of Manganese Measured at 25 and 650°C at a Strain Rate of 0.05/min. Base composition: Ni–16% Mo–7% Cr–4% Fe–0.05% C.

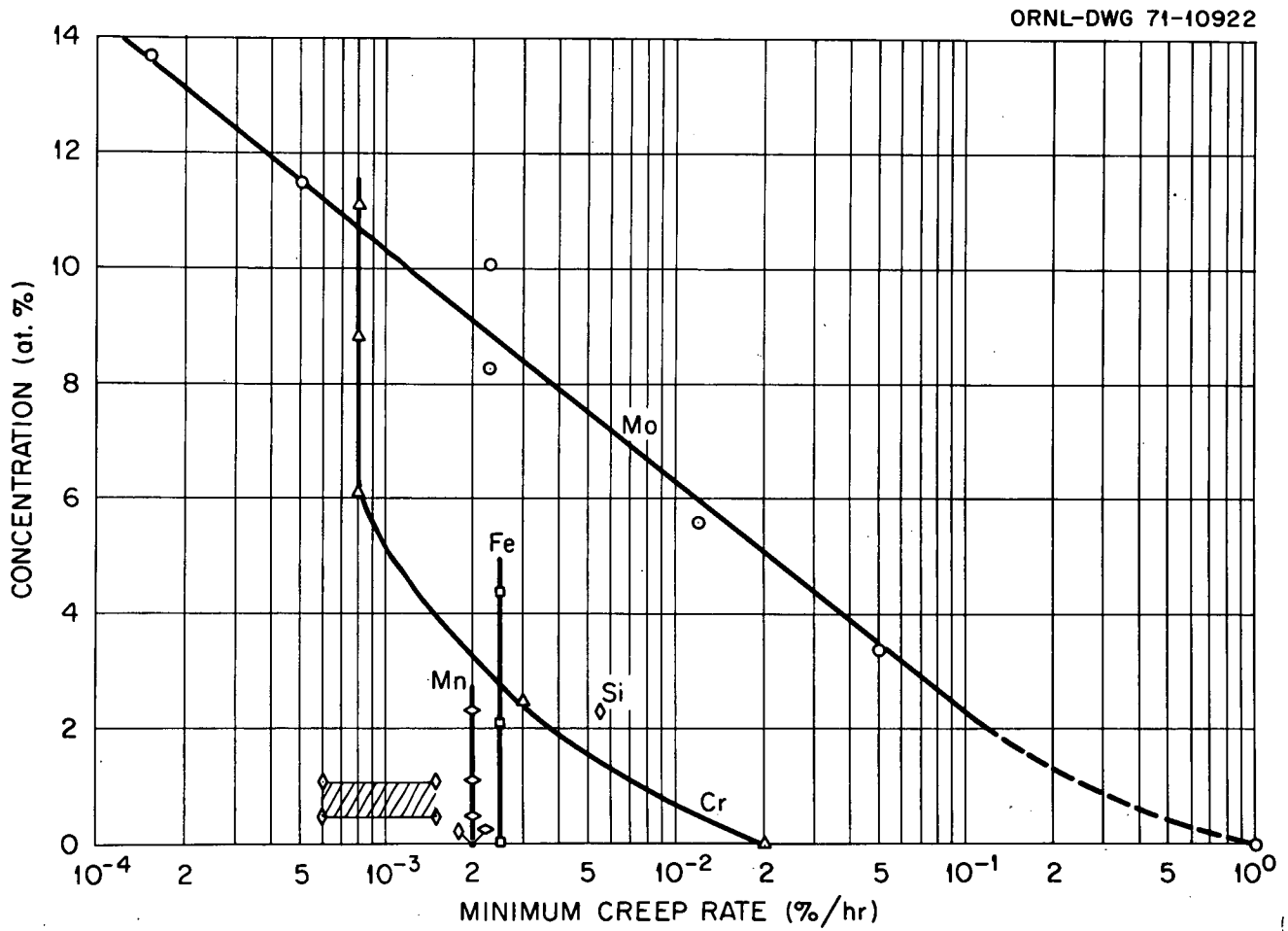

Fig. 39. Variation of the Minimum Creep Rate at 650°C and a Stress Level of 20,000 psi with Concentration of Various Alloying Additions.

were used to compute the atomic concentrations. Molybdenum has a strengthening effect that varies linearly with the logarithm of the concentration above about 3 at. %. Chromium likewise has a strengthening effect, but the effect seems to saturate above about 6 at. %. Silicon has a somewhat erratic effect, the only obvious conclusion being that concentrations as high as 2.3 at. % cause a weakening. Manganese and iron over the range studied have no effects on the creep strength.

A first estimate of the behavior of these alloying additions can be made from the binary phase diagrams involving nickel and the particular element being added. At 650°C molybdenum has a solubility of about 22% (14 at. %) in nickel,[5] so the maximum concentration studied of 18.9% likely does not exceed the solubility limit. The molybdenum atom is 9.4% larger than the nickel atom, and the observed strengthening (Fig. 39) is as expected. The respective roles of the various carbides in these alloys have not been fully evaluated, but in general, the carbides are too coarse to cause significant strengthening. However, the role of carbon in taking molybdenum out of solution may be significant. We frequently observe a carbide at high molybdenum concentrations having the composition Ni_2Mo_4C (M_6C type). If all the carbon (∿0.05%) in the alloy formed this compound, 1.6% Mo would be taken out of solution. The M_2C type carbide would remove less molybdenum. We find that silicon levels above about 0.2% favor the formation of a silicon-rich M_6C type carbide. Hence, the exact creep rates in Fig. 39 might have been different had the alloys contained 0.5% Si, but the shape of the curve would likely not have been altered.

Chromium has a very high solubility in nickel, with a value at 650°C of 33% (36 at. %) being reported.[6] However, the chromium atom is only 0.3% larger than the nickel atom, and not much strengthening would be expected. The carbides contain some chromium, but the type of carbide formed seems to be dominated more by the molybdenum and silicon concentrations. Thus, it seems unlikely that chromium would have much effect on the carbide structure in alloys that contain 16% Mo.

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[5]Max Hansen, *Constitution of Binary Alloys*, McGraw-Hill Book Co., Inc., New York, p. 968 (1958).

[6]Ibid, p. 542.

Iron does not have any detectable effect on the creep strength. Iron is quite soluble in nickel; at 650°C 86% (87 at. %) is soluble.[7] The iron atom is only 0.4% smaller than the nickel atom, and iron does not seem to influence the carbide structure. Thus, it is not surprising that iron does not have much influence on the mechanical properties. The iron series (alloys 38, 40, and 41) contains 0.40% Si, and hence the silicon-rich M_6C-type carbide forms.

The solubility of silicon in nickel at 650°C is 5% (10 at. %)[8] and the silicon atom is 5.6% smaller than the nickel atom. Thus, some lattice distortion could be caused, but silicon is likely more important in other ways. Silicon depresses the melting point of nickel; an addition of 11.5% reduces the melting point from 1453 to 1152°C. Thus, any silicon segregation may cause incipient melting, particularly during welding. As mentioned previously, silicon causes the formation of a coarse M_6C type carbide, which contains at least 3.3% Si. Thus, as much as 0.1% Si could be tied up in the carbide when 0.05% C is present. However, under the conditions studied, silicon has little effect on the strength.

The nickel-manganese phase diagram is not well established, but the available information[9] indicates a high solubility and little melting point depression with small manganese additions. Thus, the lack of an effect on strength in the concentration range studied is not surprising.

The yield stresses of the various alloys at 25 and 650°C are shown in Figs. 40 and 41, respectively. The effects are quite similar to those just discussed for creep conditions. At 25°C, the strengthening effect of molybdenum is linear, with the possible exception of the highest concentration. The strengthening effect of chromium is near linear and does not show the saturation effect that was noted in creep (Fig. 39). Iron, manganese, and silicon do not have any significant effects on the strength. At 650°C, the yield stress is linearly dependent upon molybdenum concentration, although there does seem to be an alternate way

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[7]Ibid, p. 678.

[8]Ibid, p. 1040.

[9]Ibid, p. 939.

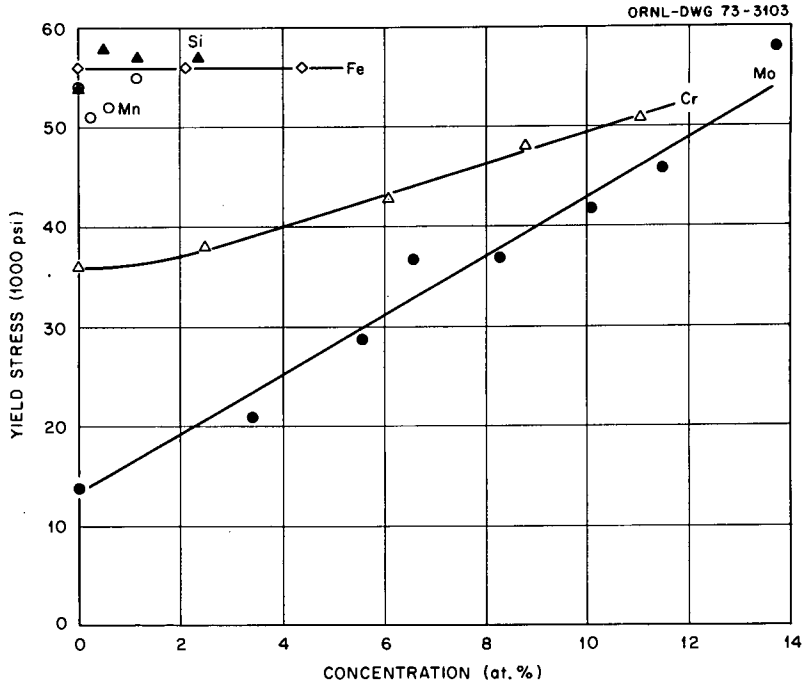

Fig. 40. Effect of Various Alloying Additions on the Yield Stress at 25°C

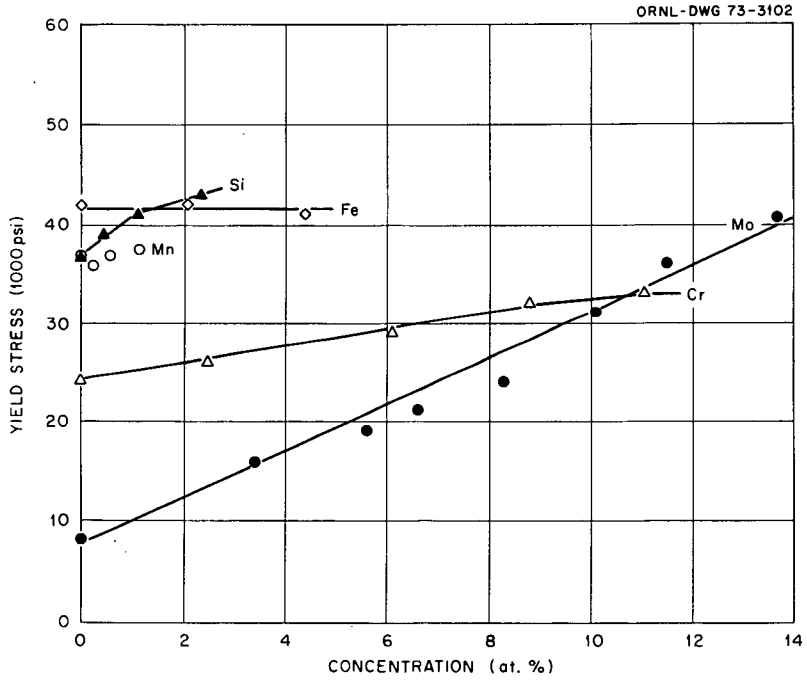

Fig. 41. Effect of Various Alloying Additions on the Yield Stress at 650°C.

(shown dashed) that the behavior could be described. The yield stress increases with chromium concentration and, like the creep strength, saturates at high chromium levels. Silicon seems to have a strengthening effect, but iron and manganese do not have a measurable effect on the yield stress.

CONCLUSIONS

The effects of Mo, Cr, Fe, Si, and Mn on the strength of nickel-base alloys at 25 and 650°C were studied. The strength at 25°C was enhanced by molybdenum and chromium and not significantly affected by iron, silicon, and manganese in the concentrations studied. At 650°C the yield stress and the creep strength were improved by additions of molybdenum, chromium, and silicon. Iron and manganese had no measurable effect. These changes are thought to be a result primarily of solid solution hardening, although molybdenum, chromium, and silicon influence the type of carbide that is formed.

ACKNOWLEDGMENTS

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