Journal of Research of the National Bureau of Standards Vol. 58, No. 4, April 1957 Research Paper 2753

Tensile Properties of Copper, Nickel, and 70-Percent-Copper–30-Percent-Nickel and 30-Percent-Copper–70-Percent-Nickel Alloys at High Temperatures

William D. Jenkins, Thomas G. Digges, and Carl R. Johnson

Short-time tensile tests were made at temperatures ranging from 75° to 1,700° F on high-purity nickel, copper, a 70-percent-nickel–30-percent-copper alloy, and a 70-percent-copper–30-percent-nickel alloy. The high-purity component metals and the two alloys were investigated in the initial conditions, as annealed for a uniform grain size, and as cold-drawn 40-percent reduction in area. The results were affected markedly by variations in the nickel content, temperature, and degree of cold-working. However, the effects of cold-drawing at room temperature were obliterated at temperatures above that of recrystallization.

The effects of cold-drawing the 30%-Ni–70%-Cu alloy different amounts and of variations in grain size of the copper on the tensile properties are evaluated. Results on the tensile properties of the same annealed materials at low temperatures are included for completeness.

1. Introduction

During the past several years, an investigation has been in progress in the Metallurgy Division, National Bureau of Standards, to evaluate the rheological behavior at subzero and elevated temperatures of high-purity nickel, copper, and certain alloys of these two elements. Some of the results obtained in this study have been presented in previous publications [1 to 7].[1] The present paper is concerned with the influence of temperature on the short-time tensile properties of the nickel, copper, and 70%-Ni–30%-Cu and 30%-Ni–70%-Cu alloys.

Tensile tests were made at temperatures ranging from 70° to 1,500° or 1,700° F on each of the four materials (table 1) in the conditions as annealed and as cold-drawn 40% reduction in area. In addition, the present program was extended to include tensile tests at various temperatures on the 30%-Ni–70%-Cu alloy as cold-drawn 25- and 70-percent reduction in area, and on the copper after annealing to produce a relatively large grain size.

TABLE 1. *Chemical composition (percentage by weight) of the metals and alloys used as determined by chemical, spectrochemical, and vacuum fusion analyses*

Metal	C	Cu	Ni	Co	Fe	Mn	Si	S	Zn	O_2	N_2	H_2	Average [c] grain diameter
													mm
Copper [a] (OFHC)	--------	99.99+	--------	------	------	------	--------	--------	------	--------	--------	--------	0.025
30%-Ni-70%-Cu	0.023	68.84	29.89	0.04	0.50	0.65	0.003	0.004	0.09	0.001	0.001	0.0002	.040
70%-Ni-30%-Cu	.017	29.71	70.08	([b])	.01	.01	.12	.002	------	.001	.0015	.0003	.025
Nickel	.007	0.009	99.85	([b])	.04	.03	.11	.002	------	.002	.001	.0002	.045

[a] The arc spectrum of the copper was examined for the sensitive lines of Ag, Al, B, Be, Co, Fe, In, Ir, Mg, Mo, Na, Ni, Pb, Sb, Si, Sn, Ti, V, and Zn. The lines for Ag, Al, Mg, and Si were identified and there was some indication of the presence of Fe, Ni, and Pb.

[b] Not detected.

[c] Values obtained on specimens prepared from the annealed bars.

2. Materials and Procedures

The chemical compositions of the four materials used are given in table 1. All the bars of each material were processed from a single heat and they were supplied in the form of $\frac{7}{8}$- or $\frac{13}{16}$-in. rounds in the conditions as annealed or as cold-drawn. The annealing treatments produced the average grain sizes listed in table 1, and these annealing treatments were also used just prior to the final cold-drawing operations.

Tensile specimens, 0.505 in. in diameter and with a 2.0-in. reduced section, were machined from one bar of each material as initially annealed and from another bar as cold-drawn. Each specimen tested at 300° F, or higher, was heated in air in an automatically controlled electric furnace and held at the reported temperature for approximately 1 hour before testing. The specimen was maintained within ±3 deg F of the reported temperature during testing. The deformation was determined by following the change in minimum diameter of the specimen during testing in tension at room temperature, and by measuring the movement of the head of the hydraulic-type machine with a Templin stress-strain

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[1] Figures in brackets indicate the literature references at the end of this paper.

TABLE 2. *Resuts of tensile tests on high-purity nickel*

Initial condition	Temperature [a]	Yield strength (0.2% offset)	Maximum load					True stress at complete fracture	Elongation in 2 in.	Reduction of area	True strain at complete fracture
			Tensile strength	True stress	Strain in 2 in.	Reduction in area [b]	True strain				
	° *F*	*lb/in* ^{2}	*lb/in* ^{2}	*lb/in* ^{2}	%	%		*lb/in* ^{2}	%	%	
Annealed	−320	17, 000	82, 000	127, 500	55. 5	35. 5	0. 44	244, 700	72	78. 5	1. 543
Do	−220	16, 700	69, 000	104, 400	51. 5	34	. 41	235, 500	63. 5	82. 5	1. 737
Do	−108	15, 000	60, 600	89, 300	47. 5	32	. 39	215, 100	60. 5	83. 5	1. 813
Do	−22	15, 000	56, 200	81, 900	46	31. 5	. 38	250, 700	59	87	2. 073
Do	75	11, 100	51, 800	74, 200	43	31	. 37	222, 900	----------	87	2. 034
Do	75	12, 500	52, 700	76, 700	45	31	. 39	278, 600	56	89	2. 27
Do	88	12, 500	51, 600	72, 300	41	29	. 34	222, 800	56	87	2. 076
Do	212	12, 000	48, 300	68, 500	42	30	. 36	224, 200	57	88	2. 11
Do	212	12, 500	48, 400	69, 200	43	31	. 37	210, 600	57	87	2. 054
Do	300	12, 900	46, 400	63, 600	37	27	. 32	194, 100	52	87	2. 053
Do	500	11, 300	43, 300	58, 900	36	26	. 31	208, 500	51	89	2. 263
Do	600	9, 900	41, 300	55, 800	35	26	. 30	243, 200	53	90	2. 515
Do	700	9, 400	36, 200	46, 700	29	23	. 26	215, 200	56	90	2. 555
Do	800	8, 900	31, 900	42, 100	32	24	. 28	189, 100	62	91	2. 586
Do	900	8, 700	28, 200	37, 500	33	25	. 29	216, 500	68	91	2. 991
Do	1, 000	8, 000	23, 200	30, 400	31	24	. 27	200, 500	77	96	3. 307
Do	1, 200	5, 600	15, 400	19, 400	26	21	. 23	40, 600	61	99. 7	5. 787
Do	1, 500	3, 750	5, 250	5, 800	11	10	. 10	-------	78	99. 99+	9. 269
Cold-drawn 40% reduction in area	75	80, 100	81, 600	82, 200	1	1	. 01	242, 900	19	81. 5	1. 685
Do	300	75, 100	76, 100	76, 900	1	1	. 01	229, 100	17	80. 5	1. 702
Do	500	65, 600	69, 800	70, 500	1	1	. 01	207, 500	18	82	1. 716
Do	700	58, 000	60, 800	61, 400	1	1	. 01	175, 200	17	83. 5	1. 798
Do	800	53, 400	56, 800	57, 400	1	1	. 01	174, 800	19	85	1. 878
Do	900	44, 900	47, 700	48, 700	2	1. 96	. 02	168, 600	21. 5	88	2. 133
Do	1, 000	39, 400	42, 000	43, 300	3	2. 5	. 03	150, 100	21	91	2. 375
Do	1, 200	6, 000	16, 700	22, 000	31. 5	24	. 274	24, 700	56	99. 5	5. 291
Do	1, 500	2, 700	7, 450	8, 600	15	13	. 140	-------	67	99. 99+	>10
Do	1, 700	1, 400	4, 450	4, 900	11	10	. 104	-------	92	99. 99+	>10

[a] Values at subzero temperatures obtained from data of Geil and Carwile [7].

[b] Reduction in area (%) $=100[(A_0-A)/A_0]=100[(L-L_0)/L_0]$.

TABLE 3. *Results of tensile tests on high-purity* 70%-Ni–30%-Cu *alloy*

Initial condition	Temperature [a]	Yield strength (0.2% offset)	Maximum Load					True stress at complete fracture	Elongation in 2 in.	Reduction of area	True strain at complete fracture
			Tensile strength	True stress	Strain in 2 in.	Reduction in area [b]	True strain				
	° *F*	*lb/in* ^{2}	*lb/in* ^{2}	*lb/in* ^{2}	%	%		*lb/in* ^{2}	%	%	
Annealed	−320	38, 000	101, 900	159, 900	57	36. 5	0. 450	282, 300	63. 5	78	1. 509
Do	−220	34, 600	88, 400	130, 800	48	32. 5	. 392	244, 800	56	79	1. 561
Do	−108	32, 100	79, 600	114, 700	45. 5	31	. 365	235, 300	56	81	1. 671
Do	−22	30, 200	73, 100	104, 300	43	30	. 356	261, 200	52. 5	84. 5	1. 875
Do	75	26, 500	67, 350	94, 550	40. 4	28. 8	. 339	304, 900	59. 1	88. 4	2. 150
Do	212	25, 250	63, 050	85, 200	35. 1	26	. 301	321, 500	51	89. 3	2. 235
Do	300	24, 050	61, 850	85, 300	37. 9	27. 5	. 321	277, 900	52	88	2. 113
Do	500	23, 600	60, 800	83, 500	37. 3	27. 2	. 317	247, 400	48. 3	85. 5	1. 929
Do	600	21, 600	61, 850	84, 300	36. 3	26. 6	. 309	221, 500	51	85	1. 894
Do	700	23, 400	59, 950	81, 250	35. 5	26. 2	. 304	227, 800	49. 2	84. 1	1. 840
Do	800	22, 150	55, 300	73, 650	33. 1	24. 9	. 286	190, 300	45. 2	81. 7	1. 698
Do	900	19, 950	50, 050	65, 800	31. 4	23. 9	. 273	153, 500	46. 8	78. 7	1. 546
Do	1, 000	17, 500	42, 050	53, 400	27	21. 3	. 239	98, 300	47	71. 6	1. 257
Do	1, 100	16, 700	31, 400	38, 450	22. 5	17. 9	. 203	53, 100	42	66. 5	1. 098
Do	1, 200	13, 500	24, 300	27, 550	13. 3	11. 7	. 125	26, 800	37. 5	58. 1	0. 869
Do	1, 350	9, 700	15, 800	17, 700	12. 1	10. 8	. 114	19, 200	35	49. 4	. 681
Do	1, 500	5, 750	10, 300	11, 250	9. 2	8. 4	. 087	9, 800	47	49	. 671
Do	1, 700	4, 500	5, 850	6, 600	13. 4	11. 8	. 127	6, 400	47. 5	45	. 598
Cold-drawn 40% reduction in area	75	97, 600	100, 800	102, 000	1	1	. 01	290, 200	17	81. 4	1. 680
Do	300	93, 400	94, 600	95, 600	1	1	. 01	258, 700	15. 5	80. 2	1. 620
Do	500	90, 800	92, 900	94, 000	1	1	. 01	228, 400	16	76. 8	1. 463
Do	700	83, 200	86, 300	87, 200	1. 5	1. 4	. 015	185, 100	15	71. 3	1. 248
Do	800	73, 900	77, 600	79, 900	3	2. 9	. 03	199, 900	19	76. 2	1. 438
Do	900	65, 300	70, 600	72, 700	3	2. 9	. 03	142, 600	18	68. 8	1. 165
Do	1, 000	51, 800	58, 200	60, 500	4	3. 9	. 039	82, 700	26	62. 9	0. 992
Do	1, 200	18, 900	31, 600	34, 600	9. 5	8. 6	. 09	72, 200	26	71. 6	1. 257
Do	1, 500	7, 750	12, 450	14, 100	13. 5	12	. 127	14, 500	34	43. 4	0. 568
Do	1, 700	4, 700	6, 750	6, 850	1	1	. 01	7, 600	35	35. 8	. 442

[a] Values at subzero temperatures obtained from data of Geil and Carwile [7].

[b] Reduction in area (%) $=100[(A_0-A)/A_0]=100[(L-L_0)/L_0]$.

recorder for the specimens tested at elevated temperatures. The rate of strain was approximately 1 percent per minute.

3. Results and Discussion

The experimental results of the tension tests made at various temperatures are summarized in tables 2 to 5. Some of the data previously obtained on the annealed materials at low temperature [7] are also included in these tables for completeness; these results were obtained on specimens prepared from different bars than those used in the present tests. The results obtained at low temperatures were presented graphically and discussed in some detail in relation to other properties in the previous publication.

3.1. True-Stress–True-Strain Relations at Room Temperature

The true-stress–true-strain curves for the annealed materials tested at room temperature are curvilinear (fig. 1A), and their slopes decrease as the true strain increases up to the beginning of fracture. The resistance to flow of the copper was considerably less than that of the other materials; the resistance of the 70%-Ni–30%-Cu alloy was appreciably greater than that of the nickel or the 30%-Ni–70%-Cu alloy. The flow curves for the nickel and the 30%-Ni–70%-Cu alloy cross at a true strain within the range of 0.4 to 0.6. Thus, the difference in curvature of the flow curves of these two materials indicate that the rate of strain hardening in the higher range of true strains is somewhat greater for the nickel than for

TABLE 4. *Results of tensile tests on* 30%–Ni–70%–Cu *alloy*

Initial condition	Temperature [a]	Yield strength (0.2% offset)	Drop of beam			Maximum load					True stress at complete fracture	Elongation in 2 in.	Reduction of area	True strain at complete fracture
			Stress at first drop of beam	Maximum drop		Tensile strength	True stress	Strain in 2 in.	Reduction in area [b]	True strain				
				Stress at occurrence	Amount of drop									
	°*F.*	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	%	%		*lb/in.*^{2}	%	%	
Annealed	−320	30,900	---	---	---	83,700	127,800	52.5	34.5	0.423	229,700	61.5	77.5	1.504
Do	−220	27,400	---	---	---	71,900	105,800	47	32	.386	195,300	57.5	77.5	1.491
Do	−108	24,000	---	---	---	64,300	91,100	41.5	29.5	.348	170,700	56	77.5	1.506
Do	−22	22,000	---	---	---	58,600	81,600	39.5	28	.331	163,700	49.5	79	1.567
Do	75	21,500	---	---	---	54,400	74,100	37	27	.309	157,500	52	80.5	1.622
Do	75	21,500	---	---	---	54,400	73,200	36	26.5	.296	157,900	54	80.5	1.625
Do	300	18,800	---	---	---	47,900	63,900	33.5	25	.288	152,500	47	81.5	1.694
Do	500	16,600	---	---	---	44,100	58,400	32.5	24.5	.281	125,900	43	77.5	1.498
Do	600	16,000	38,400	39,700	200	43,300	57,400	32.5	24.5	.281	115,100	43	74.5	1.362
Do	700	16,500	17,300	32,600	750	43,100	56,000	30	23	.262	101,700	43.5	68.5	1.155
Do	700	16,000	17,800	39,900	850	42,700	55,500	30	23	.262	106,600	44	70.5	1.218
Do	800	15,500	16,900	17,500	375	40,400	52,500	30	23	.262	70,700	37	52	0.729
Do	900	13,800	30,600	30,600	25	34,800	44,500	28	22	.247	56,900	38.5	53	.751
Do	1,000	12,500	---	---	---	28,000	34,900	24.5	19.5	.219	43,400	42	56.5	.833
Do	1,100	11,500	---	---	---	22,300	26,400	18.5	15.5	.169	36,600	37	53	.759
Do	1,200	9,200	---	---	---	16,700	19,000	14	12.5	.131	22,900	27.5	42	.547
Do	1,200	8,800	---	---	---	16,900	19,600	16	14	.148	22,200	28	41	.528
Do	1,350	5,500	---	---	---	10,800	11,700	8.0	7.5	.077	12,200	17.5	24	.277
Do	1,500	4,350	---	---	---	7,130	7,300	2.0	2	.02	7,600	17	21	.236
Do	1,700	1,550	1,550	1,550	125	4,240	4,300	1.0	1	.011	4,100	23	26.5	.307
Do	1,700	1,500	1,700	1,700	65	3,830	3,900	1.5	1.5	.015	3,500	21	24.5	.285
Cold-drawn, 25% reduction in area	75	72,400	---	---	---	74,500	75,300	1.0	1	.011	161,300	19	74	1.343
Do	300	65,000	---	---	---	68,600	69,600	1.5	1.5	.015	148,700	17	74	1.350
Do	700	55,500	57,500	56,000	250	57,600	58,200	1.0	1	.011	104,300	13	56.5	.829
Do	900	38,500	43,600	43,600	5	43,600	44,300	1.5	1.5	.015	54,900	11.5	32.5	.395
Do	1,200	9,700	---	---	---	16,900	19,300	14	12.5	.131	22,100	26	41.5	.534
Do	1,500	4,100	---	---	---	7,200	7,400	2.0	2	.020	7,200	16	22	.246
Do	1,700	1,650	1,700	1,700	100	4,110	4,200	1.5	1.5	.015	4,000	22	25.5	.293
Cold-drawn, 40% reduction in area	75	81,400	---	---	---	82,600	83,400	1.0	1	.011	165,600	17	72	1.265
Do	300	73,300	---	---	---	75,300	76,100	1.0	1	.011	154,000	15	72.5	1.286
Do	700	61,700	60,900	60,900	50	63,600	64,200	1.0	1	.011	100,800	11.5	50	0.693
Do	900	43,900	---	---	---	48,400	49,100	1.5	1.5	.015	60,100	11	32	.383
Do	1,200	9,900	---	---	---	17,300	19,100	10.5	9.5	.099	23,100	25	44	.576
Do	1,500	4,000	---	---	---	6,950	7,100	1.5	1.5	.015	7,200	18	22	.248
Do	1,700	1,700	1,850	1,850	50	3,800	3,900	1.5	1.5	.015	4,100	22.5	27	.316
Cold-drawn, 70% reduction in area	75	92,500	---	---	---	95,200	96,300	1.0	1	.011	180,100	16	71	1.242
Do	300	80,800	---	---	---	87,500	88,800	1.5	1.5	.015	194,700	16	76	1.430
Do	700	71,100	69,600	69,600	5	73,600	74,300	1.0	1	.011	135,800	11	61	0.940
Do	900	52,600	---	---	---	56,900	57,500	1.0	1	.011	72,400	14	47.5	.636
Do	1,200	9,800	---	---	---	16,900	19,800	17	14.5	.157	21,400	29	45	.594
Do	1,500	3,700	---	---	---	6,990	7,200	2.5	2.5	.025	7,900	19	22	.246
Do	1,700	1,600	1,700	1,700	50	3,680	3,700	0.5	0.5	.005	3,500	22.5	28	.329

[a] Values at subzero temperatures obtained from data of Geil and Carwile [7].

[b] Reduction in area (%)=$100[A_0-A)/A_0]=100(L-L_0)/L_0$].

TABLE 5. *Results of tensile tests on OFHC copper*

Initial condition	Temperature [a]	Yield strength (0.2% offset)	Maximum load						True stress at complete fracture	Elongation in 2 in.	Reduction of area	True strain at complete fracture
			Tensile strength	True stress	Strain in 2 in.	Reduction in area [b]	True strain					
	°*F*	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	%	%			*lb/in.*^{2}	%	%	
Annealed; 0.025-mm av grain diameter	−320	8, 100	51, 600	81, 400	58	36. 5	0. 46		176, 500	72	80. 5	1. 738
Do	−220	8, 100	43, 400	65, 700	50	34	. 41		170, 200	67	84	1. 844
Do	−108	8, 000	38, 700	56, 800	47	32	. 38		165, 000	61. 5	86. 5	1. 995
Do	−22	7, 600	35, 100	49, 400	40. 5	29	. 34		142, 300	61. 5	86	1. 973
Do	75	12, 200	31, 900	44, 000	39	28	. 33		139, 000	51	88	2. 114
Do	110	7, 300	30, 750	44, 000	43	30	. 36		144, 700	62. 5	89	2. 221
Do	250	6, 700	27, 000	38, 900	44	30. 5	. 37		128, 600	65	89	2. 224
Do	300	7, 000	25, 850	36, 800	42. 5	30	. 35		110, 900	62. 5	87	2. 067
Do	400	6, 000	22, 950	31, 700	38	27. 5	. 32		55, 900	54	70	1. 189
Do	500	4, 700	20, 750	28, 300	36. 5	27	. 31		42, 000	50	60	0. 917
Do	600	3, 800	17, 350	22, 500	29. 5	23	. 26		26, 300	40	43	. 557
Do	700	4, 200	15, 050	19, 000	26	20. 5	. 23		20, 300	34	37	. 458
Do	700	4, 000	14, 400	18, 200	26	20. 5	. 23		19, 050	33	32	. 38
Do	800	3, 750	11, 850	14, 500	22	18	. 20		15, 000	29	30	. 357
Do	900	3, 000	9, 800	11, 500	17	14. 5	. 16		11, 900	31	43	. 561
Do	1, 000	700	7, 050	7, 950	13	11. 5	. 12		9, 150	36	51	. 709
Do	1, 100	850	5, 250	5, 800	11	10	. 10		5, 700	39	49. 5	. 682
Do	1, 200	600	3, 850	4, 150	7. 5	7	. 07		4, 150	18	27	. 315
Do	1, 200	750	4, 000	4, 300	8	7. 5	. 075		--------	------	------	--------
Do	1, 500	500	2, 025	2, 200	9	8. 2	. 085		1, 900	24	19. 5	. 215
Annealed, 0.120-mm av grain diameter	75	6, 000	32, 300	43, 900	36	27	. 31		142, 600	62	85	1. 96
Do	300	3, 750	26, 350	38, 000	44	30. 5	. 37		82, 700	62. 5	79. 5	1. 581
Do	700	2, 500	14, 300	17, 300	21	17. 5	. 16		16, 800	25	22	0. 247
Do	900	1, 100	8, 400	9, 600	14	12. 5	. 13		8, 400	17. 5	16	. 175
Do	1, 200	800	3, 630	4, 000	10. 5	9. 5	. 10		3, 200	20	20. 5	. 228
Do	1, 500	600	1, 770	1, 900	7	6. 5	. 07		1, 450	10	12	. 128
Cold-drawn 40% reduction in area; 0.025-mm av grain diameter before cold-drawing	75	50, 300	51, 100	51, 500	1. 0	1. 0	. 01		137, 500	11	80	1. 608
Do	110	48, 000	50, 400	50, 700	0. 5	0. 5	. 005		144, 000	16	82	1. 622
Do	250	44, 800	46, 500	46, 700	. 5	. 5	. 005		115, 800	15. 5	79	1. 557
Do	300	42, 400	44, 450	44, 700	. 5	. 5	. 005		90, 500	14	71	1. 230
Do	500	28, 900	34, 000	34, 300	1. 0	1. 0	. 01		36, 800	8	28	0. 331
Do	600	6, 500	19, 100	23, 400	22. 5	18. 5	. 20		33, 100	35	52	. 728
Do	700	3, 000	15, 400	20, 000	30	23	. 26		24, 700	39. 5	45	. 604
Do	800	3, 000	12, 500	15, 800	26. 5	21	. 24		17, 800	36	46. 5	. 627
Do	900	1, 000	9, 700	11, 800	22	18	. 20		13, 800	39. 5	60	. 875
Do	1, 200	750	4, 075	4, 450	9. 5	8. 5	. 09		4, 800	30. 5	42. 5	. 551
Do	1, 500	400	2, 040	2, 200	9	8	. 085		1, 950	14. 5	19	. 205

[a] Values at subzero temperatures obtained from data of Geil and Carwile [7].

[b] Reduction in area (%)$=100[A_0-A)/A_0]=100[(L-L_0)/L_0]$.

the alloy. This relation is also shown by a comparison of the relative positions of the flow curves of the initially cold-drawn materials (fig. 1B); the curve for the nickel lies above that for the alloy.

The true-stress–true-strain curves obtained on the specimens prepared from the cold-drawn materials (fig. 1, B) were more nearly linear for the copper, nickel, and 70%-Ni–30%-Cu alloy than for the 30%-Ni–70%-Cu alloy. However, the slope of the three former curves depended somewhat on the chemical composition of the materials; the slopes of the curves for the nickel and the 70%-Ni–30%-Cu alloy were nearly alike, and these slopes were somewhat greater than that of the curve for the cold-drawn copper. As is illustrated by the relative positions of the flow curves, the resistance of the initially cold-drawn materials to further plastic flow in tension also varied with their copper and nickel content.

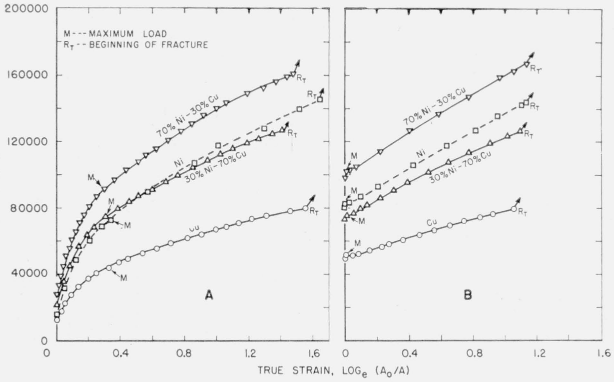

FIGURE 1. *Relation of true stress to true strain of the metals and alloys tested in tension at room temperature.*

A, Initially as annealed; B, initially as cold-drawn 40-percent reduction in area.

The effect of varying amounts of cold-drawing on the flow characteristics at room temperature of the 30%-Ni–70%-Cu alloy is shown by a comparison of the true-stress–true-strain curves of figure 2A. The resistance to flow in tension increased continuously with the amount of cold-drawing; this increase in resistance was accompanied by a decrease in amount of plasticity. The flow curves for all the cold-drawn specimens were curvilinear, with discontinuities exhibited in the region of maximum load. The relation between true stress and total true strain (due to cold-drawing and tension) is

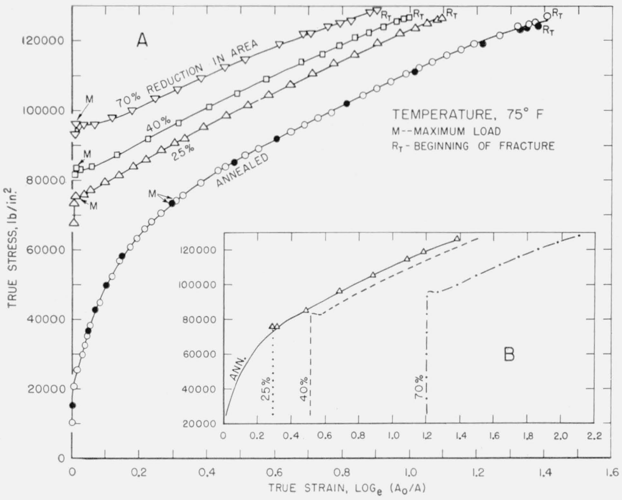

FIGURE 2. *Relation of true stress to true strain of the* 30%–Ni–70%–Cu *alloy tested in tension at room temperature.*

The alloy was initially annealed or cold-drawn different amounts as shown.

shown in figure 2B (insert). The curves for specimens as annealed or cold-drawn 25 percent coincide within the true-strain range of about 0.3 to 1.3. However, further cold-drawing either 40- or 70-percent reduction in area caused a lowering of these curves in the regions of true strains extending from the beginning of plastic deformation to fracture in tension. Thus, the positions of the true-stress–true-strain curves were affected by variations in the amount of cold-drawing and straining in tension.

3.2. Stress-Strain Relations at Elevated Temperatures

Selected autographic stress-strain curves that were obtained on some specimens of the annealed and cold-drawn 30%-Ni–70%-Cu alloy are reproduced in figure 3 as illustrative of the different types of flow observed in the tension tests at elevated temperatures. Discontinuous flow occurred in the initially annealed specimens of this alloy when extended in tension at 600°, 700°, or 800° F, as evidenced by serrations in the curve for the specimen

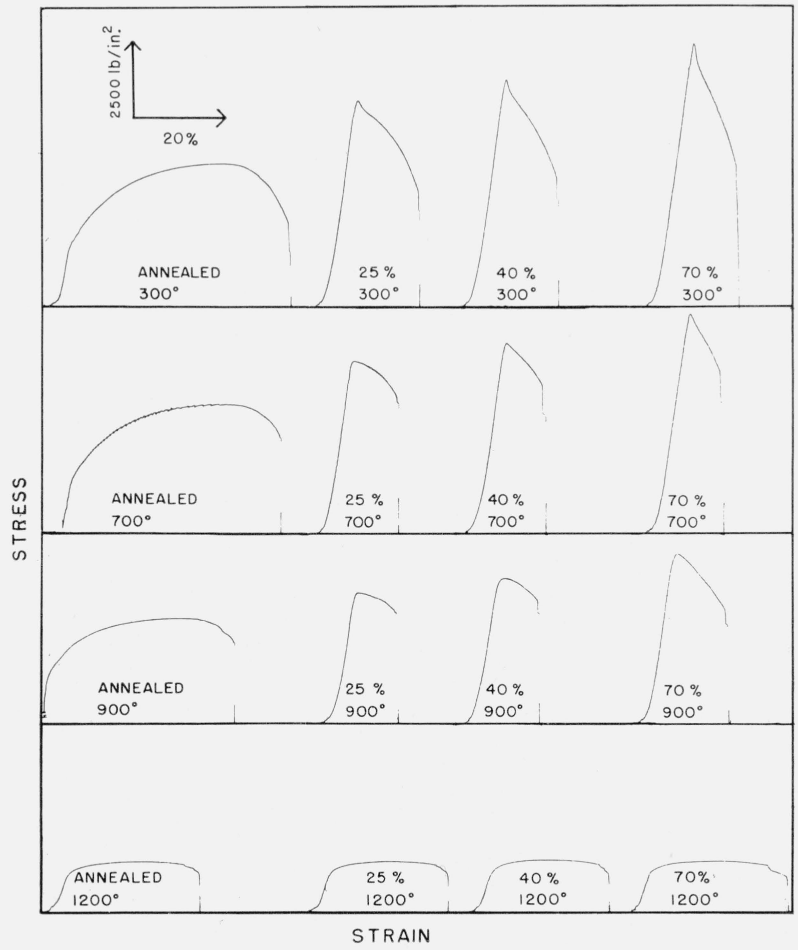

FIGURE 3. *Autographic stress-strain records of* 30%–Ni–70%–Cu *specimens tested in tension at different temperatures.*

The alloy was initially annealed or cold-drawn different amounts as shown.

at 700° F; the stress-strain curves are not shown for the specimens tested at 600° and 800° F. These serrations were more permanent in the curve for the specimen tested at 700° F than at either 600° or 800° F. However, cold-drawing this alloy 25 percent or more before testing in this temperature range reduced or entirely eliminated these serrations in the stress-strain curves. Similar serrations were observed in the curves for initially annealed specimens of the 70%-Ni–30%-Cu alloy extended in tension at temperatures ranging from 300° to 900° F, but they were not observed in the stress-strain curves for annealed specimens of the nickel or copper tested at temperatures below the start of recrystallization of these metals. The serrations that occurred in the stress-strain curves of specimens tested below the recrystallization temperature are believed to be associated with strain-aging and other atomic rearrangements. Cottrell [8] indicated the possible existence of such curves and presented experimentally an example of such a phenomenon in aluminum. Additional experimental evidence on the influence of rate of loading on the creep and aging characteristics of high-purity nickel and the effect of temperature on the aging characteristics of commercial and high-purity 70%-Ni–30%-Cu alloy has been presented by the present authors [5,6]. The breaks observed in some of the present stress-strain curves obtained on specimens at relatively high temperatures (1,200° to 1,700 ° F) are interpreted as being associated with recrystallization and grain growth in the specimens.

At temperatures below 1,200° F, the slope, height, width, and peaks in the vicinity of the maximum load of the stress-strain curves depended upon the nickel or copper content, test temperature, and initial structural condition (annealed or cold-drawn) of the material.

4. Influence of Solute Atoms and Temperature on the Tensile Properties of Nickel and Copper

A systematic analysis of the principles of solution hardening was presented recently by Parker and Hazlett [9]. They considered the mechanism of solution hardening in relation to the theories proposed by Cottrell [10], Suzuki [11], and Fisher [12]. Their interpretations were applied primarily to alloys of relatively low concentration of solute and analyzed for strength properties at small strain; the effect of solute content on ductility of the alloys was not considered in detail.

Geil and Carwile [7] pointed out that at relatively low temperatures, the difference in atomic diameters between copper and nickel is sufficient to produce strain and accompanying local residual stresses in the solvent lattice, and thereby exert a pronounced effect on the initial strength, solution hardening, and rate of work hardening of the alloys; these characteristics are also affected by temperature. As the temperature is raised, the thermal motion of the atoms is increased, and this tends to reduce the effects of the strain and local stress in the solvent lattice induced by the solute atom.

4.1. Strength

The influence of nickel content and test temperature on the yield and tensile strengths of specimens of the copper-nickel system is shown by a comparison of the results summarized in figures 4 and 5 (materials initially as annealed and as cold-drawn 40 percent, respectively). The resistance to deformation by slip or movement of dislocations in the component metals is materially increased in each by the presence of the solute atoms. This is evident even for small

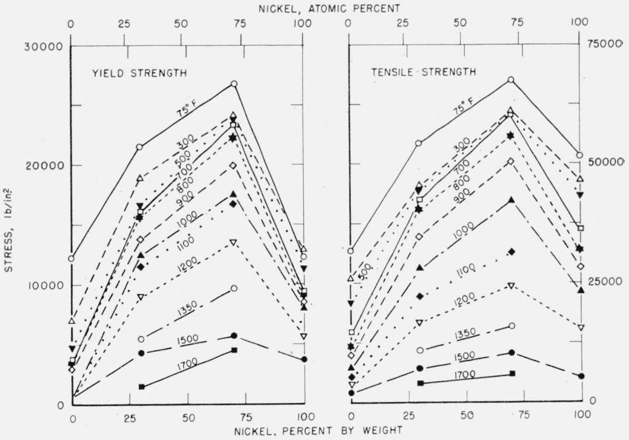

FIGURE 4. *Effect of nickel content and test temperature on the yield and tensile strengths of initially annealed specimens of the copper-nickel system.*

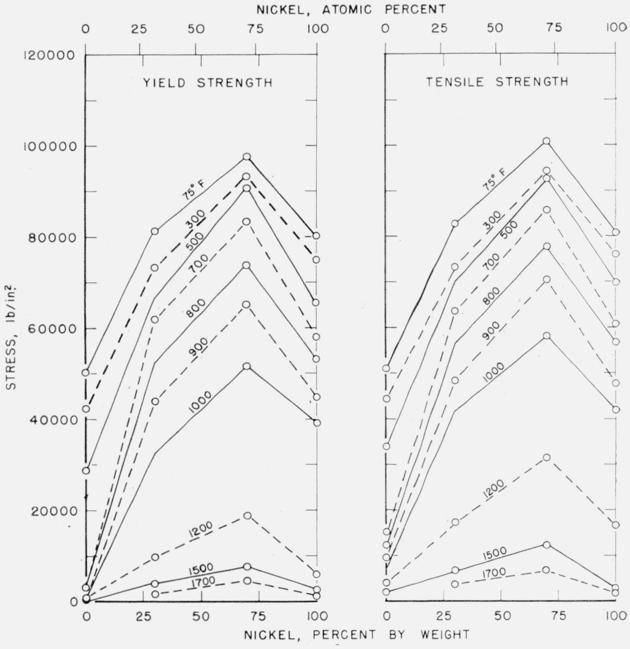

FIGURE 5. *Effect of nickel content and test temperature on the yield and tensile strengths of specimens of the copper-nickel system, initially cold-drawn 40-percent reduction in area.*

strains associated with the yield strength (0.2% offset). The strengthening effect is temperature sensitive and is affected by prior cold-working. As is shown by a comparison of the slopes of the stress-nickel-content curves, the increase in the strength properties was nonlinear as the nickel content was increased from 0 to 70 percent by weight. The latter alloy, however, was materially stronger at any temperature than its counterpart containing 30 percent of nickel.

The strengthening effect (absolute values) from the presence of a given concentration of solute atoms, in both the initially annealed and cold-drawn materials, attained a maximum at the range of about 300° to 700° F (tables 2, 3, and 4), and it is obvious that cold-drawing enhanced the strength properties. This is also the temperature range where strain-aging exerts a pronounced effect on the strength and ductility of the metals and alloys, and irregularities were observed in the stress-strain curves (fig. 3) of initially annealed specimens of the alloys.

According to Cottrell [13], aging in substitutional alloys is accelerated during plastic flow. Moreover, vacancies are created during the plastic flow, and these increase the rate of substitutional diffusion. The migrating atoms are believed, by Cottrell, to segregate to dislocations and prevent the latter from undergoing the movement that causes recovery. Hence, it would be expected that cold-drawing the present materials prior to extending in tension in the strain-aging temperature range would result in an increase in the number of vacancies, and would thus entrap the dislocations and thereby cause an increase in strength properties.

The strengthening effect of the solute atoms is also evident at the higher temperatures. At about 1,200° F, recrystallization of the initially cold-drawn materials occurred and the effects of the cold-working were diminished or removed. It is to be expected that the diffusion rate of the atoms was also increased significantly at these temperatures. The internal strains from misfit of the solute atoms in the solvent lattices and absolute values for the strength properties of the alloys were not high. However, as shown by the slope of the stress-versus-nickel-content curves, the percentage increase in the strength characteristics from the presence of the solute atoms is still appreciable.

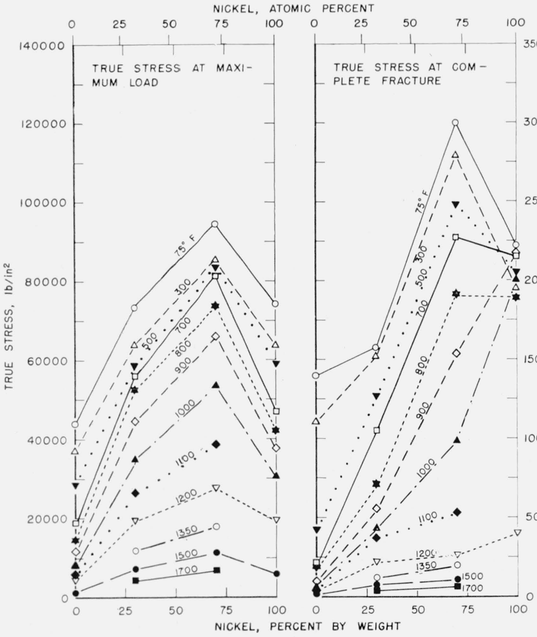

FIGURE 6. *Effect of nickel content and test temperature on various strength indices of initially annealed specimens of the copper-nickel system.*

The relations between nickel content of the materials and the true stress, both at maximum load and at fracture, are shown in figures 6 and 7, respectively. In general, these data conform to the described patterns of figures 4 and 5 except for the inconsistent behavior of the nickel at complete fracture. The relatively narrow spread in values of the true stress at fracture for the initially annealed nickel (fig. 6) or cold-drawn nickel (fig. 7), with temperatures ranging from 75° or 700° to 1,000° F, may be partly attributed to the necking characteristics and ductility of the nickel specimens.

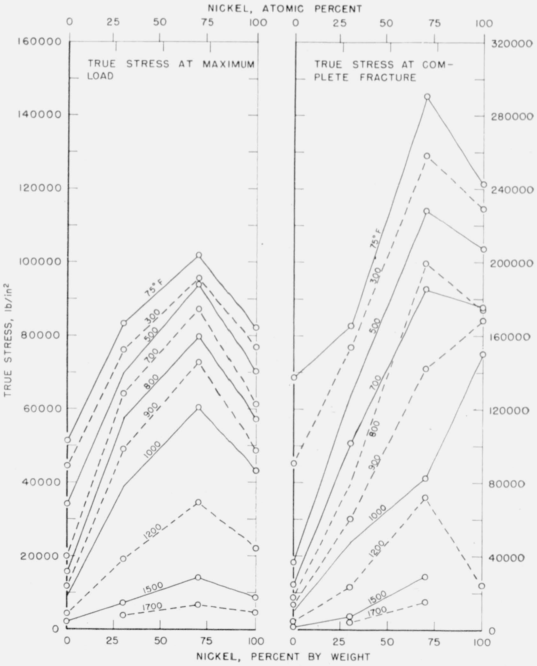

FIGURE 7. *Effect of nickel content and test temperature on various strength indices of specimens of the copper-nickel system, initially cold-drawn 40-percent reduction in area.*

4.2. Ductility

The influence of nickel content on the ductility at different temperatures of the materials as annealed or as cold-drawn 40 percent is shown in figures 8 and 9, respectively.

The ductility of the component metals is affected significantly by variations in the percentage of the solute atoms and temperature and by prior cold-working. The presence of 30 percent of nickel in

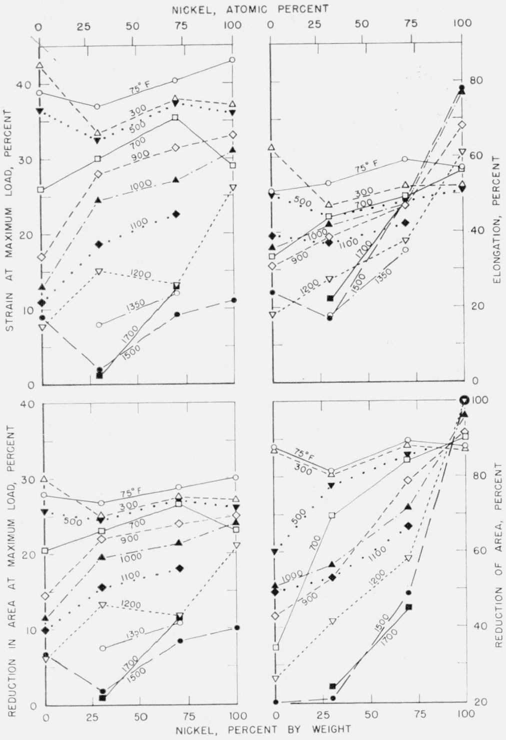

FIGURE 8. *Effect of nickel content and test temperature on the ductility of initially annealed specimens of the copper-nickel system.*

the copper of the initially annealed materials decreased the strain at maximum load in the range 75° to 500° F, and also at 1,500° F (fig. 8). At temperatures of 700° to 1,200° F, the presence of the solute atoms resulted in an appreciable increase in the strain. Similarly, the presence of 30 percent of copper in the nickel decreased the strain at maximum load at temperatures of 75°, 900°, 1,000°, 1,200°, and 1,500° F, was without significant effect at 300° or 500° F, and increased the strain markedly at 700° F. In general, the strain at maximum load of the 70%-Ni-30%-Cu alloy at any temperature was greater than that of the 30%-Ni–70%-Cu alloy; the latter alloy had the higher value for strain at 1,200° F.

Reversals are evident in some of the curves showing the relationship between the nickel content and elongation or reduction of area. However, the slopes of these lines were altered by the nonuniform deformation (necking) that occurred after the attainment of maximum-load conditions. This was especially prominent in the pure nickel specimens, as is revealed by the relatively narrow spread and high values for reduction of area.

This pattern of behavior for the annealed material was markedly changed by cold-drawing (fig. 9). The introduction of solute atoms either in the copper or in the nickel lattice did not materially affect the strain at maximum load at temperatures below that of recrystallization of the component metals and the alloys. All the initially cold-worked materials had low values for strain at maximum load at all temperatures below this range. However, at temperatures above 500° F a peak value of strain existed in each material, and its magnitude was decreased by the presence of the solute atoms. This value in each material was attained at a temperature near or above that of recrystallization and is believed to be associated with the release of the maximum amount of internal energy. The relationship between the nickel content of the materials and elongation or reduction of area also varied appreciably with test temperatures. High values for reduction of area were obtained in all the materials at 75° or 300° F; the recrystallization temperature in each material was above 75° F.

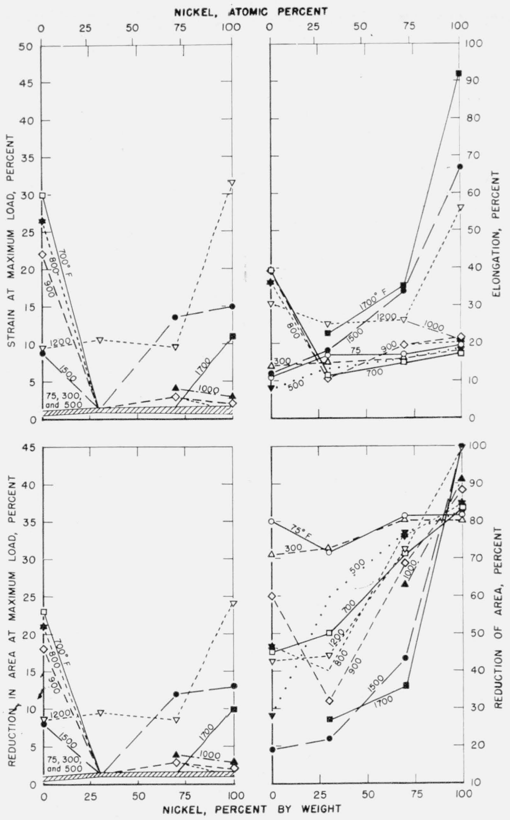

FIGURE 9. *Effect of nickel content and test temperature on the ductility of specimens of the copper-nickel system, initially cold-drawn 40-percent reduction in area.*

The spread in values for elongation attained a maximum in the pure nickel and was decreased by the solute atoms of copper. However, the spread in values for reduction of area was a maximum for the pure copper; this spread was decreased slightly by solute atoms of nickel.

5. Effects of Cold-Drawing and Temperature on the Tensile Properties of the 30%-Ni–70%-Cu Alloy

5.1. Strength

The influence of cold-drawing different amounts on the strength indices of the 30%-Ni–70%-Cu alloy at various temperatures is shown by a comparison of the results summarized in figures 10 and 11. At each temperature within the range 75° to 900° F (fig. 10), the yield and tensile strengths increased nonlinearly as the amount of cold-drawing was increased. Within the range 1,200° to 1,700° F, the cold-worked alloy recrystallized in the short-time tensile tests and no significant effect of the initial cold-drawing operations was observed on the yield and tensile strengths. The values for true stress at fracture (fig. 11) were not materially altered by cold-drawing 25- or 40-percent reduction in area, but the values at 900° F or below were increased by cold-drawing 70-percent reduction in area; there was a slight increase in the fracture values at room temperature with an increase in the amount of cold-drawing, and the effect of cold-drawing 70 percent was removed at test temperatures of 1,200° to 1,700° F.

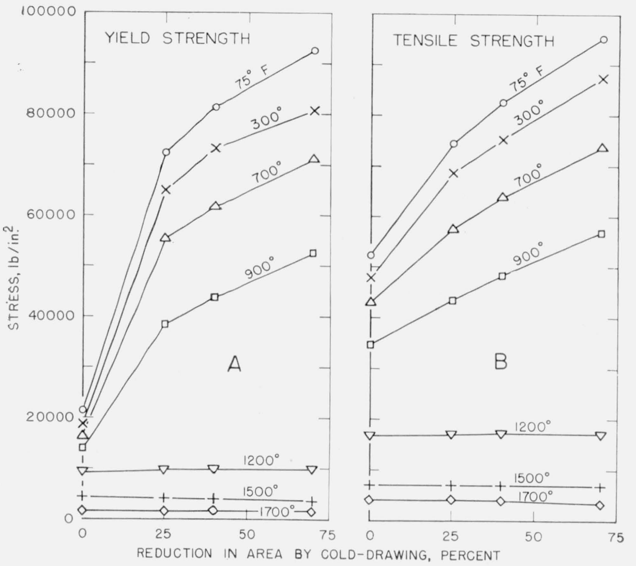

FIGURE 10. *Effect of cold-drawing and test temperature on the yield and tensile strengths of the* 30%–Ni–70%–Cu *alloy.*

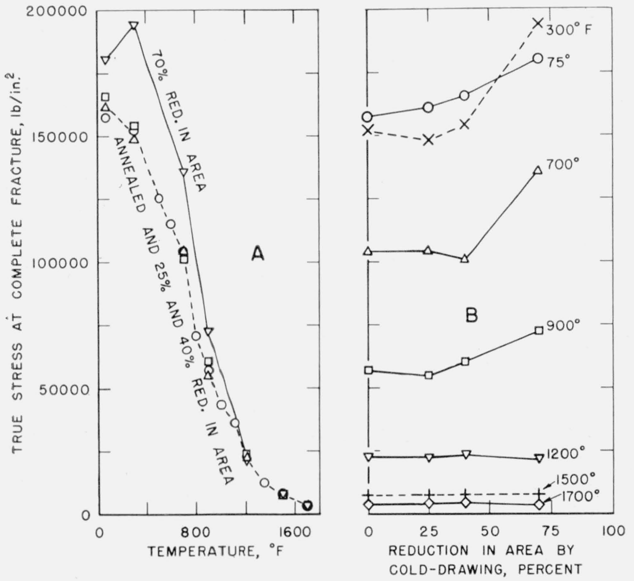

FIGURE 11. *Effect of cold-drawing and test temperature on the true stress at fracture of the* 30%–Ni–70%–Cu *alloy.*

5.2. Ductility

The values for reduction in area at maximum load, strain at maximum load and elongation of the 30%-Ni–70%-Cu alloy were decreased markedly at temperatures ranging from 75° to 900° F by cold-drawing 25-percent reduction in area, but these latter values were not changed appreciably by further cold-drawing (fig. 12, A, C, and D). The effects of cold-working on ductility of the alloy were practically eliminated at 1,200°, 1,500° or 1,700° F; the values obtained at maximum load at 1,200° F, although nearly equivalent in specimens of the initially annealed and cold-drawn alloy, were considerably higher than those obtained at 1,500° or 1,700° F.

The reduction of area was decreased slightly at 75° and 300° F by cold-drawing (fig. 12, B). The reduction of area was also decreased at 700° and 900° F by cold-drawing 25 percent or 40 percent, but with further cold-drawing the change was not so marked.

Thus, cold-drawing increased the strength of this alloy at temperatures below that of recrystallization, but this increase was accompanied by a decrease in ductility. At temperatures above that of recrystallization, the effect of cold-drawing on the strength and ductility was eliminated.

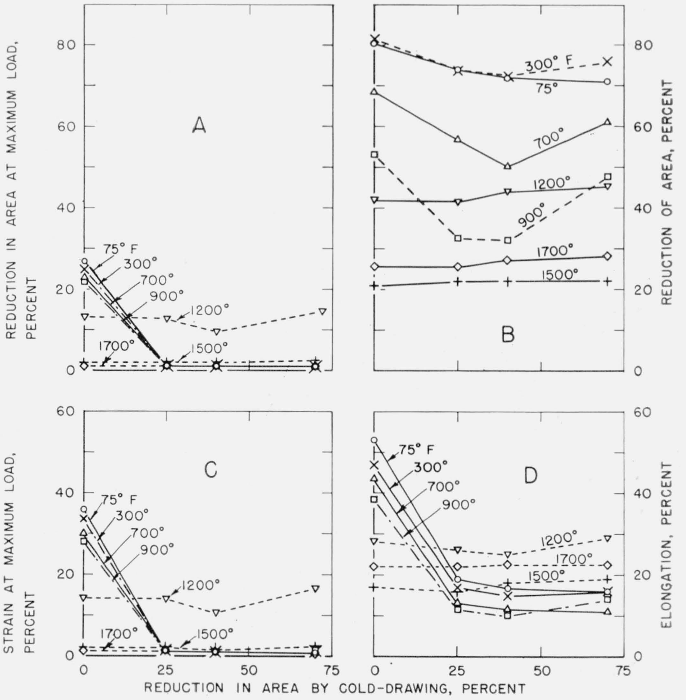

FIGURE 12. *Effect of cold-drawing and test temperature on the ductility of the* 30%–Ni–70%–Cu *alloy.*

6. Effects of Grain Size and Temperature on the Tensile Properties of Copper

The influence of grain size on the tensile properties at temperatures ranging from 75° to 1,500° F of the initially annealed high-purity copper is shown in figures 13 and 14. A change in the average grain diameter by a factor of about 5 (0.025 to 0.120 mm) had no significant effect on the tensile strength and true stress at complete fracture (fig. 13), but this increase in grain size resulted in an appreciable decrease in the yield strength at temperatures below 900° F; the grain-size effect was nil at temperatures above 1,000° F. In general, the ductility as measured by elongation and reduction of area was decreased by increasing the grain size (fig. 14). Both the fine- and the coarse-grained copper showed reversals in the curves representing the relations between reduction of area or elongation and temperature. The general trend for these values to decrease with an increase in temperature was interrupted in the ranges of about 70° to 300° F and 800° to 1,000° F; the increase in ductility with increase in temperature is especially prominent in the latter temperature range.

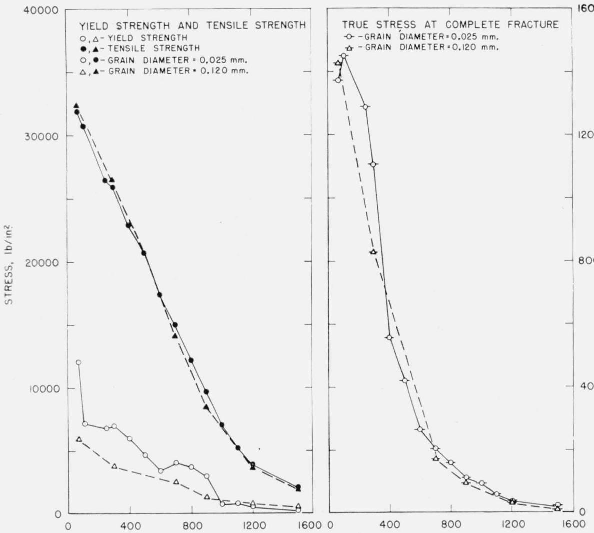

Figure 13. *Effect of grain size and test temperature on the strength of copper.*

A summation of these results shows that the strength and ductility of the annealed copper in tension is more dependent upon temperature than on the initial grain size.

7. Summary

The results of tests made in tension on metals of the nickel-copper system showed that the tensile properties were strongly dependent upon the percentage of solute atoms in the component lattices, temperature of test, and amount of cold-working. Although the strengthening effect due to the presence of the solute atoms attained a maximum in the temperature range where strain-aging occurred (300° to 700° F), the effect was also evident at all temperatures investigated.

The increase in yield and tensile strengths per percent of nickel was greater in the range 0- to 30-percent nickel than in the range 30 to 70 percent. The 70-percent-nickel alloy was appreciably stronger, at the same temperature, than the 30-percent-nickel alloy.

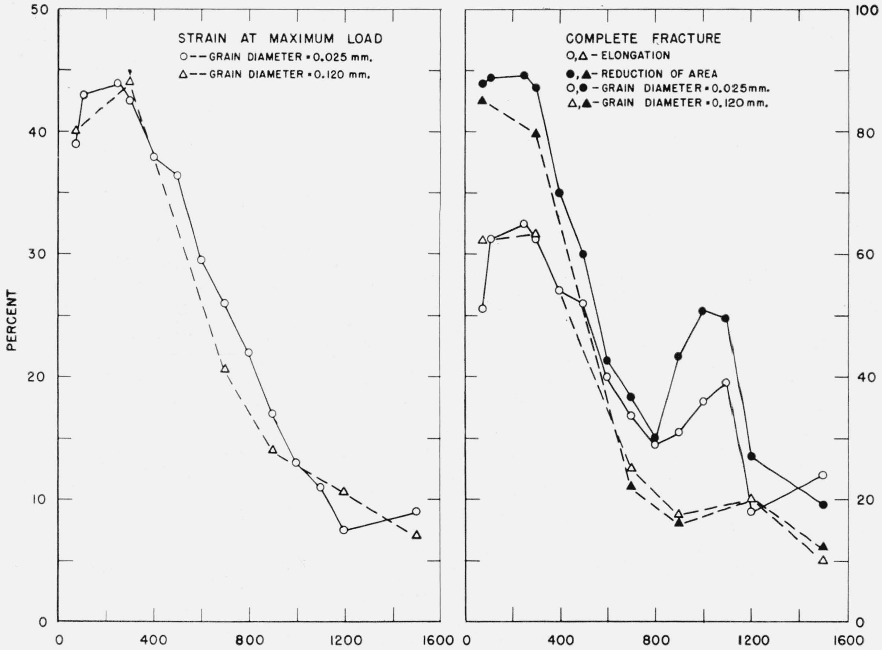

Figure 14. *Effect of grain size and test temperature on the ductility of copper.*

The effects of the solute atoms on ductility varied appreciably with the temperature, the amount of cold-drawing, and the index used to measure the ductility. However, at a given concentration of solute atoms, the effects of cold-drawing on both the strength and ductility were diminished or removed at temperatures above that of recrystallization.

Increasing the grain size of the high-purity copper decreased the yield strength at temperatures below that of recrystallization, and decreased the elongation and the reduction of area at certain temperatures above that of recrystallization.

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WASHINGTON, December 5, 1956