ORNL-TM--7174

DE91 015604

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION

ELEVATED-TEMPERATURE TENSILE PROPERTIES OF THREE HEATS OF COMMERCIALLY HEAT-TREATED ALLOY 718

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Date Published - March 1980

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Oak Ridge, Tennessee 37830
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UNION CARBIDE CORPORATION
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DEPARTMENT OF ENERGY

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ABSTRACT

Three heats of commercially heat-treated alloy 718 were tensile tested over the temperature range from room temperature to 816°C and at nominal strain rates from 6.7×10^{-6} to 6.7×10^{-3}/s. We examined data for yield strength, ultimate tensile strength, uniform elongation, total elongation, and reduction in area and also inspected tensile stress-strain behavior.

Yield and ultimate tensile strengths for commercially heat-treated alloy 718 decrease very gradually with temperature from room temperature up to about 600°C for a strain rate of 6.7×10^{-5}/s or to about 700°C for a strain rate of 6.7×10^{-4}/s. Above these temperatures the strength drops off fairly rapidly.

Reduction in area and total elongation data show minima around 700°C, with each ductility measure falling to 10% or less at the minima. This minimum is more pronounced and occurs at lower temperatures as strain rate decreases. Up to about 600°C the ductility is typically around 30%. As the temperature reaches 816°C the ductility again increases to perhaps 60%.

The uniform elongation (plastic strain at peak load) decreases only slightly with temperature to about 500°C then drops off rapidly and monotonically with temperature, reaching values less than 1% at 816°C. At the highest test temperatures the load maximum may result, not from necking of the specimen, but from overaging of the precipitation-hardened microstructure.

Stress-strain curves showed serrated deformations in the temperature range from 316 to 649°C, although they occur only for the faster strain rates at the upper end of this temperature range. The serrations can be quite large, involving load drops of perhaps 40 to 80 MPa. The serrations typically begin within the first 2% of deformation and continue until fracture, although exceptions were noted.

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*Work performed under DOE/RRT AF 15 10 15, Task OR-1.3, Mechanical Properties Design data.

INTRODUCTION

The Ni-Cr-Fe-Nb alloy 718 is a widely used structural material in elevated-temperature applications. This popularity results from its several excellent behavioral features, including high creep and creep-rupture strength, good oxidation resistance, and exceptional high-cycle fatigue strength. Current designs of the reactor upper internals and control rod drive line for the proposed Clinch River Breeder Reactor (CRBR) involve extensive use of alloy 718 in the commercially heat-treated condition. (This treatment consists of a solution anneal at 954°C plus a duplex aging treatment consists of a solution anneal at 954°C plus a duplex aging treatment at 718 and 621°C.) However, with the exception of bolting material, alloy 718 has not been approved by the American Society of Mechanical Engineers (ASME) Code for high-temperature nuclear applications. Several research programs are under way to develop the necessary information to allow use of this material under such conditions. Work at ORNL[1,2] has centered on characterization of the creep behavior of alloy 718. We report the results of our tensile tests for this material.

Table 1 characterizes the three heats of material tested in this program. All heats were solution treated for 1 h at 954°C, then air cooled to below 500°C. Subsequently, they were aged 8 h at 718°C, cooled 56°C/h to 621°C, held 8 h, then air cooled for a total aging time of 18 h. Tests were conducted over the range from room temperature to 816°C at nominal strain rates ranging from 6.7×10^{-6} to 6.7×10^{-3}/s. Strain rate control was obtained by maintaining the rate of movement of the crosshead of the testing machine. Thus, the true strain rate during the tests varied slightly. Table 2 lists the data generated in this program. Properties listed therein and examined in this report include yield strength (0.2% offset), ultimate tensile strength, uniform elongation, total elongation to fracture (in 25.4 mm), and reduction in area.

Table 1. Heats of Material Tested[a]

Heat	Product Form	ASTM Grain Size[b]	Content, wt %														
			C	Mn	Si	P	S	Cr	Co	Mo	Nb + Ta	Ti	Al	Fe	Cu	Ni	B
2180-5-9419	13-mm Plate	8	0.05	0.23	0.10	<0.005	<0.005	18.02	0.27	3.02	5.13	1.06	0.54	Bal	0.05	52.63	0.003
2180-4-9497	19-mm Plate	8	0.05	0.17	0.03	<0.005	<0.005	18.15	0.42	3.10	5.08	0.98	0.57	Bal	0.02	52.37	0.006
2180-5-9422	203-mm Forging	2–8	0.05			0.005	0.002	17.71	0.33	3.07	5.11	1.02	0.52	19.02	0.03	Bal	0.003

[a] All material was "commercially" heat-treated as follows: solution annealed for 1 h at 954°C, then air cooled; aged 8 h at 718°C, furnace cooled at 56°C/h to 621°C, held at 621°C for approximately 8 h until total aging time reached 18 h, and then air cooled.

[b] Mill annealed.

Table 2. ORNL Alloy 718 Tensile Data

HEAT NUMBER	TEST NUMBER	TEMP (C)	STRAIN RATE (%/MIN)	YIELD STRENGTH (MPA)	ULTIMATE STPESS (MPA)	UNIFORM ELONG. (%)	TOTAL ELONG. (%)	REDUCTION IN AREA (%)
2180-4-9497	4010	427.	0.040	992.	1199.	13.97	24.300	37.75
2180-4-9497	4011	538.	0.040	929.	1208.	13.67	19.700	20.36
2180-4-9497	4003	593.	0.040	949.	1089.	5.00	7.000	12.50
2180-4-9497	19058	649.	0.040	823.	927.	2.67	10.060	10.13
2180-4-9497	19068	704.	0.040	752.	802.	0.75	12.170	11.79
2180-4-9497	4006	760.	0.040	522.	522.	0.49	27.900	36.87
2180-4-9497	4007	816.	0.040	305.	303.	0.36	34.400	34.14
2180-4-9497	3885	25.	4.000	1026.	1351.	17.94	26.400	39.31
2180-4-9497	3892	25.	4.000	1077.	1349.	16.79	27.400	42.89
2180-4-9497	4050	25.	4.000	1030.	1374.	16.15	26.600	36.31
2180-4-9497	4008	316.	4.000	938.	1213.	17.36	28.300	41.73
2180-4-9497	19064	538.	4.000	909.	1141.	17.00	27.770	42.74
2180-4-9497	4068	593.	4.000	861.	1119.	14.80	25.000	42.84
2180-4-9497	19063	593.	4.000	864.	1119.	15.34	24.980	41.90
2180-4-9497	4067	649.	4.000	825.	1066.	14.27	23.600	23.91
2180-4-9497	19089	649.	4.000	876.	1107.	13.52	24.970	27.34
2180-4-9497	19090	649.	4.000	860.	1087.	13.25	25.820	25.28
2180-4-9497	19092	649.	4.000	867.	1103.	13.89	24.670	27.20
2180-4-9497	4004	704.	4.000	795.	942.	7.78	16.300	16.42
2180-4-9497	4066	704.	4.000	731.	908.	9.19	17.300	16.41
2180-4-9497	19057	704.	4.000	793.	953.	9.18	16.980	8.07

Table 2. (Continued)

HEAT NUMBER	TEST NUMBER	TEMP (C)	STRAIN RATE (%/MIN)	YIELD STRENGTH (MPA)	ULTIMATE STRESS (MPA)	UNIFORM ELONG. (%)	TOTAL ELONG. (%)	REDUCTION IN AREA (%)
2180-4-9497	19060	704.	4.000	818.	963.	8.29	17.900	16.35
2180-4-9497	19098	704.	4.000	798.	962.	8.31	18.870	17.95
2180-4-9497	4064	760.	4.000	638.	761.	4.20	14.000	16.22
2180-4-9497	19091	760.	4.000	671.	765.	3.72	8.510	14.98
2180-4-9497	19050	816.	4.000	547.	568.	0.45	40.710	65.23
2180-4-9497	19094	816.	4.000	550.	579.	0.66	43.650	65.73
2180-4-9497	19080	649.	40.000	846.	1082.	12.82	23.190	44.54
2180-4-9497	4005	704.	40.000	795.	1000.	12.37	26.000	30.47
2180-4-9497	3891	25.	0.400	1057.	1370.	17.09	26.000	42.16
2180-4-9497	4009	316.	0.400	964.	1210.	18.71	28.100	43.96
2180-4-9497	19056	538.	0.400	949.	1208.	11.83	20.220	34.19
2180-4-9497	19065	593.	0.400	907.	1172.	12.94	21.770	20.44
2180-4-9497	19051	649.	0.400	858.	1027.	7.47	13.500	12.02
2180-4-9497	19052	649.	0.400	859.	1032.	7.36	12.630	13.80
2180-4-9497	3888	704.	0.400	783.	862.	2.22	11.000	7.71
2180-4-9497	19081	704.	0.400	806.	876.	2.51	10.850	10.55
2180-4-9497	4065	721.	0.400	698.	828.	1.63	14.500	16.36
2180-4-9497	19095	816.	0.400	440.	454.	0.42	37.470	45.96
2180-5-9419	19047	649.	0.040	864.	944.	2.22	9.360	15.42
2180-5-9419	19054	704.	0.040	728.	764.	0.64	35.640	46.27
2180-5-9419	4051	25.	4.000	1074.	1437.	18.65	24.640	31.02

Table 2. (Continued)

HEAT NUMBER	TEST NUMBER	TEMP (C)	STRAIN RATE (%/MIN)	YIELD STRENGTH (MPA)	ULTIMATE STRESS (MPA)	UNIFORM ELONG. (%)	TOTAL ELONG. (%)	REDUCTION IN AREA (%)
2180-5-9419	19062	538.	4.000	947.	1179.	17.46	26.710	41.62
2180-5-9419	4052	593.	4.000	937.	1175.	14.72	23.400	45.28
2180-5-9419	4053	649.	4.000	909.	1104.	9.91	25.790	30.48
2180-5-9419	19079	649.	4.000	900.	1123.	13.34	29.040	34.22
2180-5-9419	4054	704.	4.000	799.	941.	6.62	16.900	19.14
2180-5-9419	19059	704.	4.000	844.	986.	5.70	16.050	15.96
2180-5-9419	4057	732.	4.000	736.	848.	3.87	15.700	18.50
2180-5-9419	4049	760.	4.000	632.	689.	2.72	20.400	30.51
2180-5-9419	4013	649.	40.000	933.	1139.	8.49	18.600	35.59
2180-5-9419	19082	704.	40.000	841.	1037.	9.68	25.900	34.42
2180-5-9419	19085	704.	40.000	810.	1020.	11.71	30.260	37.81
2180-5-9419	19067	538.	0.400	948.	1227.	14.90	23.730	39.53
2180-5-9419	19055	649.	0.400	914.	1066.	5.21	11.920	10.82
2180-5-9419	19086	704.	0.400	776.	870.	1.87	10.380	14.87
2180-5-9422	19097	649.	0.040	865.	932.	1.76	6.660	10.23
2180-5-9422	19061	704.	0.040	777.	804.	0.55	9.710	10.53
2180-5-9422	3890	25.	4.000	1085.	1254.	14.24	20.100	22.07
2180-5-9422	4058	25.	4.000	1053.	1266.	15.04	21.870	33.18
2180-5-9422	3886	538.	4.000	757.	1043.	10.73	20.740	23.38
2180-5-9422	19069	538.	4.000	912.	1080.	10.56	17.400	21.65
2180-5-9422	19070	538.	4.000	893.	1053.	13.76	20.380	22.58

Table 2. (Continued)

HEAT NUMBER	TEST NUMBER	TEMP (C)	STRAIN RATE (%/MIN)	YIELD STRENGTH (MPA)	ULTIMATE STRESS (MPA)	UNIFORM ELONG. (%)	TOTAL ELONG. (%)	REDUCTION IN AREA (%)
2180-5-9422	4012	593.	4.000	932.	1067.	9.96	16.600	22.97
2180-5-9422	4059	593.	4.000	882.	1010.	11.04	18.600	29.28
2180-5-9422	3893	649.	4.000	862.	1025.	10.82	17.700	22.35
2180-5-9422	4060	649.	4.000	877.	998.	10.13	19.300	21.97
2180-5-9422	4061	704.	4.000	782.	871.	6.04	13.600	17.14
2180-5-9422	19048	704.	4.000	855.	944.	4.61	14.170	13.89
2180-5-9422	19049	704.	4.000	760.	902.	7.13	12.320	13.08
2180-5-9422	4062	732.	4.000	698.	804.	5.01	11.900	13.58
2180-5-9422	4063	760.	4.000	658.	749.	3.10	12.200	15.49
2180-5-9422	19093	760.	4.000	672.	759.	4.53	9.500	15.50
2180-5-9422	19053	816.	4.000	577.	605.	0.55	36.280	60.97
2180-5-9422	4055	649.	40.000	878.	989.	8.54	17.100	31.91
2180-5-9422	3887	704.	40.000	759.	913.	12.47	19.700	24.57
2180-5-9422	3889	25.	0.400	1077.	1260.	10.40	14.200	16.10
2180-5-9422	19066	593.	0.400	904.	1071.	8.79	14.450	17.83
2180-5-9422	4056	649.	0.400	877.	991.	5.47	10.000	11.44
2180-5-9422	19087	649.	0.400	853.	968.	4.38	9.150	14.77
2180-5-9422	19083	704.	0.400	778.	848.	2.40	8.800	14.22
2180-5-9422	19084	704.	0.400	785.	850.	1.94	7.280	8.95
2180-5-9422	19071	760.	0.400	663.	691.	0.82	10.440	13.50
2180-5-9422	19088	816.	0.400	454.	476.	0.43	37.540	66.57

TEMPERATURE EFFECTS ON PROPERTIES

The variations of the above properties with temperature at strain rates of 6.7 × 10^{-5} and 6.7 × 10^{-4}/s are shown in Figs. 1 and 2. The three heats all exhibit similar behavior, although there are, of course, differences that can be ascertained from an examination of the figures. The trends in behavior are also similar at the two different strain rates, although strain rate does influence the behavior. Effects of strain rate will be examined in more detail in the next section.

The yield strength of these heats of alloy 718 decreases very gradually with temperatures up to about 600°C for a strain rate of 6.7 × 10^{-5}/s or to about 700°C for a strain rate of 6.7 × 10^{-4}/s. Above these temperatures the strength drops off fairly rapidly. These trends are essentially the same as those exhibited by the ultimate tensile strength values.

The reduction in area and total elongation values change little with temperature to about 550°C at 6.7 × 10^{-5}/s and to about 600°C at 6.7 × 10^{-4}/s. The values then rapidly decrease with temperature, exhibiting a ductility minimum slightly below 700°C at the lower strain rate and slightly above 700°C at the higher. The ductility values then again rapidly increase. At 816°C they are as high or higher than the room temperature values. This phenomenon, a common one for nickel-base alloys,[3-4] will be discussed in more detail below.

The uniform elongation does not display a minimum with temperature. Rather, it remains approximately constant from room temperature to about 450°C at 6.7 × 10^{-5}/s or to about 550°C at 6.7 × 10^{-4}/s. The values then rapidly and monotonically decrease with temperature, reaching very low (<1%) values at the highest test temperatures.

STRAIN RATE EFFECTS ON PROPERTIES

Figure 3 illustrates the variation of properties of heat 9497 with temperature for four different strain rates. (Note that variable strain rate data were obtained only in the temperature range from 538 to 816°C.) Trends for the other heats are similar, although this heat is represented

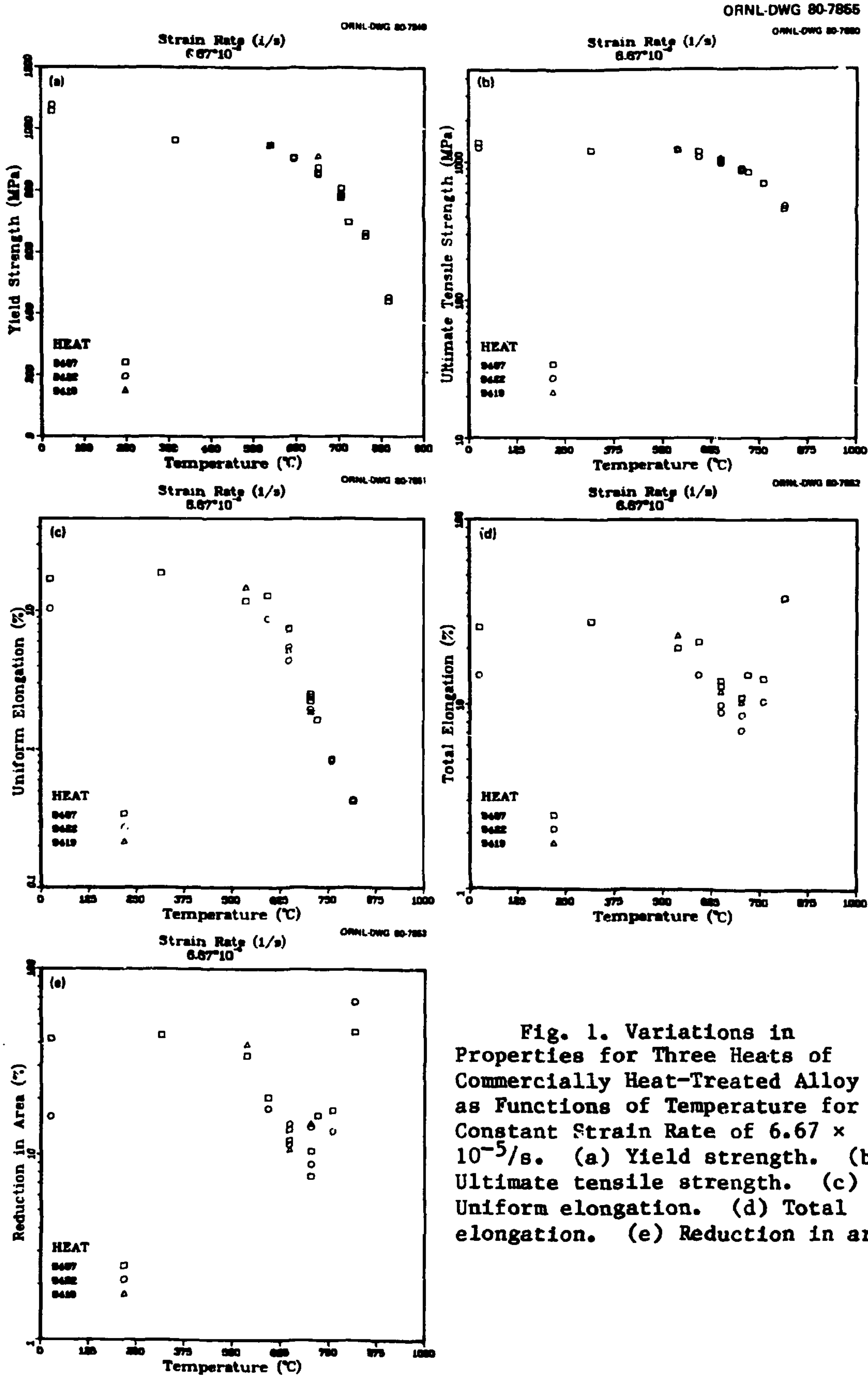

Fig. 1. Variations in Properties for Three Heats of Commercially Heat-Treated Alloy 718 as Functions of Temperature for a Constant Strain Rate of 6.67 × 10^{-5}/s. (a) Yield strength. (b) Ultimate tensile strength. (c) Uniform elongation. (d) Total elongation. (e) Reduction in area.

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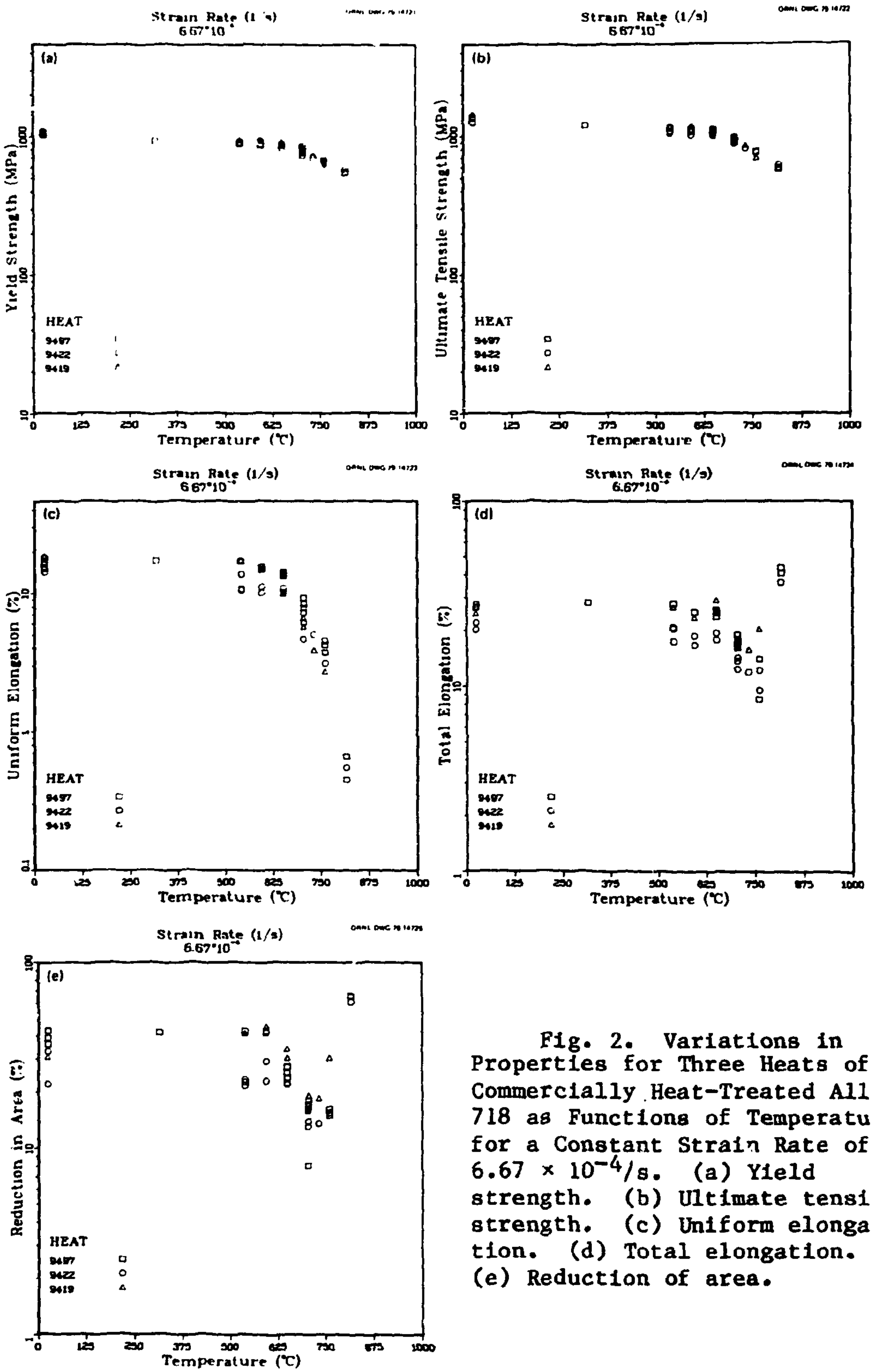

Fig. 2. Variations in Properties for Three Heats of Commercially Heat-Treated Alloy 718 as Functions of Temperature for a Constant Strain Rate of 6.67×10^{-4}/s. (a) Yield strength. (b) Ultimate tensile strength. (c) Uniform elongation. (d) Total elongation. (e) Reduction of area.

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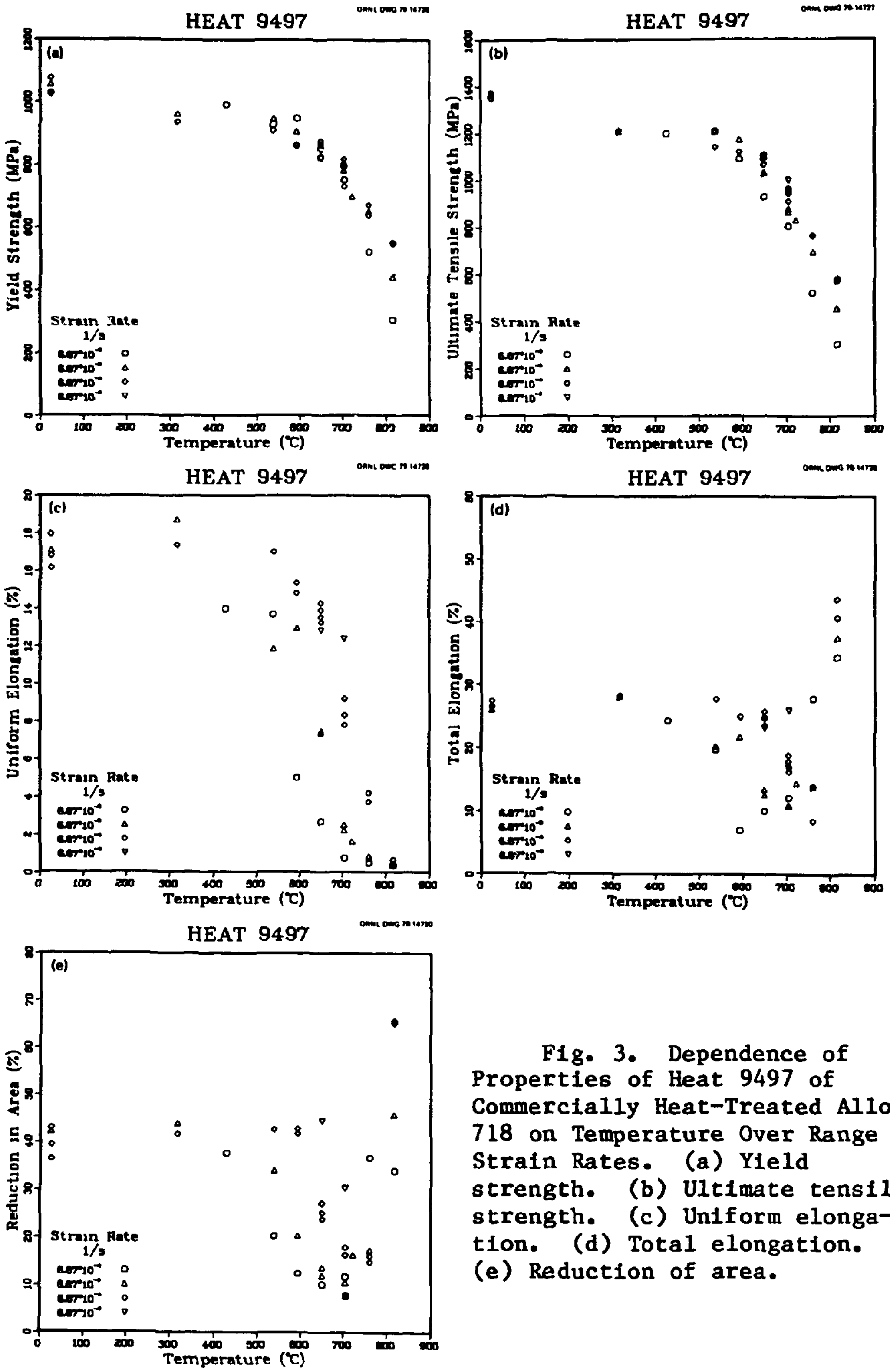


Fig. 3. Dependence of Properties of Heat 9497 of Commercially Heat-Treated Alloy 718 on Temperature Over Range of Strain Rates. (a) Yield strength. (b) Ultimate tensile strength. (c) Uniform elongation. (d) Total elongation. (e) Reduction of area.

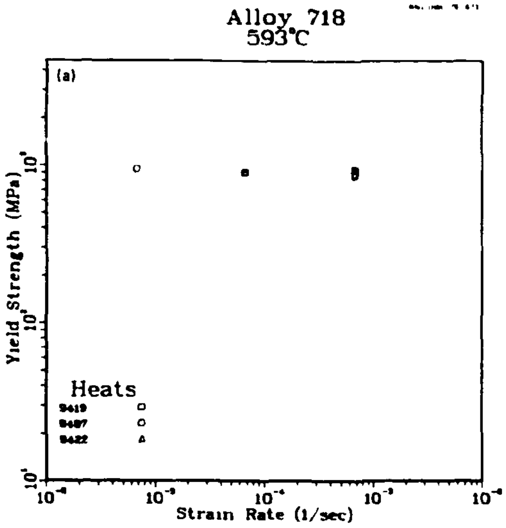
by the most extensive data. Briefly and generally, the values of both strength properties tend to increase with strain rate at the higher test temperatures, while uniform elongation tends to increase with strain rate at virtually all test temperatures. The trends in total elongation and reduction in area are more complicated as a result of the ductility minimum phenomenon. The primary effects here are that lower strain rates yield the minima at lower temperatures and that the depth of the ductility "trough" is increased for lower strain rates.

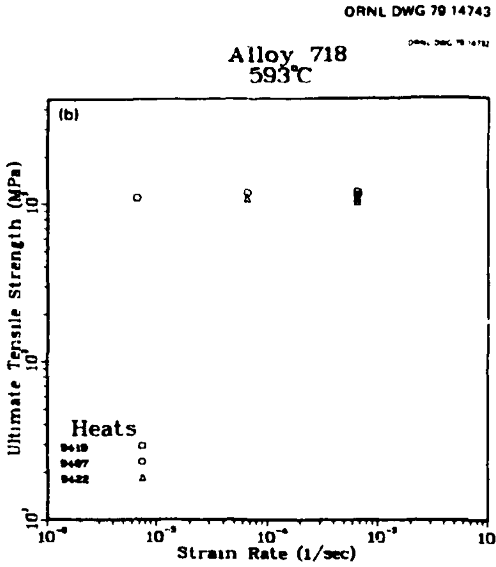
Strain rate effects can be examined more directly from plots such as those in Figs. 4 through 8, in which the various properties are shown directly as functions of strain rate at given temperatures. Table 3 summarizes the net effects of strain rate on the various properties at different temperatures over the range of strain rates covered by the data.

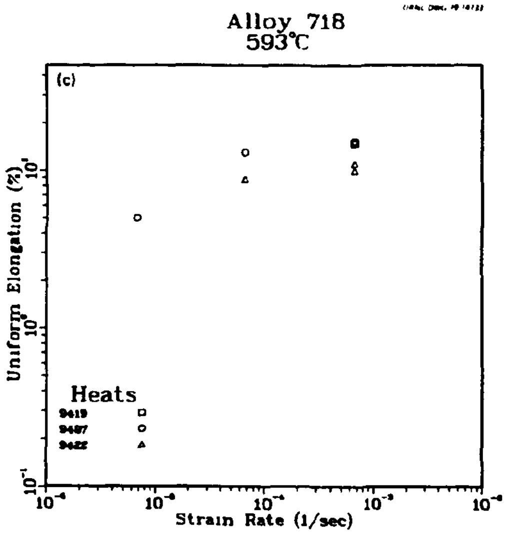
Table 3. Effects of Strain Rate[a] on Tensile Properties of Alloy 718

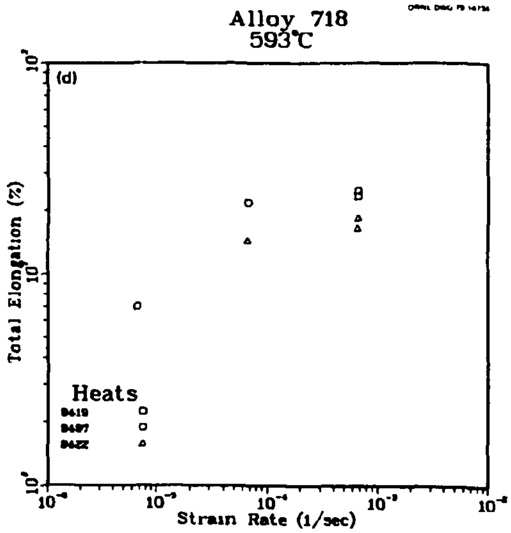
Property	Temperature, °C				
	593	649	704	760	816
Reduction of Area	+	+	+	0	0
Total Elongation	+	+	+	0	0
Uniform Elongation	+	+	+	+	+
Ultimate Strength	0	+	+	+	+
Yield Strength	0	0	0	0	+

[a] In general strain rate varied from 6.67×10^{-6} to 6.67×10^{-3}/s. A "+" in the table indicates that the value of the property generally increased as strain rate increased over this range; a "0" indicates no substantial effect of strain rate.









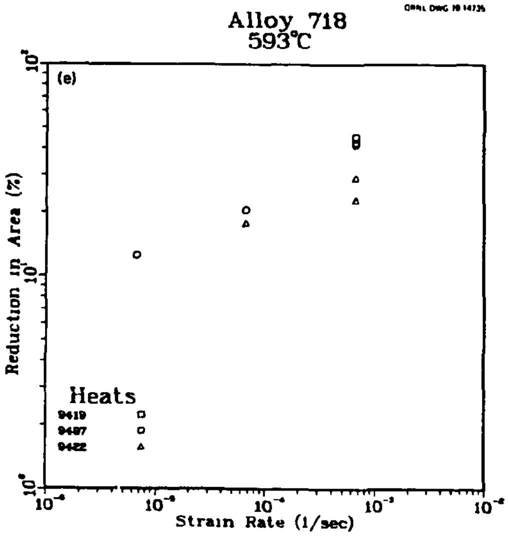
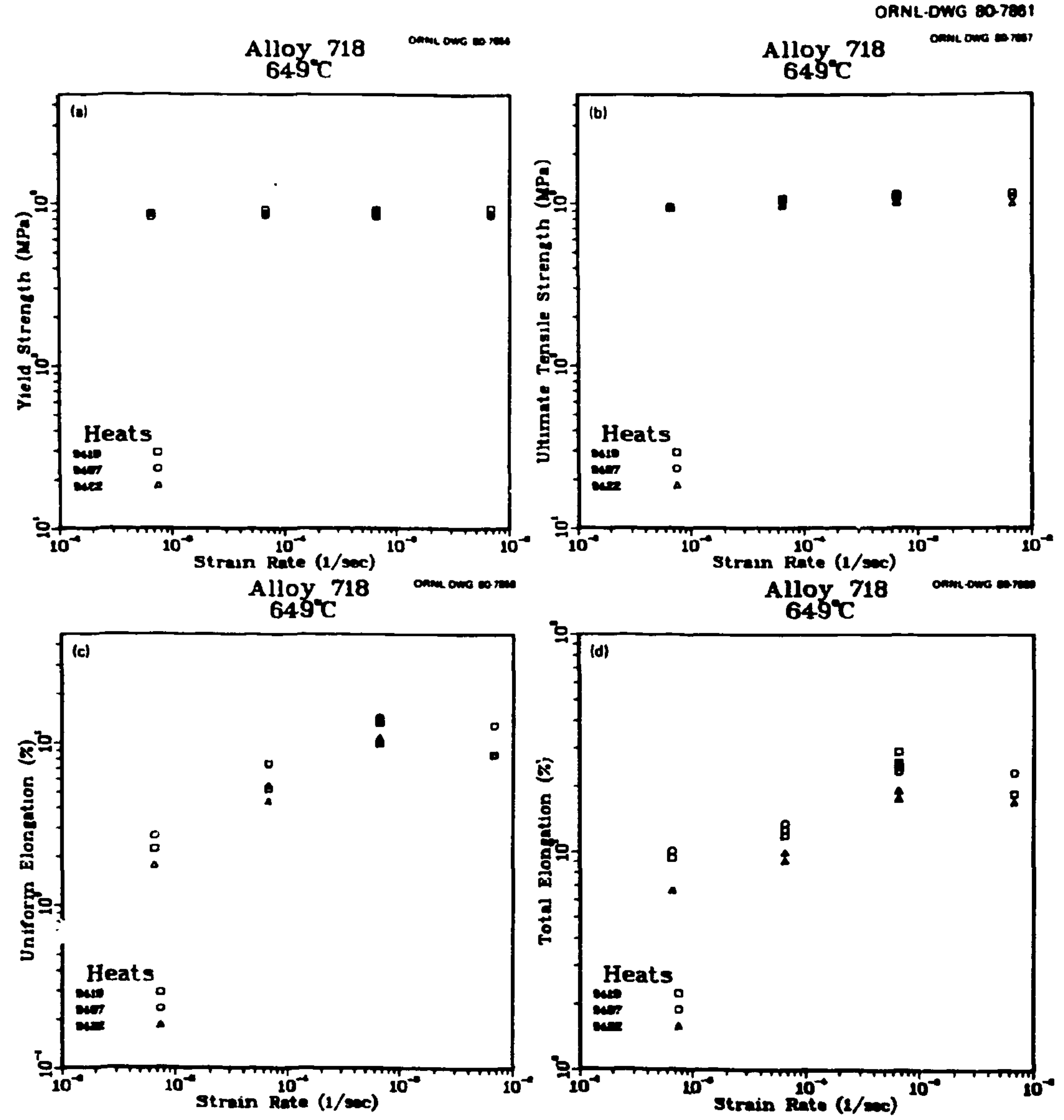


Fig. 4. Effects of Strain Rate for Tests Run on Three Heats of Commercially Heat-Treated Alloy 718 at 593°C on (a) Yield Strength, (b) Ultimate Tensile Strength, (c) Uniform Elongation, (d) Total Elongation, and (e) Reduction of Area.



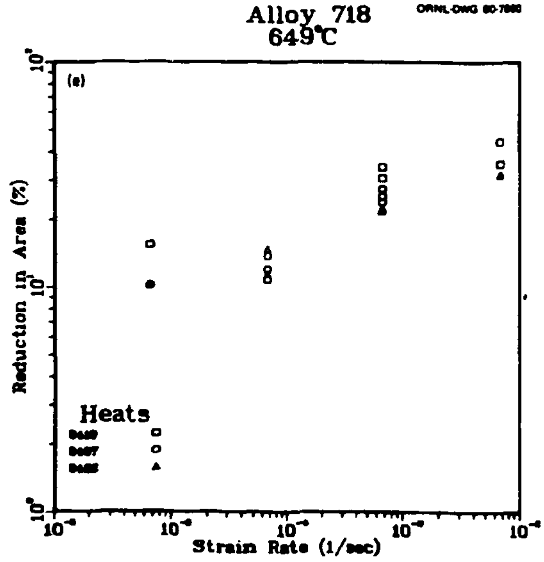


Fig. 5. Effects of Strain Rate for Tests Run on Three Heats of Commercially Heat-Treated Alloy 718 at 649°C on (a) Yield Strength, (b) Ultimate Tensile Strength, (c) Uniform Elongation, (d) Total Elongation, and (e) Reduction in Area.

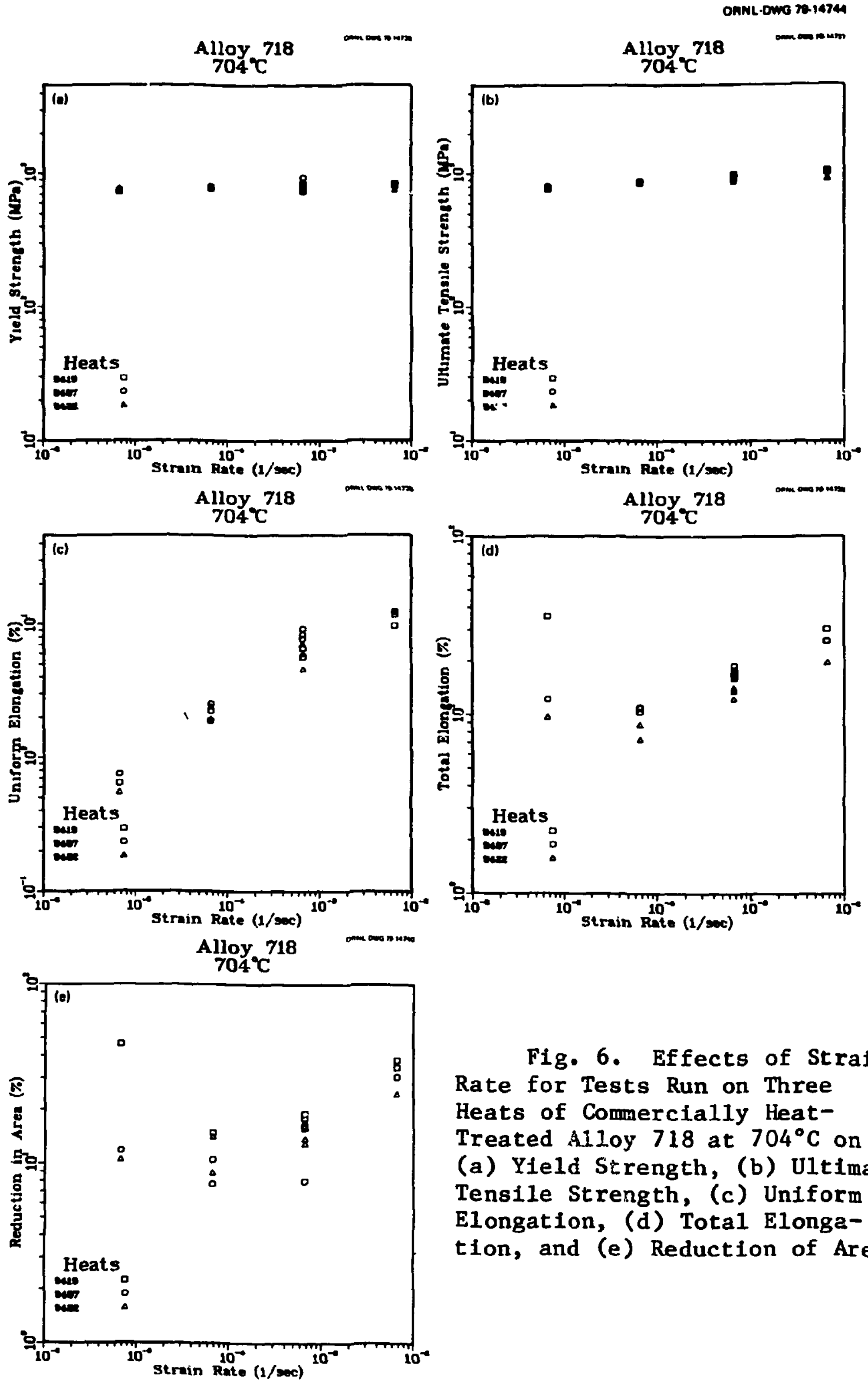


Fig. 6. Effects of Strain Rate for Tests Run on Three Heats of Commercially Heat-Treated Alloy 718 at 704°C on (a) Yield Strength, (b) Ultimate Tensile Strength, (c) Uniform Elongation, (d) Total Elongation, and (e) Reduction of Area.

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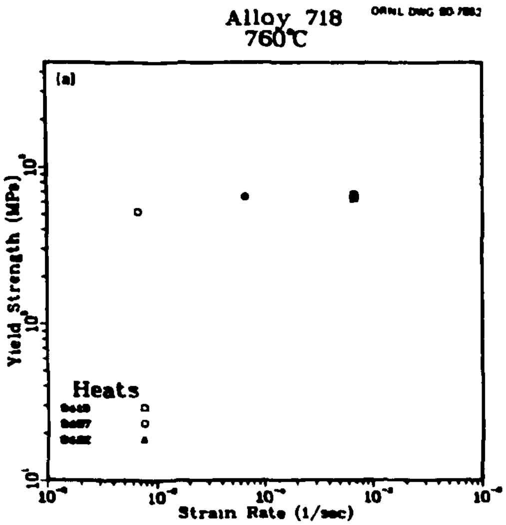

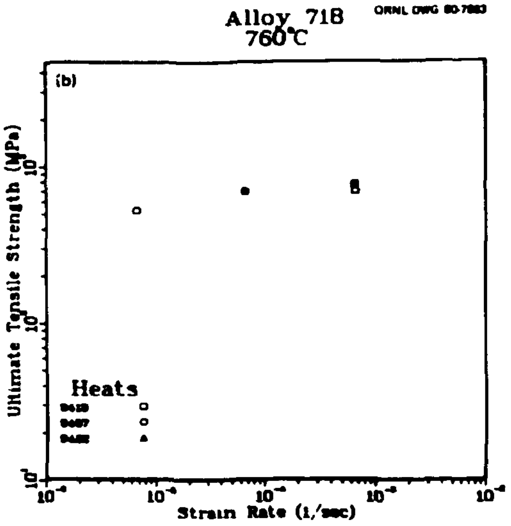

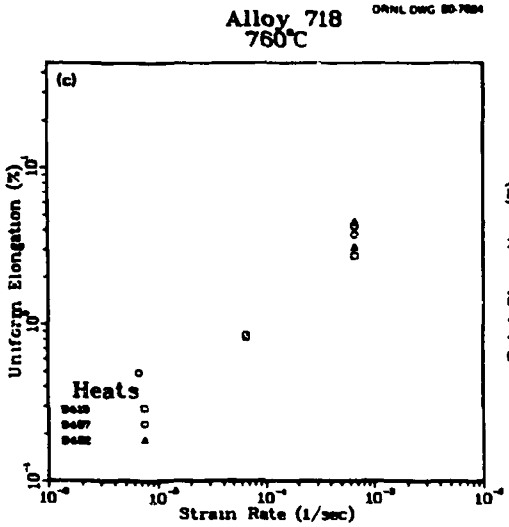

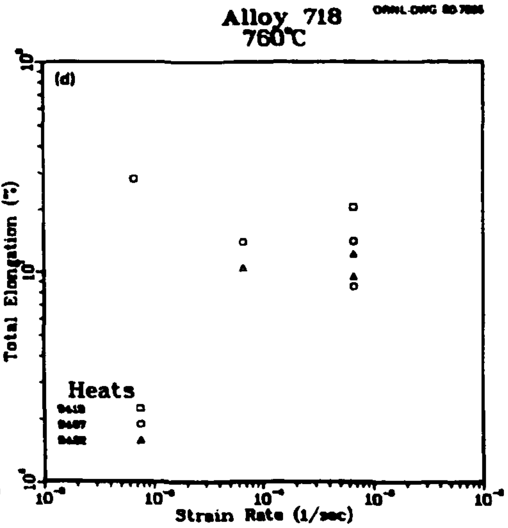

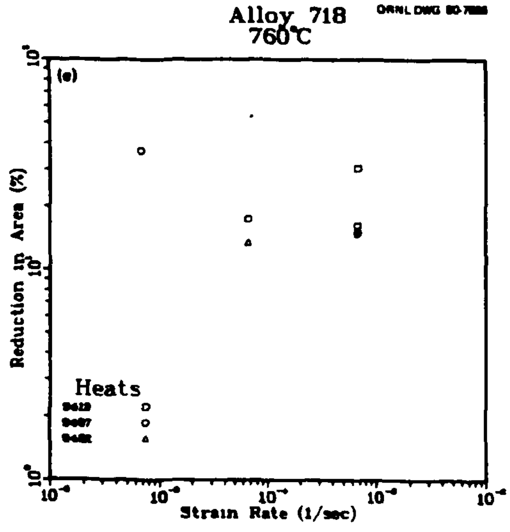

Fig. 7. Effects of Strain Rate for Tests Run on Three Heats of Commercially Heat-Treated Alloy 718 at 760°C on (a) Yield Strength, (b) Ultimate Tensile Strength, (c) Uniform Elongation, (d) Total Elongation, and (e) Reduction in Area.

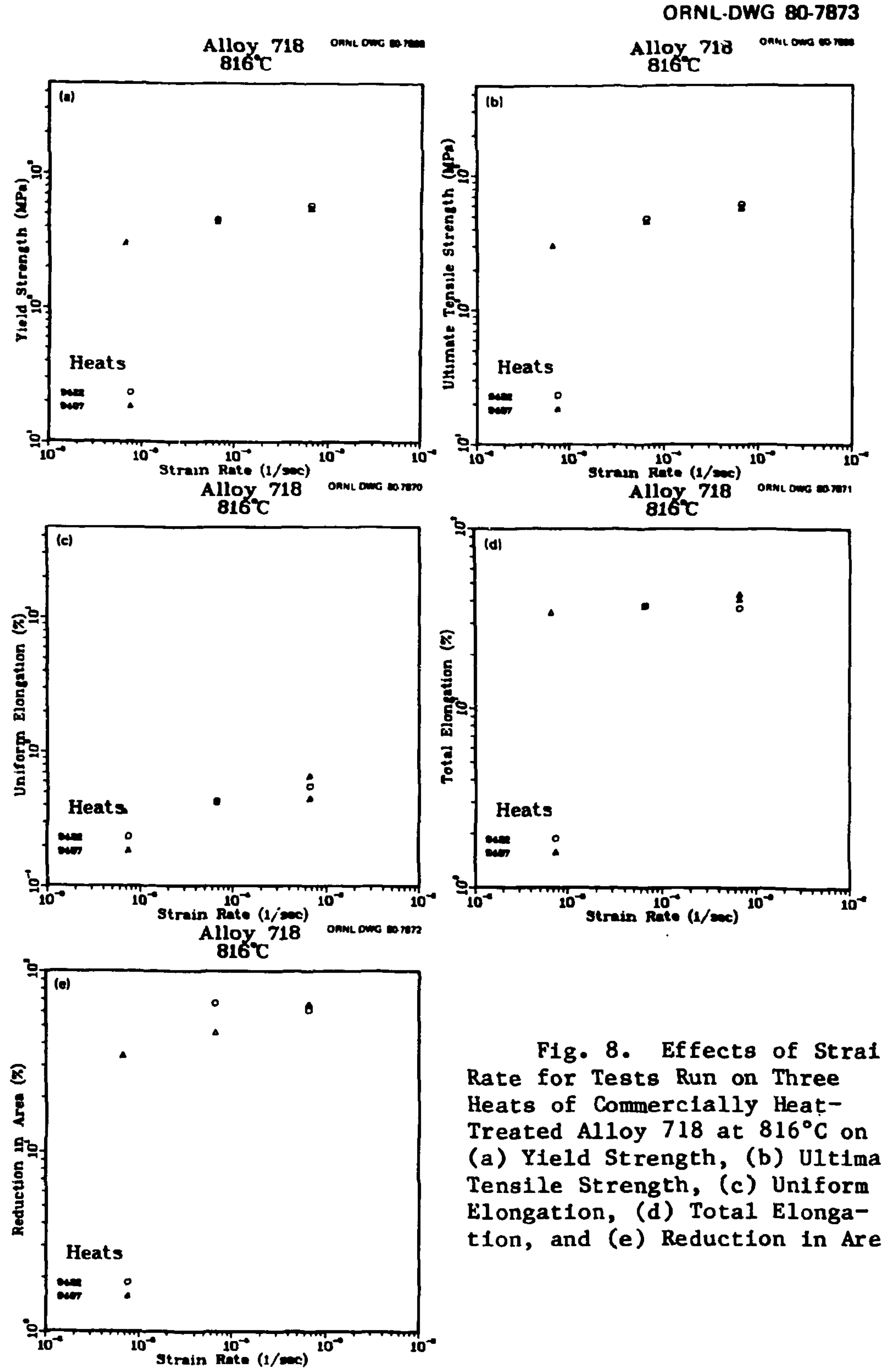

Fig. 8. Effects of Strain Rate for Tests Run on Three Heats of Commercially Heat-Treated Alloy 718 at 816°C on (a) Yield Strength, (b) Ultimate Tensile Strength, (c) Uniform Elongation, (d) Total Elongation, and (e) Reduction in Area.

STRESS-STRAIN BEHAVIOR

We have not analyzed the stress-strain behavior observed in these tests in detail since these data were primarily generated in support of the development of design allowable stress limits. However, some general qualitative observations can be made by considering Fig. 9 which schematically represents the types of stress-strain curves seen.

The curve type shown in Fig. 9(a) was the most common. It is characterized by a fairly rapid initial strain hardening followed by virtually constant or slightly increasing stresses for most of the test. Near fracture the stress again drops off suddenly. The curve type shown in Fig. 9(b) is really a variation of that in Fig. 9(a), the difference being that the stress tends to "peak" more and to drop off gradually through the latter part of the test before the final load drop to fracture. These curve types were observed in the temperature range from 649 to 760°C at the higher strain rates.

The curve type shown in Fig. 9(c) appears to simply be a continuation of the progression seen from Fig. 9(a) to (b). In this type the stress peaks early in the test then gradually decreases through the majority of the test until the final load drop to failure. This type of curve occurred for all the tests at 816°C and for the lower strain rate tests in the range 704 to 760°C. Thus, taking the curve in Fig. 9(a) as a baseline, the general trend is for the stress to peak earlier and to decrease more before failure as temperature increases or strain rate decreases.

In the temperature range 316 to 649°C, the curves displayed serrated deformation, as schematically shown in Fig. 10(a). However, for the lowest strain rate at 538°C, the two lowest strain rates at 593°C, and all but the highest strain rate at 649°C, no serrations were observed.

The serrations typically occur as load drops only, that is, the load suddenly falls below the normal level of the stress-strain curve, then slowly rises back to that curve but does not rise above it. The load drops can be quite large, a nominal stress decrease of 40 to 80 MPa being typical. The serrations typically begin within the first 2% of deformation and continue until fracture.

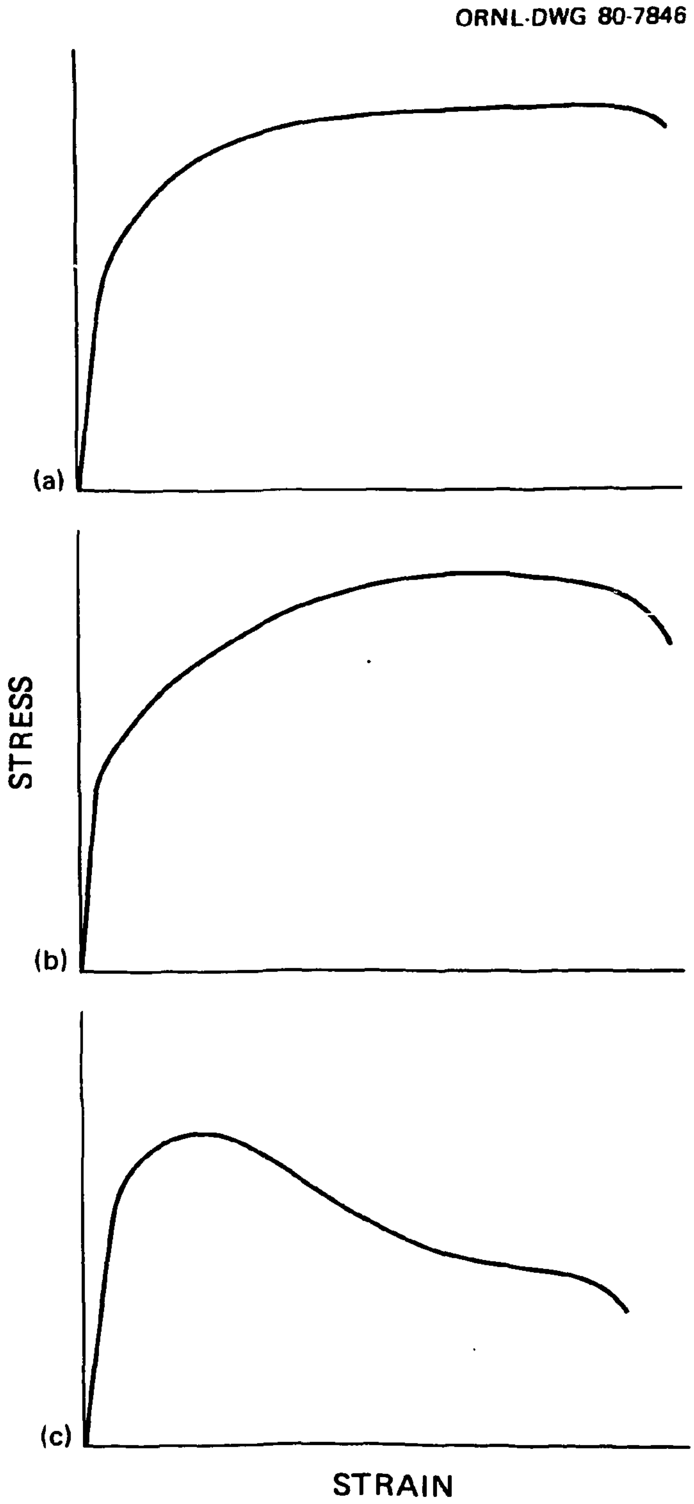

Fig. 9. Schematics of Stress-Strain Curves for Alloy 718. (a) Typical curve. (b) Curve at higher temperatures or lower strain rates than for (a). (c) Curve at temperatures from 704 to 816°C and at low strain rates.

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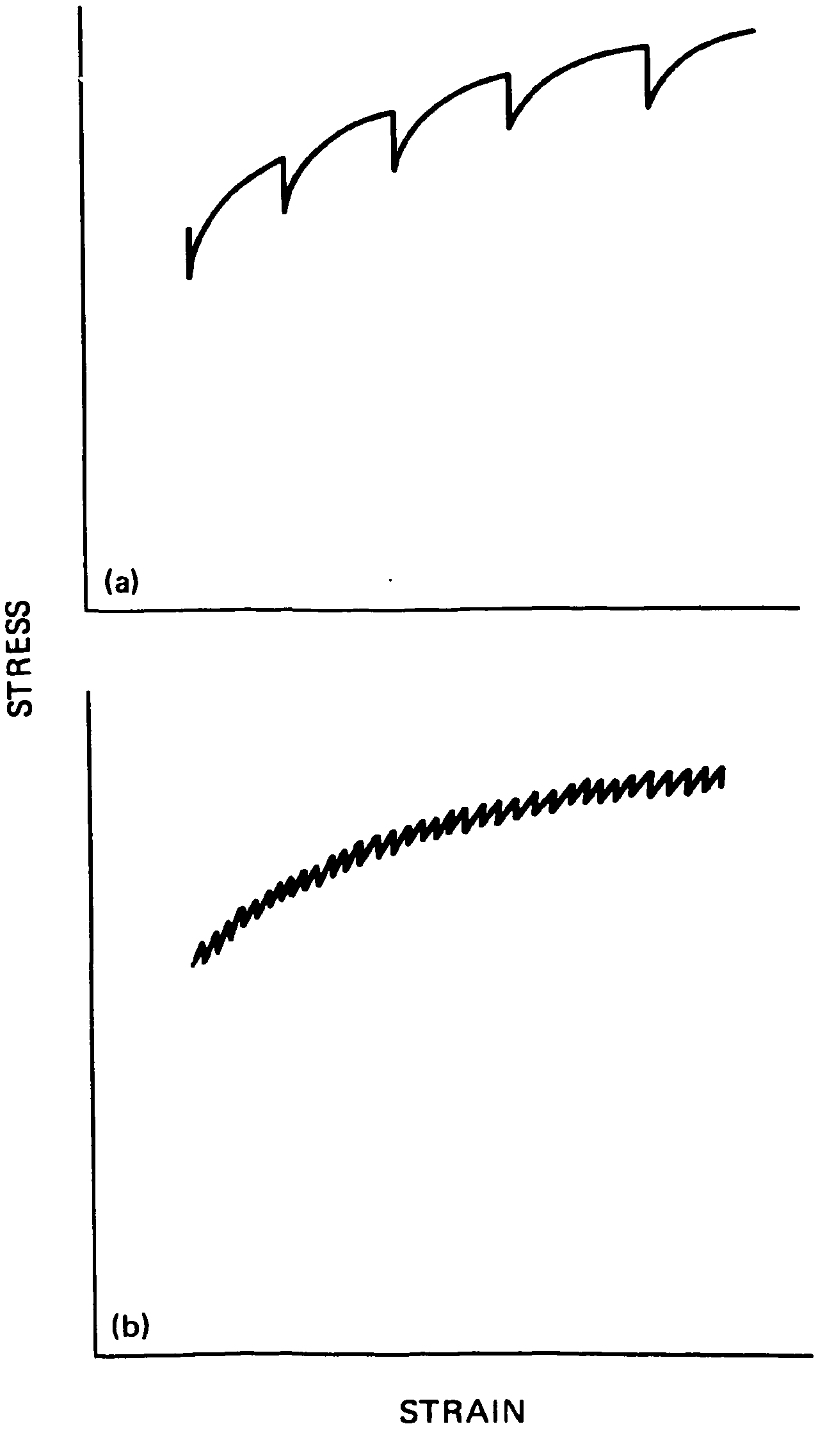

Fig. 10. Serrated Deformations in Alloy 718. (a) Typical deformation in the range 427 to 649°C. (b) Deformation at 316°C.

Exceptions occur at 649°C, where the serrations stop abruptly a few percent strain before fracture in all cases in which they are present (i.e., at the $6.7 \times 10^{-3}/s$ strain rate). Also, at 316°C the serrations have a somewhat different character from those at the higher temperatures, being typically of the type shown in Fig. 10(b). Figure 11 summarizes the temperature-strain rate regimes in which serrations either did or did not occur.

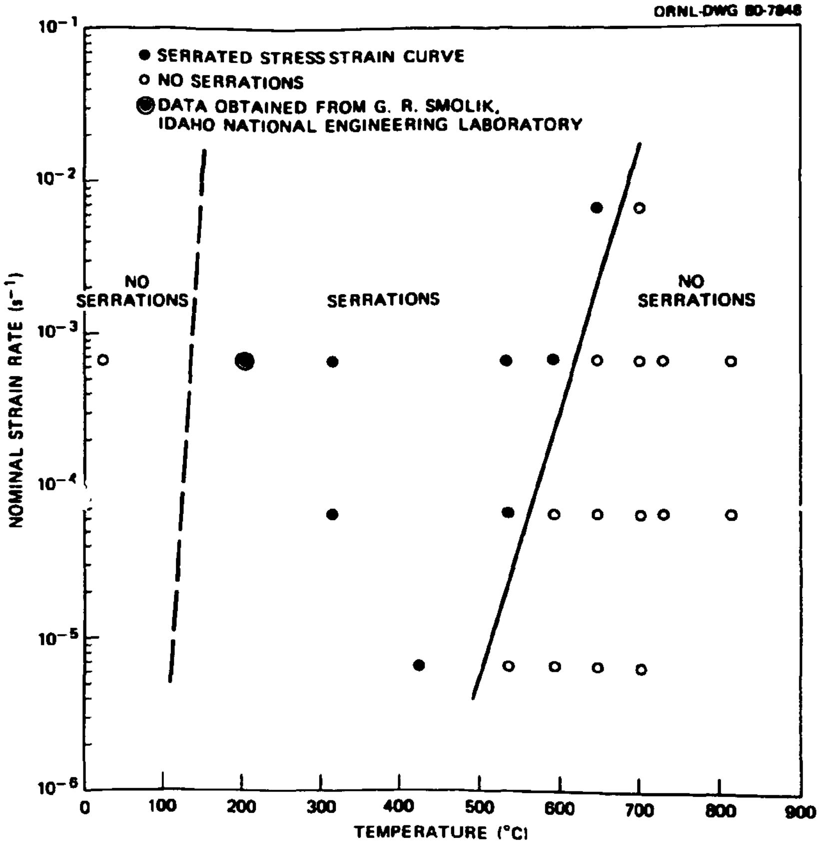

Fig. 11. Summary of Temperature-Strain Rate Regimes in Which Serrated Deformation Occurs.

DISCUSSION

Comparison With Standard Properties

The temperature effects observed from the current data can be compared with a recent analysis reported in ref. 5. In that investigation a large compilation of data from many heats of commercially heat-treated alloy 718 were analyzed by using the common "ratio technique,"[6] resulting in an estimate of lower limits on properties as functions of temperature from room temperature to 760°C.

Figure 12 compares the "minimum" values of various properties from ref. 5 with the data obtained in this investigation at a strain rate of 6.7×10^{-4}/s. In general, for this and other strain rates the current ductility data fall above the "minimum," although the analysis in ref. 5 did not reflect the existence of a ductility minimum in total elongation and reduction in area (partially because no data at temperatures above 760°C were examined and partially because heat-to-heat variations obscured the trends in the data). However for yield and ultimate tensile strengths, some of the data does fall below the "minimum." This tendency is not terribly surprising, since the ratio technique does not yield a physically or statistically valid measure of minimum but is merely an arbitrary empirical limit.

In general, the data presented here appear consistent with the general trends in behavior observed in this material.

Strain Rate Effects

The unusually high matrix strength of commercially heat-treated alloy 718 can be attributed to the existence of a finely distributed precipitated phase throughout the matrix.[7-8] This phase is deposited in the matrix during the duplex aging heat treatment. It has commonly been identified primarily as a gamma-prime (γ')[7] or gamma-double-prime (γ'')[9] phase,* although several other phases are also present. Most recent evidence[9-13] seems to support the view that γ'' is the major strengthening element.

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*Gamma-prime (γ') is an A_3B compound in which the A is primarily Ni and the B is mostly Nb but also includes some Ti and Al.[8] It has an ordered face-centered cubic (fcc) structure and is coherent with the gamma matrix in alloy 718.

Gamma-double-prime (γ'') is an A_3B compound of similar composition but has an ordered body-centered tetragonal (bct).

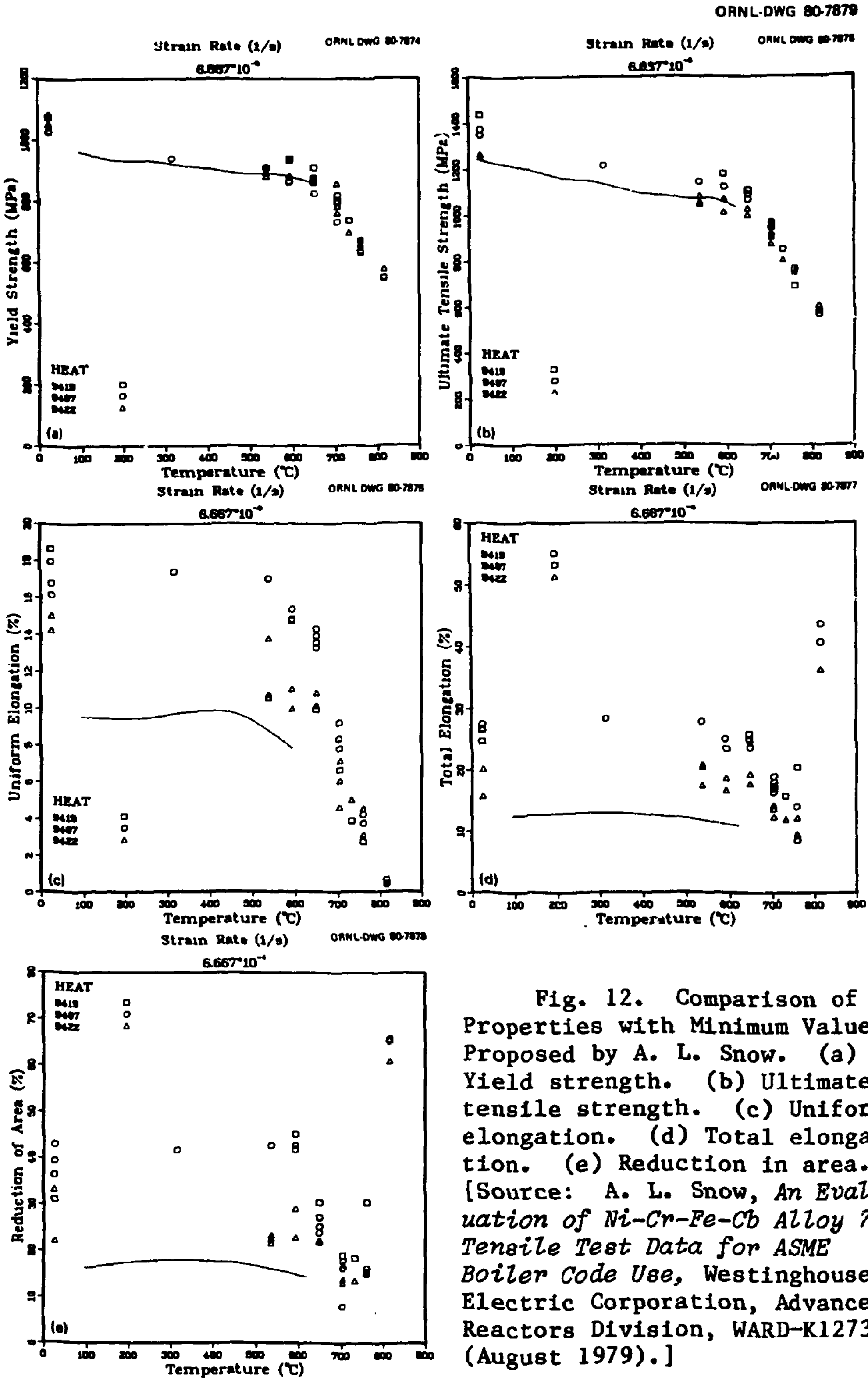

Fig. 12. Comparison of Properties with Minimum Values Proposed by A. L. Snow. (a) Yield strength. (b) Ultimate tensile strength. (c) Uniform elongation. (d) Total elongation. (e) Reduction in area. [Source: A. L. Snow, *An Evaluation of Ni-Cr-Fe-Cb Alloy 718 Tensile Test Data for ASME Boiler Code Use*, Westinghouse Electric Corporation, Advanced Reactors Division, WARD-K1273-1 (August 1979).]

The strengthening associated with γ'' comes primarily[13] from coherency straining resulting from atomic mismatch between the γ'' particles and the gamma-phase matrix. This microstructure appears to deform by massive heterogeneous planar slip. Since nickel has a low stacking-fault energy, alloy 718 would not be expected to undergo cross slip with screw dislocations. Therefore, at lower temperatures dislocations cannot bypass the γ'' particles by cross slip but must instead cut through the particles. For temperatures of 649°C and above, overaging may cause coarsening of the particles and dislocations may bypass them by looping or by dislocation climb mechanisms.[8]

This overaging may occur[9] either from coarsening of the fine γ'' precipitate particles or from partial solution of both the γ'' and γ' phases with concurrent formation of a stable orthorhombic Ni_3Cb. This overaging has been observed as low as 649°C, but may require fairly long exposure at this temperature.

The drop-off in strength of alloy 718 with temperature can be explained by this overaging and activation of new deformation mechanisms at higher temperatures. The decreases in ultimate tensile strength with decreasing strain rate can be explained both by the introduction of time-dependent strains at the lower strain rates and by the effects of thermal aging on the microstructure of the material during testing. The lower strain rates provide more time for creep and for particle coarsening, thus lowering the strength. The increases in ductility with strain rate at the intermediate temperatures are consistent with the same effects and with a probable tendency toward more matrix deformation and less grain boundary deformation at higher strain rates. (Grain boundary deformation leading to intergranular cracking would be expected to cause relatively low ductility.) However, at the very highest test temperatures, overaging may deplete the matrix strength so rapidly that considerable intragranular deformation occurs at all strain rates. This results in the relative insensitivity of failure ductility to strain rate at these temperatures. On the other hand, the strength becomes more sensitive to strain rate as time-dependent strain becomes a more significant factor.

Ductility Minimum

The minimum in ductility with temperature can be explained in the same concepts as those described above. As temperature increases on the lower side of the minimum, the incidence of intergranular cracking increases, and ductility goes down. This grain boundary cracking occurs as a result of the extremely high strength of the γ''-hardened matrix and may be accentuated by the existence[7] of gamma phase zones near the grain boundaries that are denuded of hardening elements, thus causing the strain to concentrate in those areas. On the upper side (in temperature) of the minimum, overaging depletes the matrix, strains can again occur throughout the grains, and ductility goes up. This scenario is consistent with the above-mentioned effects of strain rate on the depth and position of the minimum.

On the other hand, if the above explanation is correct, strain rate and temperature should be virtually interchangeable as variables. In other words, an isothermal plot of ductility vs strain rate should also show the minimum. Figures 4 through 8 clearly do not show such an effect, but the tensile strain rates used here may all lie on the high side of the minimum. To obtain a wider range of strain rates, we added available creep data[2] for heats 9419 and 9497 to the tensile data in the manner of Sikka[14] for austenitic stainless steels. For the strain rate in the creep tests, we used the average creep rate to rupture, given as the ratio of creep rupture strain to rupture time. Figure 13 shows the resultant relationship between reduction in area and strain rate for temperatures of 593 and 649°C. In both cases there is a minimum in ductility with strain rate. However, the low strain rate "upswing" in ductility at 593°C is very small as a result of the small effect of overaging at this temperature within the time span of the creep data (up to 20,000 h).

Finally as seen in Fig. 14, long-term aging that results in significant coarsening of the precipitates particles and weakening of the matrix also results in the removal of the ductility minimum. This effect is consistent with the above discussion and with other results[4] on similar materials.

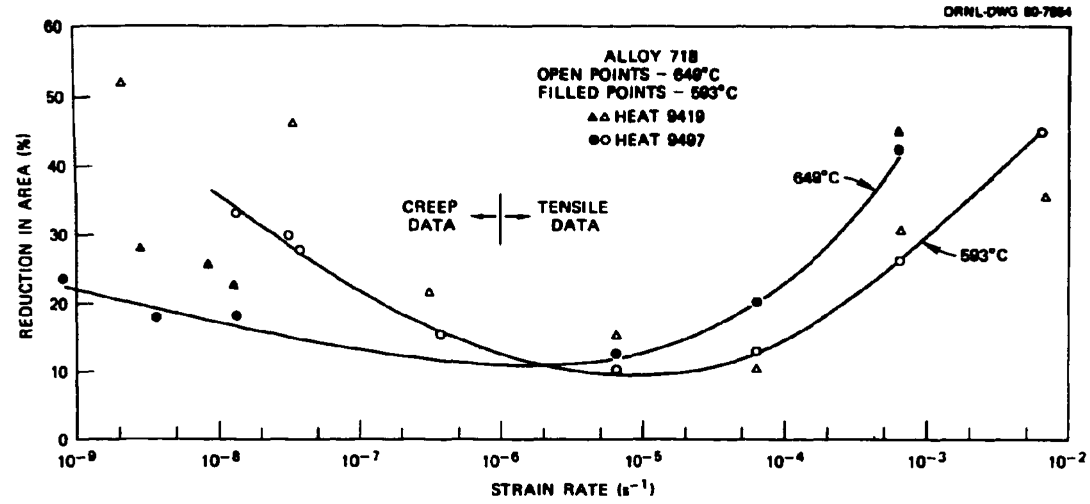

Fig. 13. Influence of Strain Rate on Reduction in Area in Creep and Tensile Tests at 593 and 649°C.

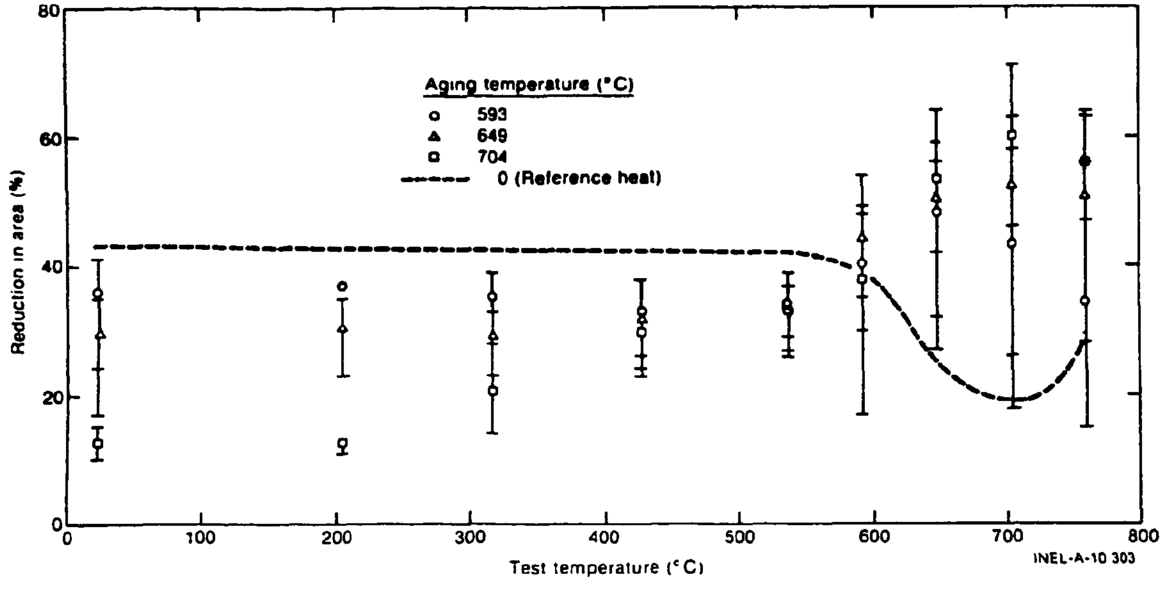

Fig. 14. Effect of Long-Term (10,000-h) Aging on the Relationship Between Reduction in Area and Temperature for Several Heats of Alloy 718. Data were privately supplied by G. E. Korth and G. R. Smolik of Idaho National Engineering Laboratory, January 1979.

Serrated Stress-Strain Behavior

The currently available information is insufficient to allow a full explanation of the effects causing the serrations noted on the stress-strain curves for this material. The serrations appear to be inherent to the deformation behavior and may be related to the heterogeneous planar slip mode of deformation and to the precipitation-hardened microstructure. For example,[15] thermally aged commercially heat-treated material or material given the so-called "INEL" heat treatment[16] seems to display smaller and fewer serrations. Both microstructures contain coarser precipitate particles than the regular commercially heat-treated material. A further investigation of this phenomenon might be useful in developing a better understanding of the mechanisms of deformation in this material. However, such an investigation is beyond the scope of this analysis.

CONCLUSIONS

Examination of tensile test data for three heats of commercially heat-treated alloy 718 over the range from room temperature to 816°C and at strain rates from 6.7×10^{-6} to 6.7×10^{-3}/s led to the following conclusions:

1. Yield and ultimate tensile strengths for commercially heat-treated alloy 718 decrease very gradually with temperature from room temperature up to about 600°C for a strain rate of 6.7×10^{-5}/s or to about 700°C for a strain rate of 6.7×10^{-4}/s. Above these temperatures the strength drops off fairly rapidly.

2. Reduction in area and total elongation data show minima around 700°C, with each ductility measure falling to 10% or less at the minima. This minimum is lower and occurs at lower temperatures as strain rate decreases. Up to about 600°C the ductility is typically around 30%. As temperatures reach 816°C the ductility again increases to perhaps 60%.

3. The uniform elongation (plastic strain at peak load) decreases only slightly with temperature to about 500°C, then drops off rapidly and monotonically with temperature, reaching values less than 1% at 816°C. At

the highest test temperatures the load maximum may result not from necking of the specimen, but from overaging of the precipitation-hardened microstructure.

4. Stress-strain curves showed serrated deformation in the temperature range from 316 to 649°C, although they occur only for the faster strain rates at the upper end of this temperature range. The serrations can be quite large, involving load drops of perhaps 40 to 80 MPa. The serrations typically begin within the first 2% of deformation and continue until fracture, although exceptions were noted.

5. All data appear consistent with other available data for this material and with the microstructural state of the material.

ACKNOWLEDGMENTS

The authors would like to thank G. R. Smolik of the Idaho National Engineering Laboratory for providing data and for helpful discussions of those data for use in this report. Thanks also go to J. P. Hammond, J. P. Strizak, and C. R. Brinkman for reviewing the contents of this report. Finally, we would like to thank B. G. Ashdown for editing and K. A. Witherspoon for preparing the final manuscript.

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