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EFFECT OF STRAIN RATE ON THE TENSILE PROPERTIES OF IRRADIATED INCONEL 718

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ABSTRACT

The effect of strain rate on the tensile properties of neutron irradiated Inconel 718 has been experimentally determined. Specimens were irradiated in the Experimental Breeder Reactor-II to total neutron fluences of 0.6 to 1.0 x 10^{22} n/cm^2 (at 400°C), 1.0 to 2.4 x 10^{22} n/cm^2 (at 593°C) and 3.1 to 3.4 x 10^{22} n/cm^2 (at 649°C). Test conditions included nominal strain rates from 3 x 10^{-5} to 1 sec^{-1} and temperatures from 232 to 649°C. For the temperature range of this study the strength and ductility of unirradiated material were essentially insensitive to increasing strain rate. Neutron irradiation at a temperature of 400°C did not alter this behavior since both strength and ductility remained essentially unaffected by increasing strain rate. At the higher irradiation temperatures (593°C and above) strength properties were consistent with unirradiated behavior and pre- and postirradiation ductility values were essentially identical at the lower test temperatures (< 550°C). At test temperatures above 550°C all irradiated specimens exhibited very low ductility as a result of helium embrittlement. Increasing strain rate at these temperatures reduced the effect of this embrittlement and resulted in ductility values approaching those observed prior to irradiation.

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INTRODUCTION

Inconel 718, a precipitation hardenable nickel-base alloy, is being used in a variety of structural components in liquid metal fast breeder reactor systems. Applications in the various components include thermal liners, springs, connectors, shear pins, and wear pads. Service conditions potentially include temperatures to 650°C and total neutron fluences to greater than 1×10^{23} n/cm^2. Mechanical properties data representative of these service conditions are needed for safety analyses and operations guidance for the associated structural components. Of special significance are irradiation effects data representative of postulated accident conditions.

The elevated temperature mechanical properties of unirradiated Inconel 718 have been extensively characterized [1,3] and limited data are available on the effects of neutron irradiation on these properties [4,6]. Claudson [4] has shown that irradiation (to 1×10^{21} n/cm^2, E > 1 MeV) in a thermal reactor significantly reduces elevated temperature (740°C) tensile ductility with little effect on strength and Bohm et al. [5] demonstrated that thermal-reactor irradiation at a fluence of 8.1×10^{21} n/cm^2 (E > 1 MeV) significantly reduces the 650°C rupture life and ductility. Recently, Ward et al. [6] reported tensile data for the subject material which had been irradiated in a fast reactor (EBR-II) at temperatures to 649°C and total fluences to 3.4×10^{22} n/cm^2. These results revealed that irradiation did not greatly alter strength properties; however, ductility was severely reduced when test temperatures approached 649°C. Of the available information, none indicates the effect of strain rate on the tensile properties of irradiated material.

In the present study, the effect of strain rate on the tensile properties of unirradiated and irradiated Inconel 718 has been determined. Irradiation conditions included fast fluences of 1.0×10^{22} n/cm^2 (at 391°C), 2.4×10^{22} n/cm^2 (at 593°C), and 3.4×10^{22} n/cm^2 (at 649°C). Test parameters include strain rates to 1.0 sec^{-1} and temperatures to 649°C.

EXPERIMENTAL PROCEDURE

Test Material and Specimens

The Inconel 718 used in this study was obtained in the form of 1.27 cm thick plate. Miniature buttonhead tensile specimens (Figure 1) were fabricated from the longitudinal forming direction of the plate and subsequently used for control testing and the irradiation experiment. Heat treatment of the test material consisted of annealing at 954°C for 0.5 hours followed by aging at 717°C for 8 hours, furnace cooling to 621°C, and holding at 621°C until the total aging time reached 18 hours. The chemical composition for the test material is presented in Table I.

TABLE I

CHEMICAL COMPOSITION OF INCONEL 718-HEAT 52C9EK (Wt. %)

C - 0.07	Al - 0.59
Mn - 0.08	Ti - 1.08
Fe - 18.19	P - 0.007
S - 0.007	Co - 0.03
Si - 0.17	Mo - 0.03
Cu - 0.11	B - 0.0032
Ni - 53.44	Cb + Ta - 5.10
Cr - 18.11	

Irradiation Experiment

The Experimental Breeder Reactor-II (EBR-II) at the Idaho National Engineering Laboratory was used for the irradiation experiment. The experiment was conducted in a Row 2 core position in structural materials subassemblies designated X-195 and X-198. All test specimens were irradiated in a sodium environment. Irradiation conditions included the following total fluences and temperatures: 0.5 to 1.0 x 10^{22} n/cm^2 at 391 to 404°C, 1.0 to 2.4 x 10^{22}n/cm^2 at 593°C, and 3.1 to 3.4 x 10^{22} n/cm^2 at 649°C.

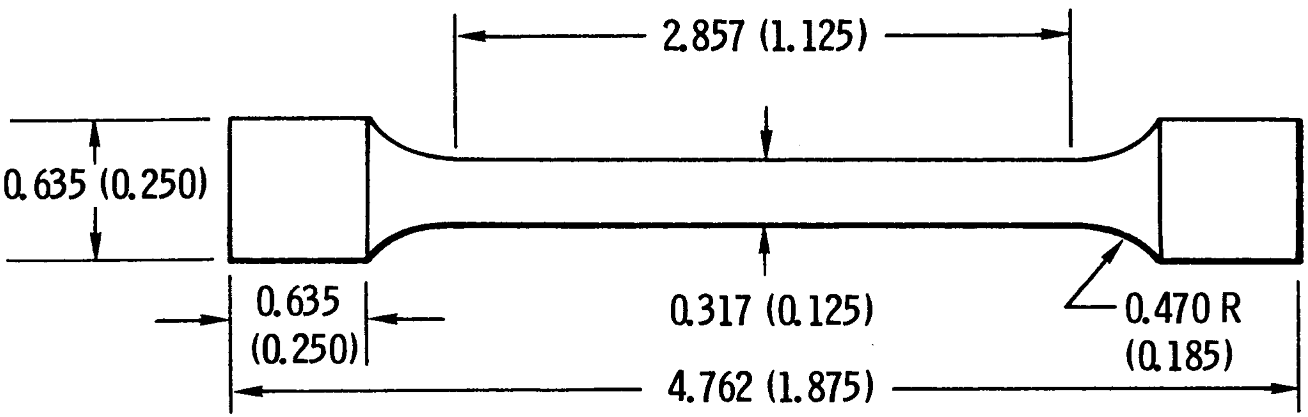

FIGURE 1. Tensile Specimen Geometry. Dimensions in cm (in.).

Test Procedure

All tests were performed on hard beam machines. An Instron Tensile Machine was utilized for all tests at strain rates to 7.4 x 10^{-3} sec^{-1} and an MTS Electro-Hydraulic test machine for strain rates from 7.4 x 10^{-3} to 1.0 sec^{-1}. Both machines were operated at constant crosshead velocity and strain rate values given here are based on the crosshead velocity and initial specimen gauge length. Ductility data reported in this report were obtained from pre- and post-test specimen measurements.

RESULTS AND DISCUSSION

Unirradiated Behavior

Tensile testing of unirradiated Inconel 718 was performed at temperatures from room temperature to 760°C and strain rates from 3 x 10^{-5} to 1.0 sec^{-1}. Results of these tests provided a description of unirradiated tensile properties and also established a basis for ascertaining the effects of neutron irradiation. Tensile property data obtained from each test included the 0.2% yield and ultimate strengths, total and uniform elongations, and reduction of area. These data are tabulated in Table II.

The temperature and strain rate dependence of the ultimate strength of unirradiated Inconel 718 is presented in Figure 2. At any given rate the ultimate strength decreases with increasing temperature. At room temperature a positive strain rate sensitivity is observed, i.e., the ultimate strength increases with increasing strain rate. Increasing test temperature to 232°C alters this behavior sinch a slightly negative strain rate sensitivity is observed. At temperatures of 427 and 538°C the ultimate strength is essentially insensitive to strain rate. For temperatures of 649 and 760°C there is a clear departure from the strain rate dependence observed at the lower temperatures. For strain rates below about 10^{-3} sec^{-1} (at 649°C) and 10^{-2} sec^{-1} (760°C) the ultimate strength is strongly strain rate dependent. Such dependence, reported previously for other austenitic materials [7,8] has been attributed to the dominance of creep deformation at these temperatures and low strain rates. As strain rate is increased, creep (time and temperature dependent) is progressively restricted until it no longer exerts a pronounced influence at the higher strain rates.

TABLE II

ELEVATED TEMPERATURE TENSILE PROPERTIES OF INCONEL 718 AT VARIOUS STRAIN RATES

Temp. °C	$\dot{\varepsilon}$ Sec^{-1}	Strength - MPa (Ksi) PEL		0.2% Yield		Ultimate		Elongation-% Total	Uniform	Reduction of Area - %	Site Sequence
22	3×10^{-5}	785	(113.8)	1065	(154.5)	1365	(198.0)	16.4	15.5	30.9	HO 4781
		840	(121.9)	994	(144.2)	1267	(183.7)	20.0	18.8	30.9	4782
		816	(118.4)	1053	(152.7)	1318	(191.1)	19.0	18.2	28.5	4794
		814	(118.0)	1038	(150.5)	1326	(192.3)	19.5	18.0	38.2	4796
	3×10^{-3}	1096	(159.0)	1158	(168.0)	1393	(202.0)	15.6	10.9	31.5	4862
	6×10^{-2}	1031	(149.6)	1177	(170.7)	1413	(204.9)	15.0	8.3	31.7	4833
	1.0	929	(134.8)	1168	(169.3)	1404	(203.7)	14.5	10.0	36.1	4831
232	3×10^{-5}	735	(106.6)	1073	(155.6)	1314	(190.6)	14.2	12.9	22.1	4812
		836	(125.9)	1054	(152.8)	1284	(186.3)	16.2	11.8	29.0	4803
	3×10^{-3}	840	(121.9)	1034	(150.0)	1278	(185.4)	15.3	12.4	35.8	4863
	6×10^{-2}	918	(133.2)	1078	(156.4)	1255	(182.0)	13.8	9.3	32.8	4834
	1.0	833	(120.8)	1000	(145.0)	1218	(176.7)	16.1	11.5	37.5	4832
427	3×10^{-5}	774	(112.2)	931	(135.1)	1147	(1664)	17.4	13.5	30.9	4784
		751	(108.9)	919	(133.3)	1131	(164.1)	17.9	14.4	30.9	4785
	3×10^{-3}	840	(121.9)	1006	(145.9)	1197	(173.6)	13.3	11.1	33.3	4864
	6×10^{-2}	820	(118.9)	967	(140.3)	1201	(174.2)	12.2	11.0	29.8	4828
	1.0	942	(136.6)	995	(144.3)	1171	(169.9)	10.8	10.0	35.0	4832
538	3×10^{-5}	673	(97.6)	897	(130.1)	1120	(162.4)	17.9	15.5	30.1	4786
		718	(104.1)	889	(129.0)	1104	(160.1)	13.6	12.2	25.2	4787
	3×10^{-3}	791	(114.7)	991	(143.8)	1187	(172.1)	12.5	10.9	32.0	4865
		814	(118.0	971	(140.9)	1158	(168.0)	12.7	9.4	32.8	4866
	6×10^{-2}	838	(121.6)	974	(141.2)	1133	(164.4)	12.8	8.9	32.0	4829
	1.0	800	(116.1)	934	(135.5)	1134	(164.5)	12.8	11.2	31.5	4837
593	3×10^{-5}	712	(103.2)	897	(130.1)	1108	(160.7)	15.0	14.0	25.2	4788
		701	(101.6)	891	(129.3)	1101	(159.7)	14.3	12.9	24.4	4790
	3×10^{-3}	796	(115.4)	973	(141.1)	1171	(169.9)	11.6	9.2	25.2	4867
		796	(115.4)	964	(139.8)	1166	(169.1)	12.1	8.8	32.5	4868
	6×10^{-2}	863	(125.2)	965	(140.0)	1122	(162.8)	13.7	11.9	32.0	4825
	1.0	647	(93.9)	906	(131.4)	1129	(163.7)	14.0	10.5	33.1	4826

TABLE II

ELEVATED TEMPERATURE TENSILE PROPERTIES OF INCONEL 718 AT VARIOUS STRAIN RATES (Continued)

Temp. °C	$\dot{\varepsilon}$ - Sec^{-1}	Strength - MPa (Ksi) PEL		0.2% Yield		Ultimate		Elongation-% Total	Uniform	Reduction of Area - %	Site Sequence
649	3 x 10^{-5}	616	(89.4)	826	(119.8)	939	(136.2)	6.8	6.3	17.1	HO 4792
		673	(97.6)	855	(124.0	962	(139.5)	7.2	6.8	15.4	4793
	3 x 10^{-3}	736	(106.7)	965	(129.9)	1101	(159.7)	14.0	9.8	28.5	4869
		778	(112.9)	937	(135.9)	1071	(155.3)	15.1	11.9	30.6	4870
	6 x 10^{-2}	855	(124.0)	938	(136.0)	1092	(158.4)	11.4	8.9	30.4	4830
	1.0	826	(119.8)	926	(134.3)	1096	(158.9)	13.4	8.3	31.5	4827
760	3 x 10^{-5}	471	(68.3)	610	(88.5)	621	(90.1)	4.2	2.3	13.8	4789
		493	(71.5)	621	(90.0)	632	(91.6)	8.4	2.8	15.4	4791
	3 x 10^{-3}	628	(91.1)	770	(111.7)	870	(126.2)	7.4	4.4	11.4	4871
	6 x 10^{-2}	706	(102.4)	787	(114.1)	967	(140.3)	15.5	8.9	25.8	4836
	1.0	620	(89.7)	759	(110.1)	984	(142.7)	13.4	11.3	29.8	4835

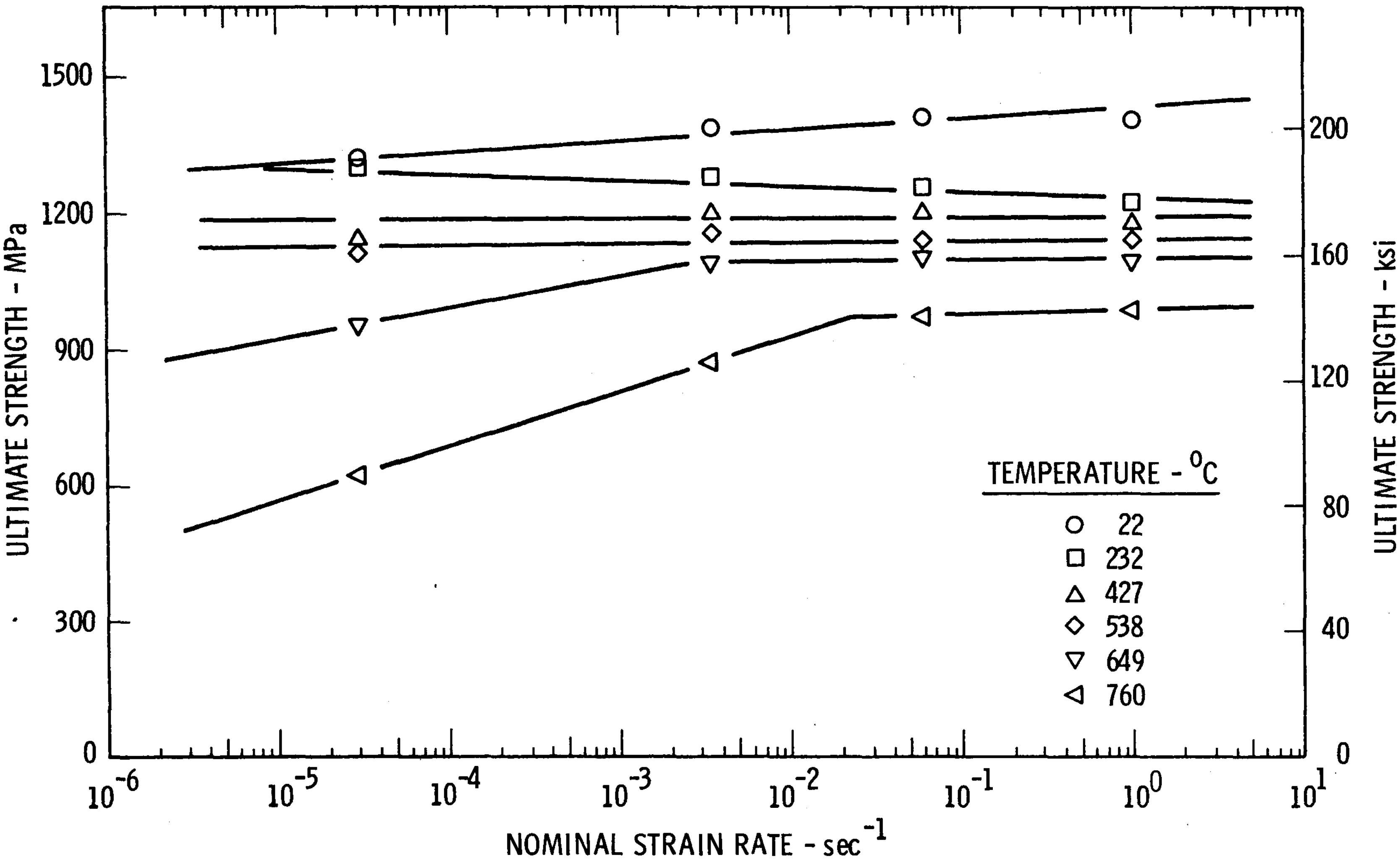

FIGURE 2. Temperature and Strain Rate Dependence of the Ultimate Strength of Unirradiated Inconel 718.

The temperature dependence of the 0.2% yield strength is similar to that of the ultimate strength in that both decrease with increasing test temperatures (Figure 3). Increasing the strain rate at temperatures between room temperature and 538°C increases the yield strength only slightly while at temperatures of 649 and 760°C it is increased substantially. Behavior at these higher temperatures is consistent with that observed for the ultimate strength.

The ductility (total and uniform elongation and reduction of area) of unirradiated material is influenced by strain rate at the various temperatures as shown in Figures 4-6. For temperatures to 538°C, both total and uniform elongation (elongation at maximum load) moderately decrease with increasing strain rate. At the higher test temperatures (649 and 760°C) both properties increase thus producing a tendency toward convergence with the low temperature results. Reduction of area increases with strain rate at all temperatures (Figure 6). As with total and uniform elongation, the largest increases in reduction of area occur at the higher temperatures.

As previously mentioned, the strain-rate response of Inconel 718 is similar to that reported for other austenitic materials. For test temperatures from 232 to 538°C the ultimate strength and ductility decrease slightly or are unaffected by increasing strain rate. This decrease has been observed in other austenitic materials and has been related to dynamic strain aging [8]. Dynamic strain aging is characterized by serrated stress-strain curves and results from dislocation interactions with interstitial carbon and nitrogen atoms [9]. Its influence on tensile behavior is to enhance both strength and ductility. Increasing strain rate has been shown to restrict dynamic strain aging thus producing lower strength and ductility [8].

In the present study extensive dynamic strain aging was observed (as evidenced by serrations) in the autographic records of tests performed at the lowest strain rate and temperatures of 232, 427, and 538°C (Figure 7). Additionally, the magnitude of the serrations was largest at 538°C (> 40 MPa) and non-existant at 649°C. Increasing strain rate altered the serrations at temperatures of 427 and 649°C as illustrated in Figures 8 and 9.

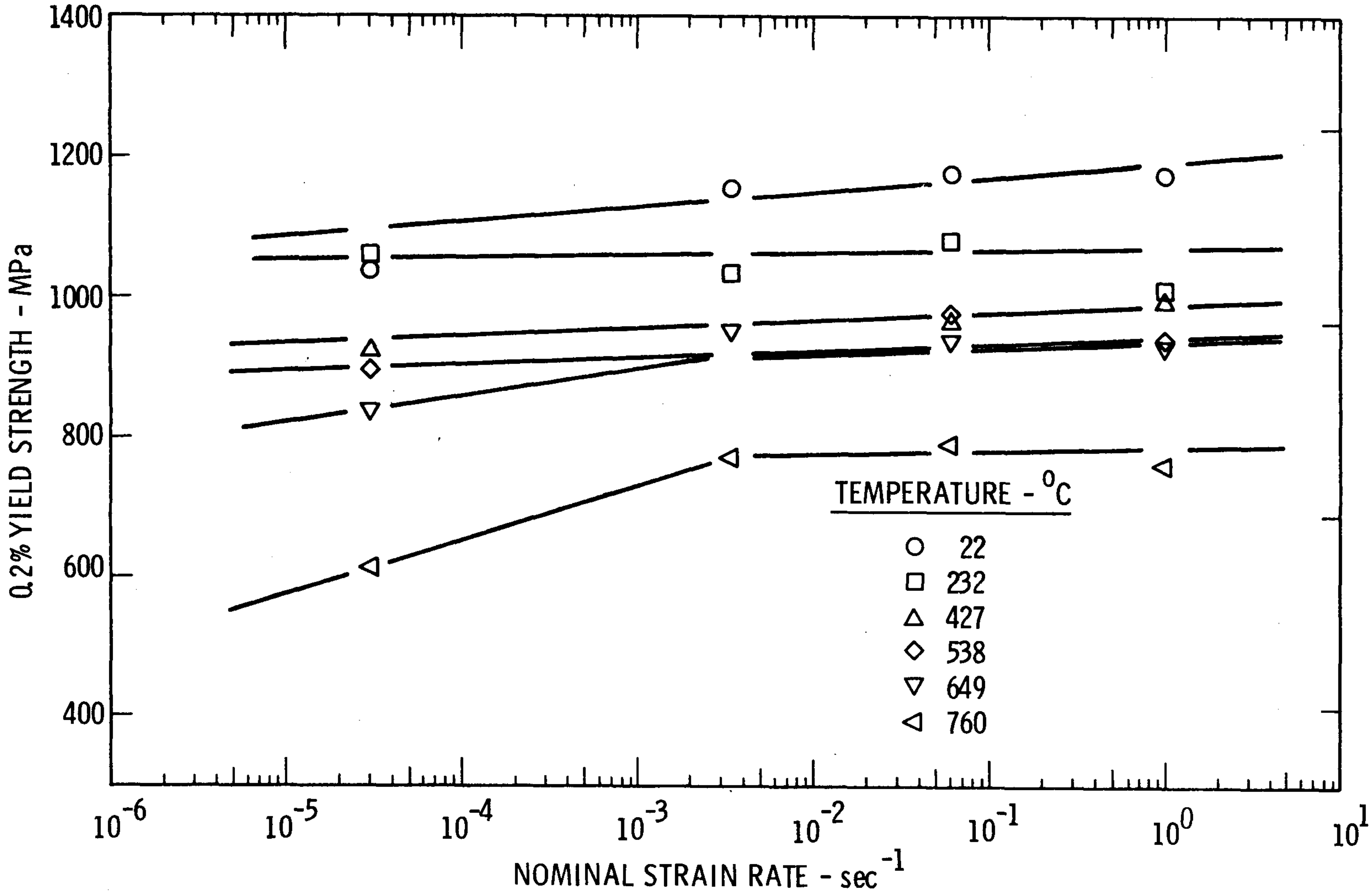

FIGURE 3. Temperature and Strain Rate Dependence of the 0.2% Yield Strength of Unirradiated Inconel 718.

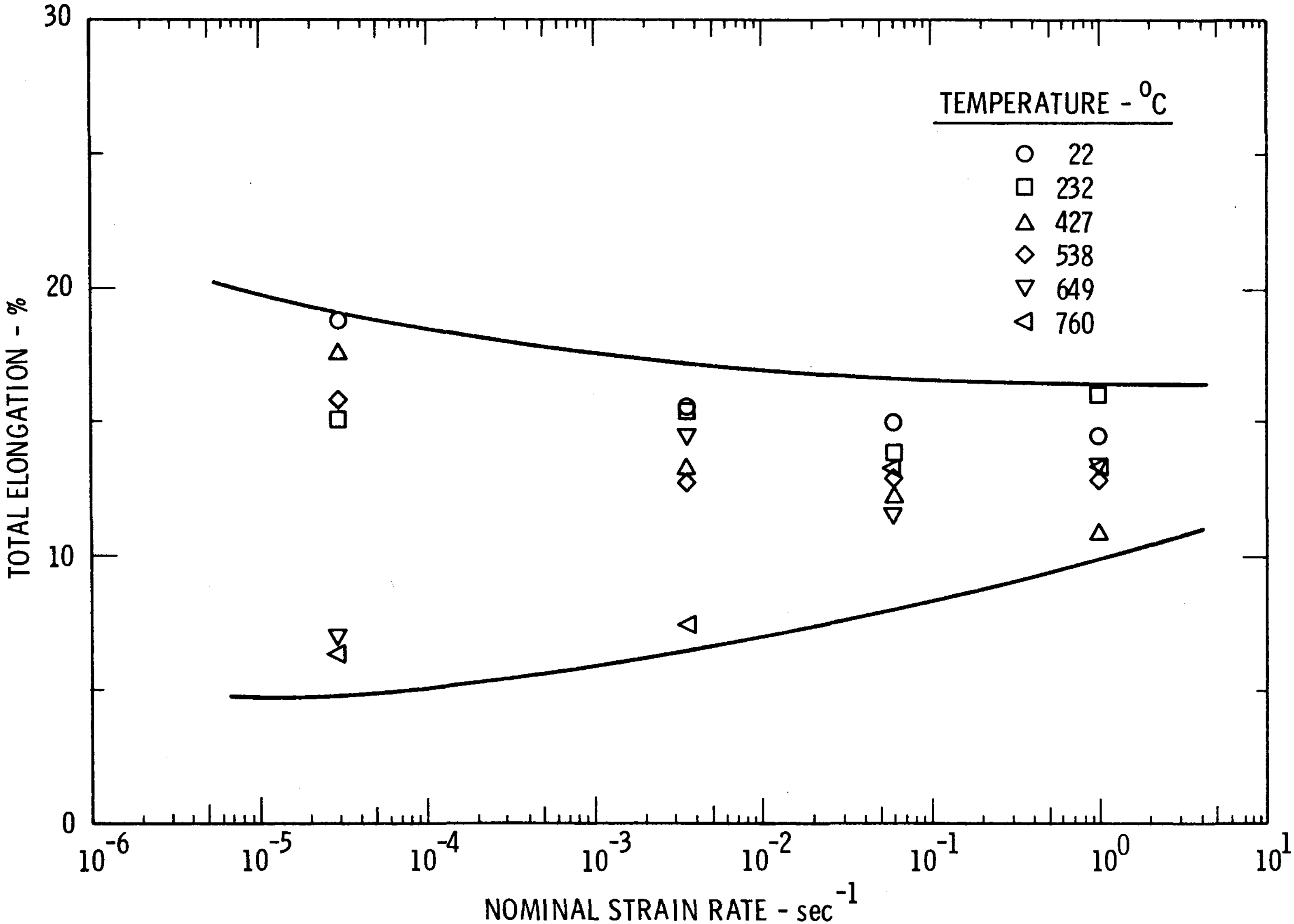

FIGURE 4. Temperature and Strain Rate Dependence of the Total Elongation of Unirradiated Inconel 718.

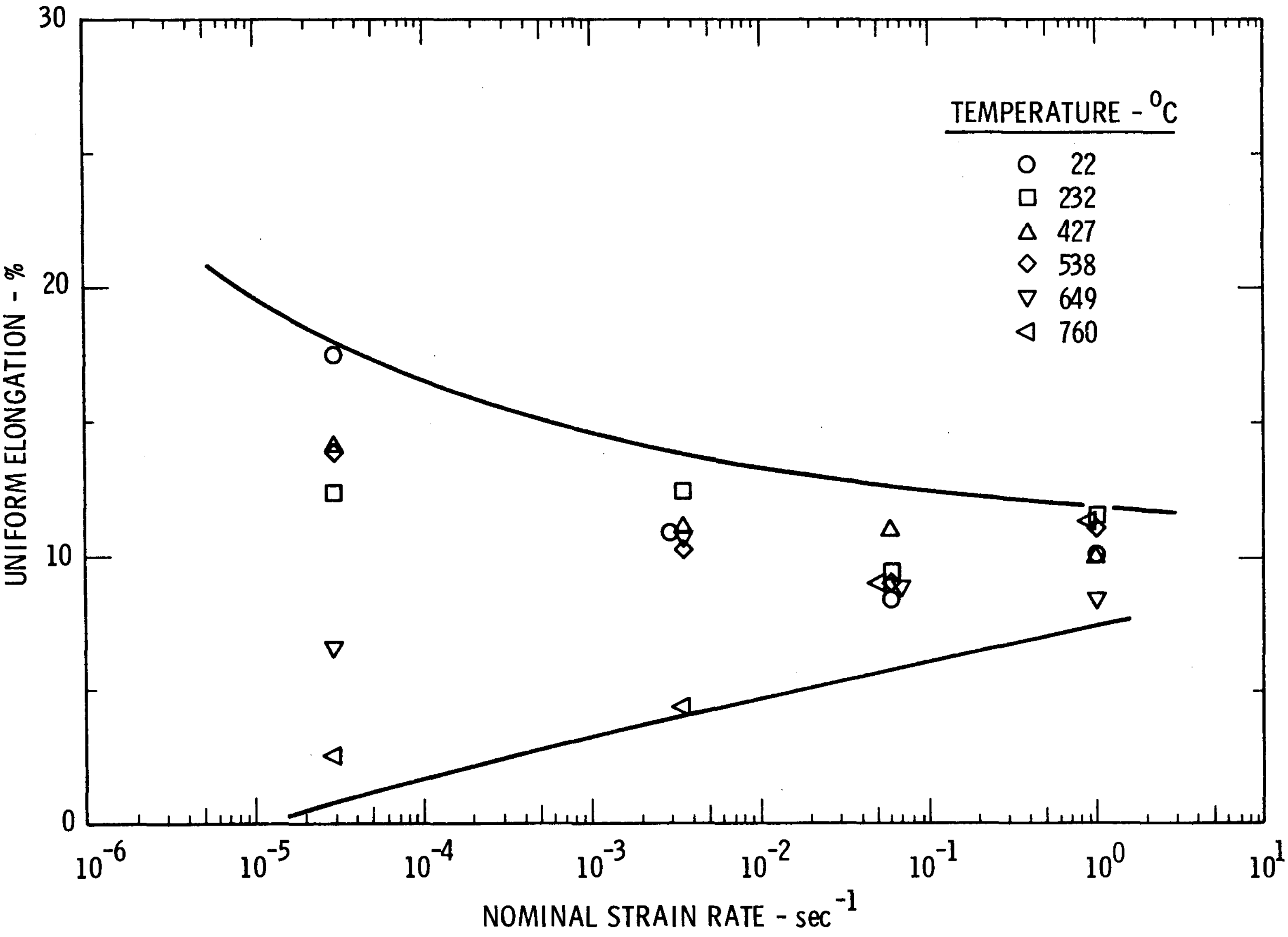

FIGURE 5. Temperature and Strain Rate Dependence of the Uniform Elongation of Unirradiated Inconel 718.

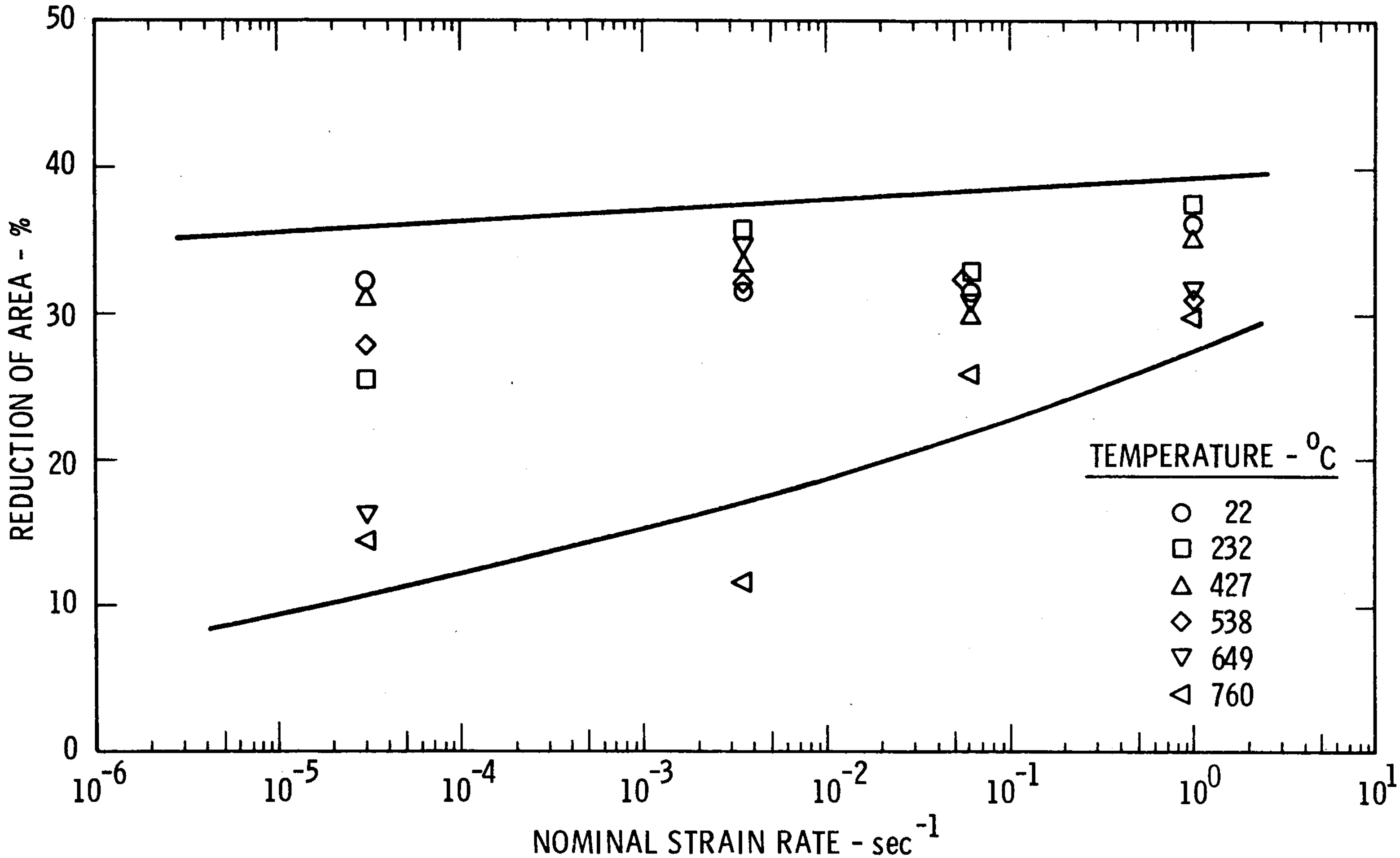

FIGURE 6. Temperature and Strain Rate Dependence of the Reduction of Area of Unirradiated Inconel 718.

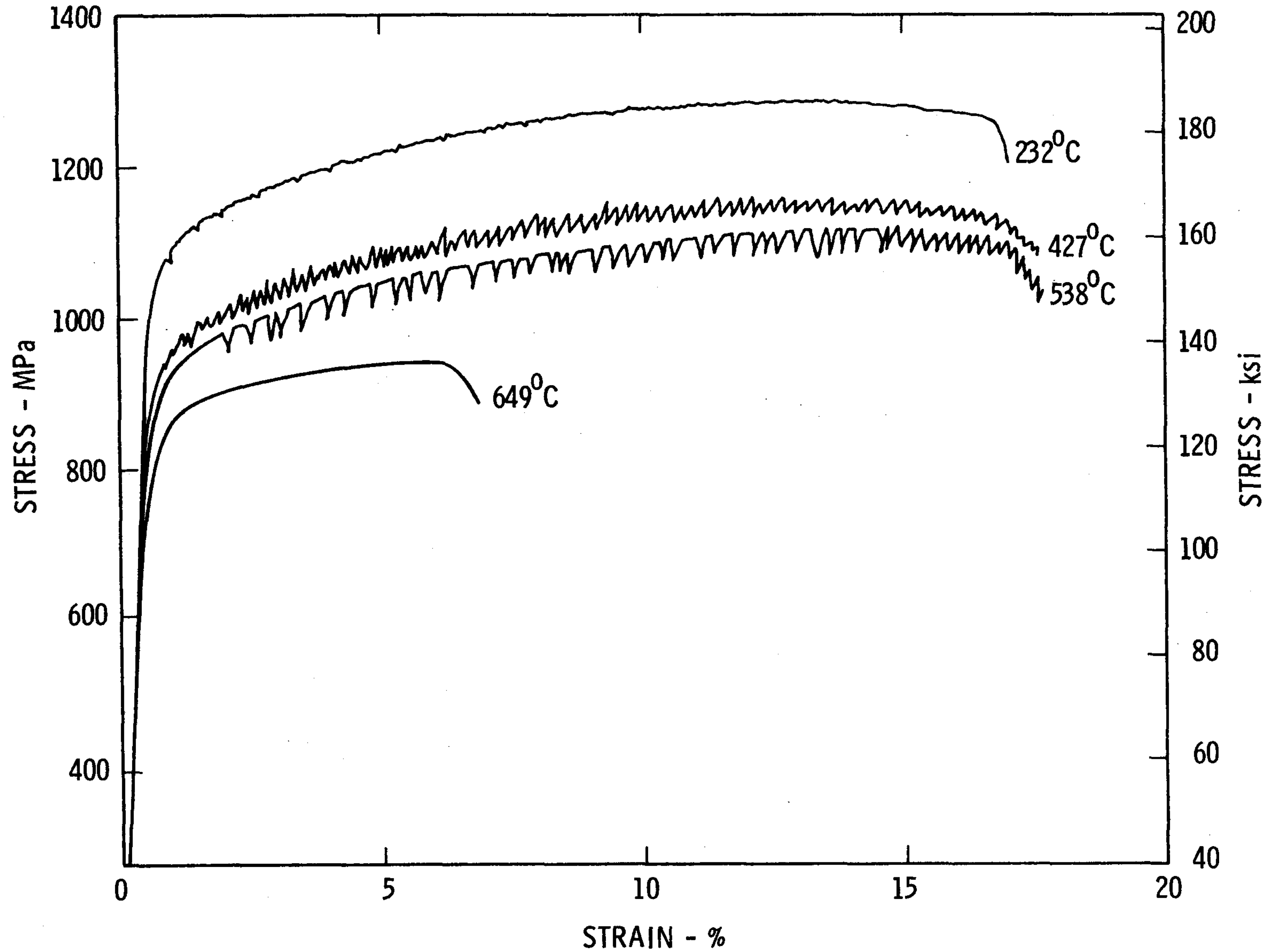

FIGURE 7. Stress-Strain Behavior of Unirradiated Inconel 718 at a Strain Rate of 3×10^{-5} sec^{-1}.

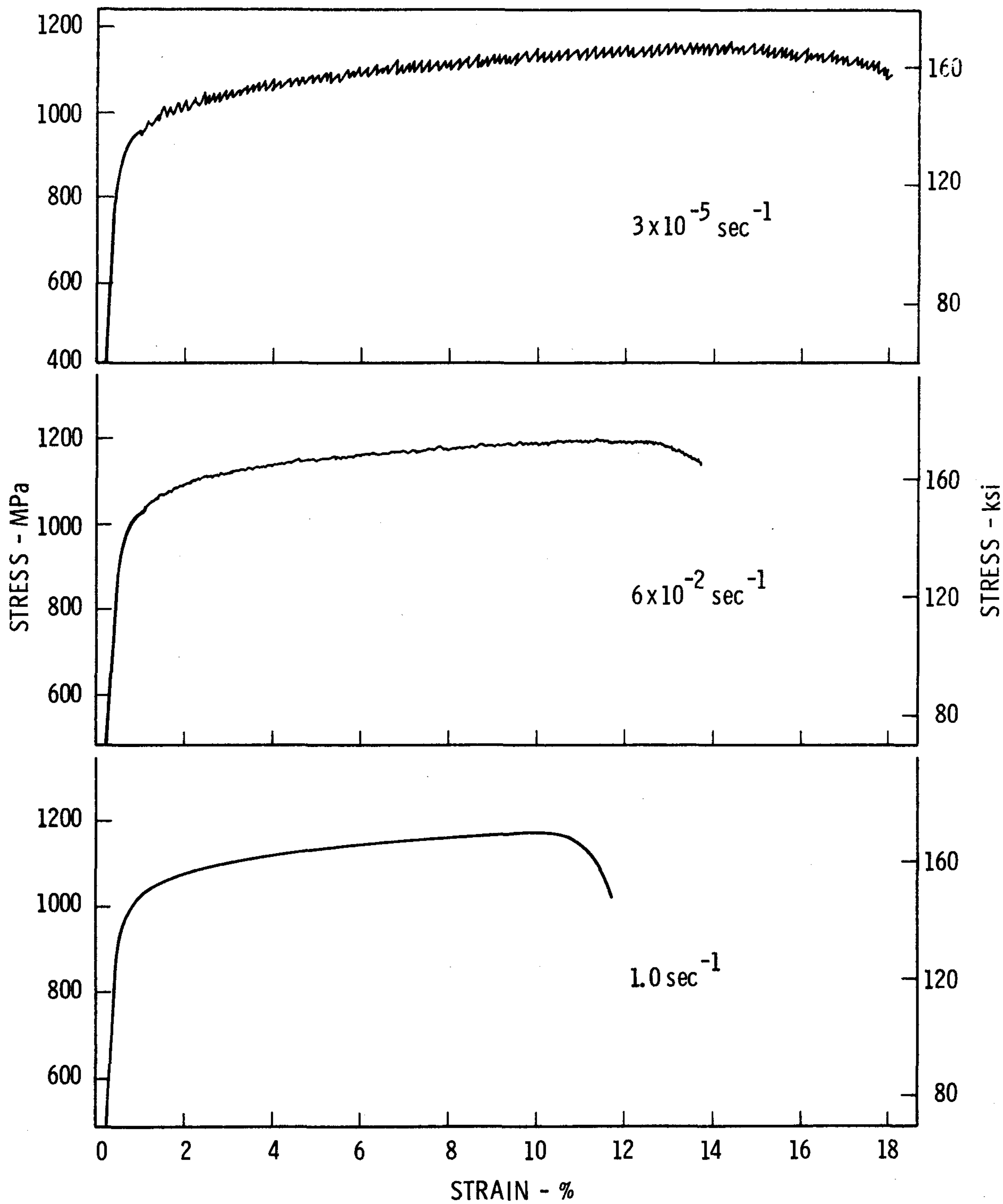

FIGURE 8. Effect of Strain Rate on the Stress-Strain Behavior of Unirradiated Inconel 718 at 427°C.

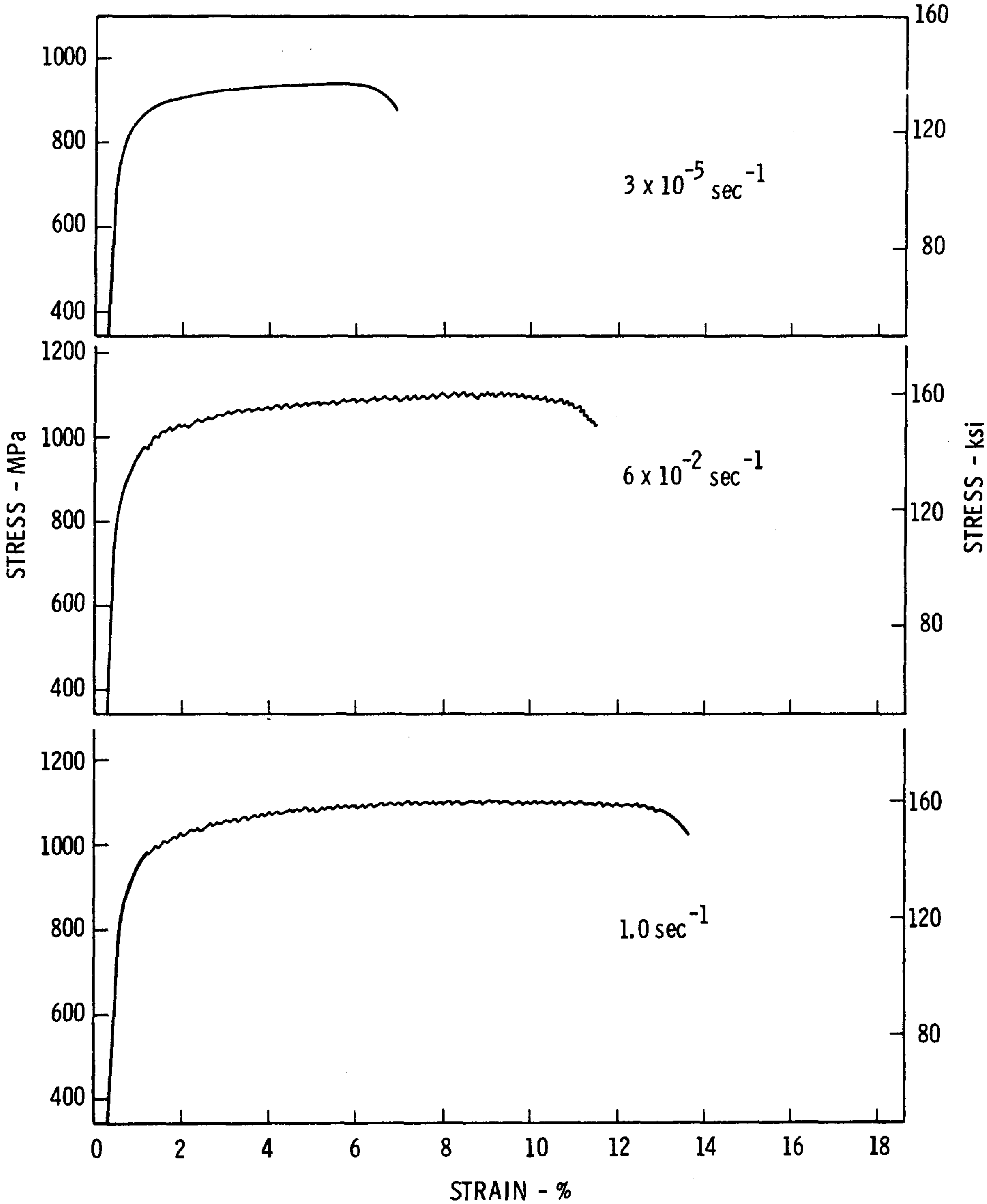

FIGURE 9. Effect of Strain Rate on the Stress-Strain Behavior of Unirradiated Inconel 718 at 649°C.

At the lowest strain rate (3×10^{-5} sec^{-1}) and 427°C, extensive serrations were observed in the stress-strain curve (Figure 8). Increasing strain rate to 6×10^{-2} sec^{-1} reduced the magnitude of the serrations, and reduced the ductility, but had little or no effect on strength properties. At a strain rate of 1.0 sec^{-1} the serrations were essentially eliminated and the total and uniform elongation values further reduced. Therefore, it is thought that the stress-strain behavior observed at 1.0 sec^{-1} would not be changed significantly by further increases in strain rate.

At 649°C, serrations were not observed at the lowest test rate (Figure 9). In this temperature-strain rate region, creep controls deformation and dynamic strain aging does not greatly influence properties. A minimal influence would be expected because the temperature is high enough and strain rate low enough to allow interstitial atoms to migrate along with dislocations [9]. As strain rate increases, the interstitial atoms retard dislocation movement. This results in the flow curve serrations observed for a rate of 6×10^{-2} sec^{-1} in Figure 9. Increasing the strain rate to 1.0 sec^{-1} produced slight serrations and total and uniform elongation values slightly greater than those observed at 6×10^{-2} sec^{-1}.

Irradiated Behavior

Test parameters for the irradiated material included temperatures from 232 to 649°C and strain rates to 1.0 sec^{-1}. However, due to the limited number of irradiated specimens the majority of testing was done at two temperatures: 232°C and at the irradiation temperature. A temperature of 232°C was employed in this evaluation because it represents the approximate refueling temperature of LMFBR's and because Inconel 718 is used in refueling equipment. Results from tensile tests conducted at a conventional strain rate on irradiated material are presented in Table III and results of the high strain tests in Table IV. Included in these tables are total and fast fluences for each of the test specimens.

The temperature dependence of the tensile properties of irradiated Inconel 718 has been reported previously [6]. Since the specimen material and irradiated experiment were identical to those of the present study, the

TABLE III

TENSILE PROPERTIES OF IRRADIATED INCONEL 718
(Annealed 1750°F/0.5 Hr. - Aged 1325°F/8 Hr. + 1150°F/10 Hr.)

Irrad. Temp. °C	Fluence- Total	10^{22}n/cm^2 E>0.1 MeV	Test Temp. °C	$\dot{\varepsilon}$- Sec^{-1}	Strength - MPa (Ksi) PEL		0.2% Yield		Ultimate		Elongation-% Total	Unif.	Reduction of Area-%	Site Sequence
391	0.93	0.80	22	3x10^{-5}	791	(114.7)	1153	(167.2)	1300	(188.5)	10.3	6.4	27.9	HO 4804
			232		803	(116.4)	1017	(147.5)	1153	(167.2)	10.5	6.9	32.8	4805
			427		818	(118.7)	1006	(145.9)	1107	(160.6)	8.4	4.0	26.8	4806
			427		695	(100.8	942	(136.6)	1121	(162.6)	8.4	5.7	26.8	4824
			538		803	(116.4)	1009	(146.3)	1118	(162.2)	4.1	2.7	11.5	4807
			649								0.7	0.7	2.5	--
404	0.55	0.41	22	3x10^{-5}	796	(115.4)	1027	(149.0)	1245	(180.5)	17.2	12.8	35.8	4808
			232		859	(124.6)	1021	(148.1)	1255	(182.0)	17.8	14.4	32.8	4809
			427		661	(95.9)	897	(130.1)	1107	(160.6)	19.3	14.3	26.8	4810
			538		616	(89.4)	884	(128.2)	1071	(155.3)	12.8	11.2	17.1	4811
			649		622	(90.2)	797	(115.6)	879	(127.5)	6.1	4.7	11.5	4861
593	0.86	0.71	22	3x10^{-5}	656	(95.1)	910	(132.0)	1305	(189.3)	24.5	21.3	38.5	4818
	0.86	0.71	232		610	(88.5)	814	(118.0)	1160	(168.2)	24.4	22.3	30.3	4819
	0.98	0.86	232		616	(89.4)	863	(125.2)	1208	(175.2)	21.7	18.9	33.3	4822
	0.98	0.85	427		701	(101.6)	854	(123.8)	1136	(164.7)	21.4	17.4	27.9	4851
	0.98	0.85	538		644	(93.4)	814	(118.0)	1086	(157.3)	18.1	17.0	22.1	4852
	0.86	0.71	593		587	(85.2)	769	(111.5)	968	(140.4)	9.0	8.1	18.0	4820
	0.94	0.81	593		678	(98.4)	832	(120.7)	1039	(150.7)	7.7	7.4	13.1	4850
	0.98	0.86	593		599	(86.9)	812	(117.8)	1027	(149.0)	9.4	8.7	9.0	4823
	0.86	0.71	649		554	(80.3)	738	(107.1)	825	(119.7)	4.4	3.2	7.3	4821
593	1.78	1.30	22	3x10^{-5}	628	(91.1)	914	(132.5)	1281	(185.8)	21.2	19.5	29.3	4843
	2.44	1.96	232		718	(104.1)	912	(132.3)	1232	(178.7)	20.3	18.7	25.2	4841
	2.44	1.96	427		746	(108.2)	893	(129.5)	1140	(166.8)	18.1	15.8	22.1	4915
	1.78	1.30	538		684	(99.2)	841	(122.0)	1080	(156.7)	14.6	13.2	17.1	4857
	2.44	1.96	593		658	(95.5)	877	(127.2)	1029	(149.2)	5.5	5.0	1.6	4838
	1.78	1.30	649		656	(95.1)	791	(114.7)	838	(121.6)	2.5	2.3	0.8	4840
649	3.13	2.65	22	3x10^{-5}	712	(103.3)	996	(144.4)	1274	(184.8)	17.0	12.7	28.7	4844
	3.13	2.65	232		718	(104.1)	910	(132.0)	1232	(178.7)	20.3	18.7	25.2	4842
	3.13	2.65	427		684	(99.2)	946	(137.0)	1191	(172.8)	16.0	14.3	19.5	4839
	3.26	2.77	538		--		--		--		3.1	3.1	4.1	--
	3.13	2.65	649		650	(94.3)	866	(125.6)	945	(137.1)	1.7	1.6	3.2	4914
	3.34	2.89	649		847	(122.9)	877	(127.2)	877	(127.2)	0.3	0.3	2.4	4913
	3.42	2.98	649		684	(99.2)	850	(123.3)	850	(123.3)	0.1	0.1	0.8	4912

TABLE IV

HIGH STRAIN RATE TENSILE PROPERTIES OF IRRADIATED INCONEL 718

Irrad. Temp. °C	Fluence-Total	10^{22} n/cm^2 E>0.1 MeV	Test Parameters Temp. °C	$\dot{\varepsilon}$ -Sec^{-1}	Strength - MPa (Ksi) PEL	0.2% Yield	Ultimate	Elongation-% Total	Unif.	Reduction of Area-%	Site Sequence
396	0.86	0.71	232	7.4×10^{-3}	803 (116.4)	1014 (147.0)	1170 (169.7)	7.2	5.9	26.2	HO 4847
	0.86	0.71	427		780 (113.1)	982 (142.5)	1081 (156.8)	5.7	4.4	28.7	4848
	0.86	0.71	649		960 (139.3)	982 (142.4)	1001 (145.2)	3.9	3.2	14.7	4860
396	0.86	0.71	232	1.0	1042 (151.2)	1135 (164.6)	1253 (181.7)	9.6	5.7	30.9	4905
	0.93	0.80	427		925 (134.1)	1051 (152.4)	1135 (164.6)	5.8	3.6	18.7	4904
	0.86	0.71	649		834 (120.9)	989 (143.4)	1011 (146.7)	4.7	3.8	27.9	4906
593	0.94	0.81	232	7.4×10^{-3}	667 (96.7)	845 (122.5)	1164 (168.8)	17.0	15.6	27.9	4849
	0.94	0.81	593		622 (90.2)	801 (116.2)	1038 (150.6)	13.2	13.2	22.1	4846
	0.96	0.83	649		650 (94.3)	823 (119.3)	1044 (151.4)	10.2	10.2	18.7	4845
593	0.98	0.86	232	1.0	840 (121.9)	950 (137.8)	1228 (178.1)	16.8	14.1	41.3	4894
	0.97	0.84	538		729 (105.7)	827 (120.0)	1074 (155.7)	16.5	13.3	24.6	4897
	0.98	0.86	593		791 (114.7)	859 (124.6)	1057 (153.3)	18.0	16.2	24.6	4895
	0.97	0.84	649		803 (116.4)	851 (123.4)	1037 (150.4)	12.6	12.0	18.9	4896
593	1.48	0.99	232	7.4×10^{-3}	757 (109.8)	900 (130.5)	1219 (176.8)	16.7	15.5	35.0	4858
	2.44	1.96	593		791 (114.7)	904 (131.1)	1107 (160.6)	12.5	10.7	23.8	4856
	1.48	0.99	649		672 (97.5)	801 (116.2)	994 (144.2)	7.7	7.6	11.5	4859
593	1.36	0.88	232	1.0	820 (118.9)	897 (130.1)	1185 (171.9)	19.5	16.9	39.0	4902
	1.48	0.99	593		780 (113.1)	853 (127.3)	1011 (146.7)	14.2	10.6	32.0	4901
	1.25	0.80	649		603 (87.4)	729 (105.7)	989 (143.5)	19.0	19.0	26.8	4903
649	3.34	2.89	232	7.4×10^{-3}	925 (134.1)	1087 (157.7)	1289 (181.0)	10.9	9.1	22.8	4854
	3.34	2.89	649		791 (114.7)	955 (138.5)	1094 (158.6)	6.4	4.8	13.1	4853
649	3.34	2.89	232	1.0	989 (143.4)	1108 (160.7)	1274 (184.8)	12.5	9.4	28.7	4898
	3.42	2.98	538		847 (122.9)	989 (143.4)	1173 (170.1)	11.1	8.1	27.9	4900
	3.42	2.98	649		855 (124.0)	1009 (146.3)	1152 (167.1)	8.7	8.0	13.3	4899

available data provided results for this study at the lowest strain rate of interest, 3×10^{-5} sec^{-1}. As shown in Reference 6, the ultimate and 0.2% yield strengths were not greatly affected by neutron irradiation at test temperatures to 649°C. However, there was a consistent trend toward slightly lower 0.2% yield strength at each test temperature for specimens irradiated at temperatures of 593 and 649°C. Since Inconel 718 is generally considered metallurgically stable at these temperatures for the time under irradiation (slightly less than 4000 hours) [10], it is possible that irradiation has enhanced the thermal overaging process thus resulting in the slight softening.

Consistent with the reduced 0.2% yield strengths, the ductility of irradiated material was slightly higher than unirradiated material for test temperatures to 538°C [6]. As temperature is increased above 538°C the ductility is severely reduced and approached 2 per cent and less. This decrease has been attributed to helium embrittlement [6].

The effect of strain rate on the tensile properties of irradiated Inconel 718 is illustrated in Figures 10-14. In each figure, data are presented for test temperatures of 232, 538, 593, and 649°C. Data from unirradiated materials (closed symbols) are included for comparison. The effect of strain rate on the ultimate strength is illustrated in Figure 10. For all irradiation and test conditions, the strength of irradiated material is very similar to that of the unirradiated material and the strain rate dependencies are nearly identical. Similar behavior is observed for the 0.2% yield strength as shown in Figure 11.

The strain rate dependence of the total and uniform elongation and reduction of area of irradiated material is presented in Figures 12, 13 and 14, respectively. For all test temperatures presented, the strain rate dependence of irradiated material approximates that for unirradiated material. Of significance is the fact that for test temperatures of 593 and 649°C, all ductility parameters increase with increasing strain rate.

To illustrate the effect of strain rate on the tensile properties of irradiated material, results from tests where the irradiation and test temperature were essentially identical are presented in Figure 15. Data are

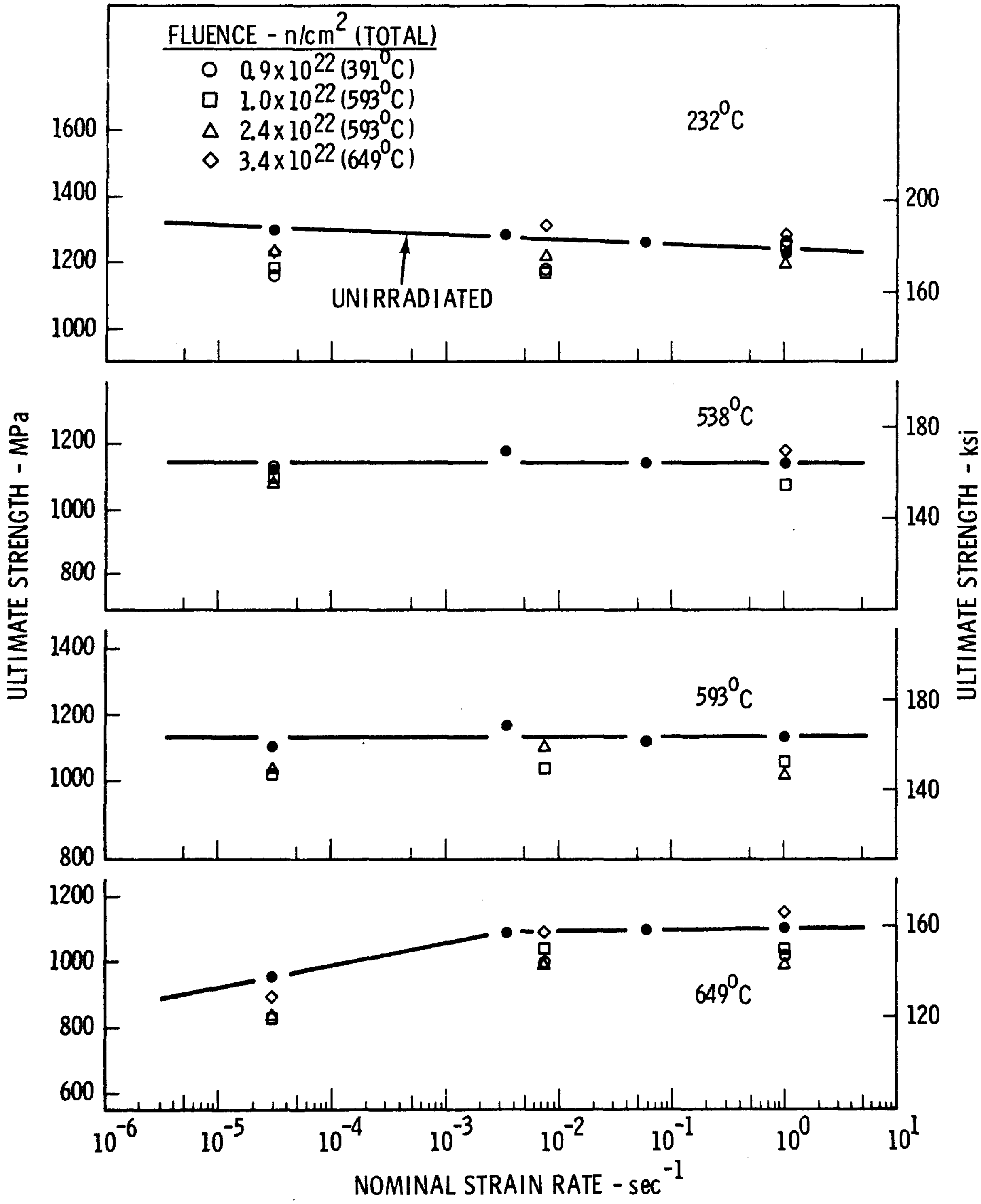

FIGURE 10. Strain Rate Dependence of the Ultimate Strength of Irradiated Inconel 718.

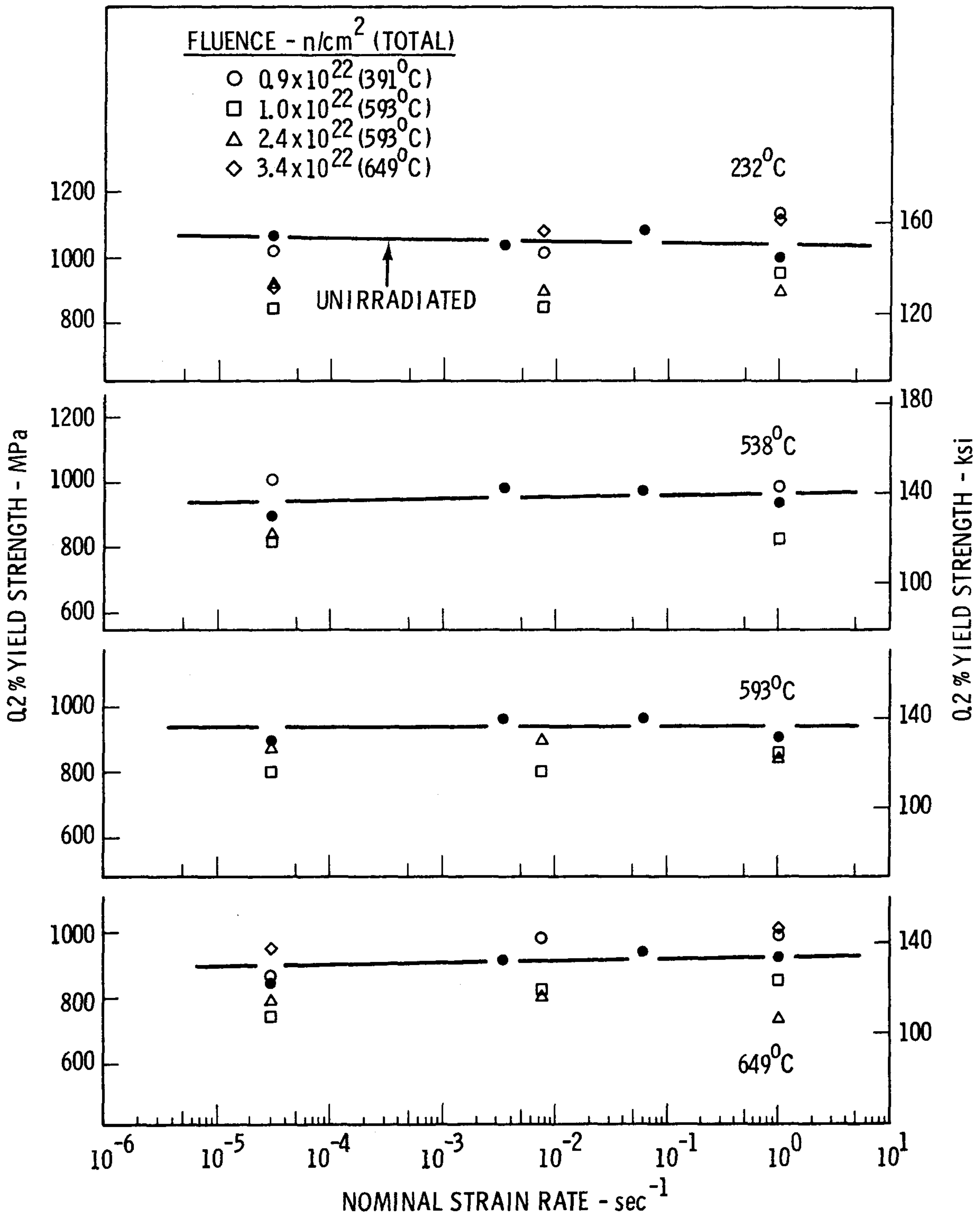

FIGURE 11. Strain Rate Dependence of the 0.2% Yield Strength of Irradiated Inconel 718.

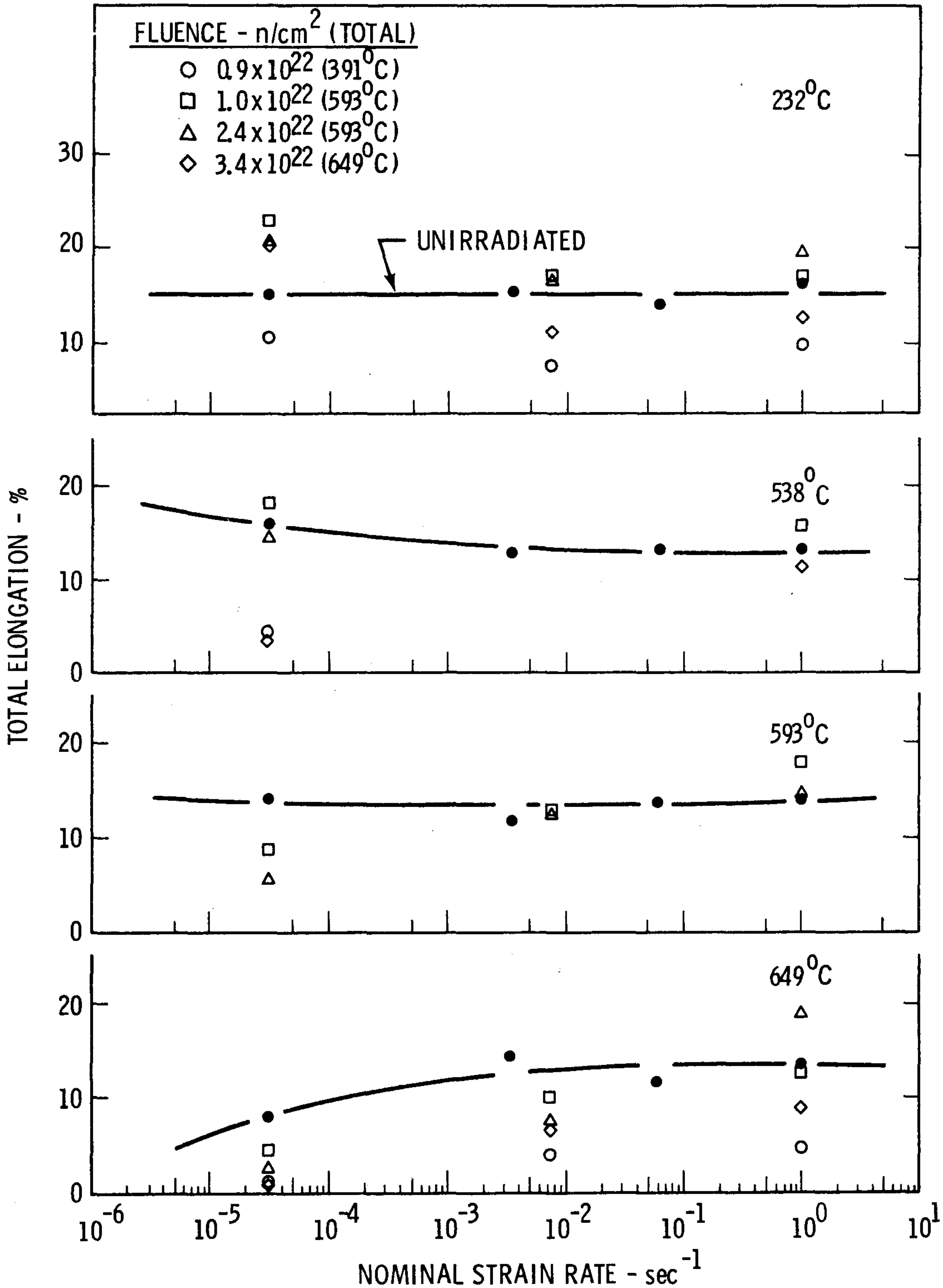

FIGURE 12. Strain Rate Dependence of the Total Elongation of Irradiated Inconel 718.

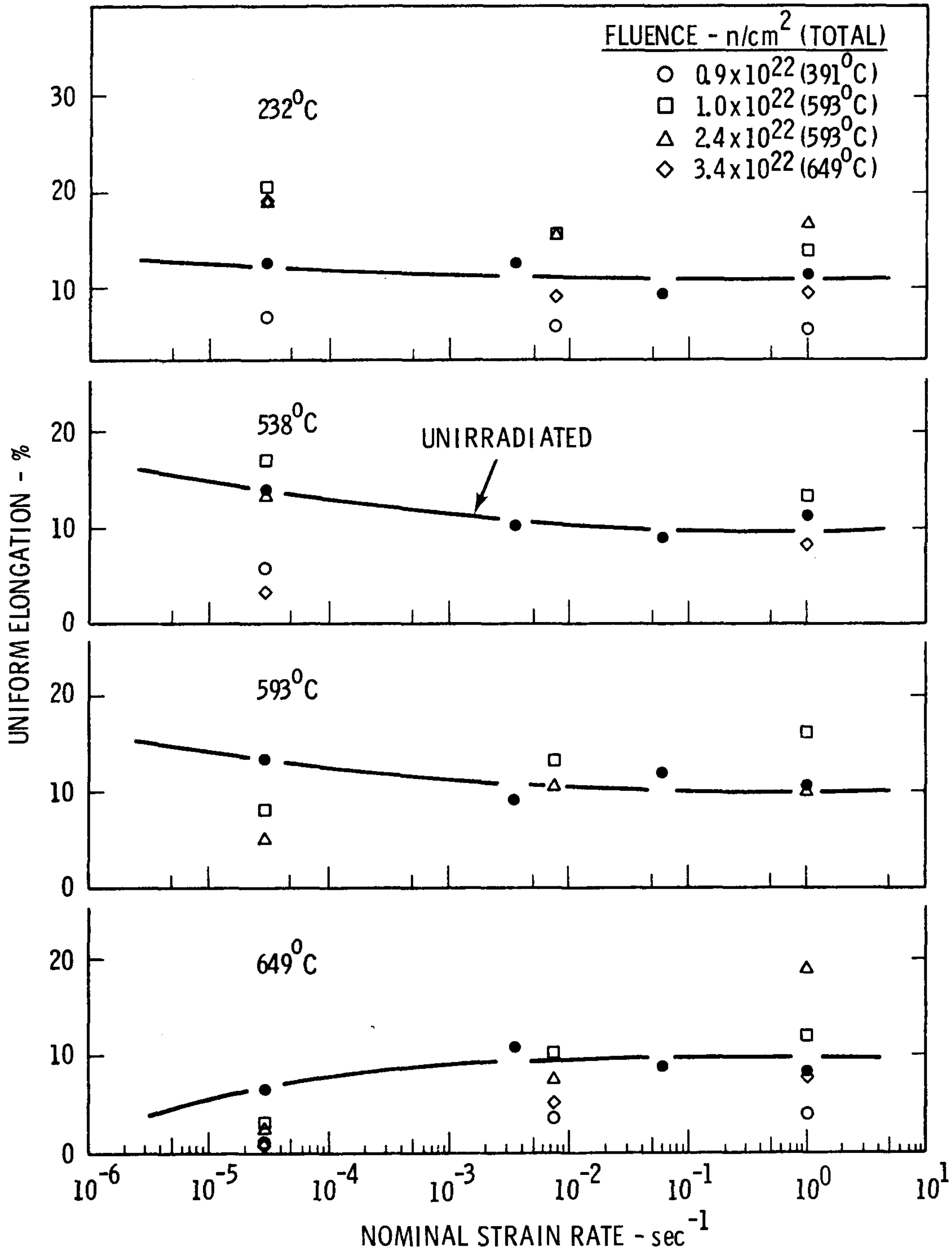

FIGURE 13. Strain Rate Dependence of the Uniform Elongation of Irradiated Inconel 718.

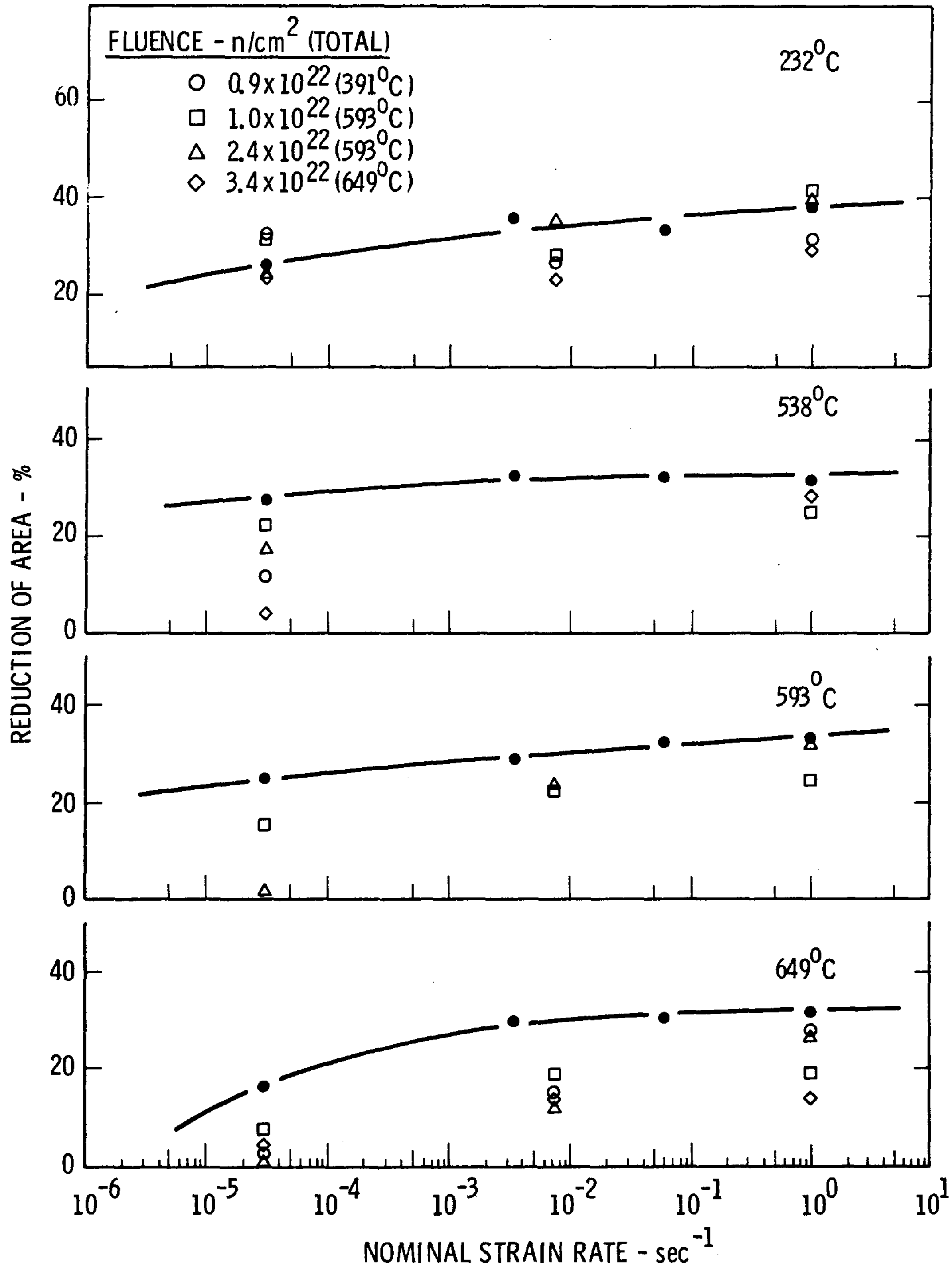

FIGURE 14. Strain Rate Dependence of the Reduction of Area of Irradiated Inconel 718.

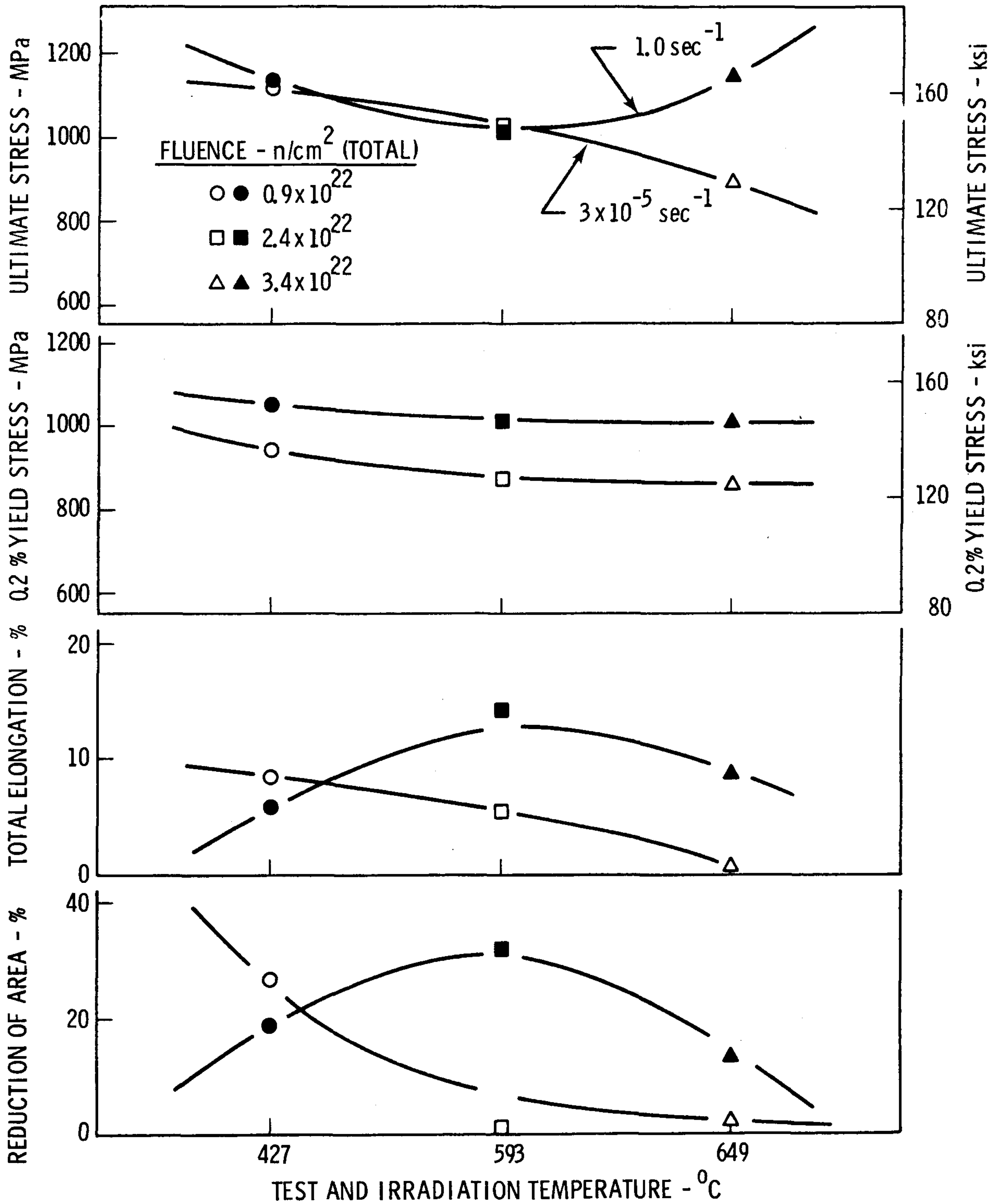

FIGURE 15. Tensile Properties of Irradiated Inconel 718 for Tests at the Irradiation Temperature.

included for two strain rates, 3×10^{-5} and 1.0 sec^{-1}. For irradiation and test temperatures of 427 and 593°C the ultimate strengths are identical between the two rates. At 649°C the ultimate strength is significantly higher at the higher strain rate. For each temperature the 0.2% yield strength is increased by increasing strain rate. Total elongation and reduction of area are decreased slightly at the highest strain rate at 427°C and significantly increased at the same strain rate at temperatures of 593 and 649°C. These trends are comparable with those of unirradiated material (Figure 16).

At irradiation temperatures of $\sim$400 and 593°C specimens were exposed to different fluence levels thus allowing a comparison of strain rate effects at various fluences. For the lower irradiation (400°C) and test temperature (427°C) the ultimate strength appeared to decrease slightly with increasing fluence and no effect of strain rate was observed (Figure 17). The 0.2% yield strength slightly increased with fluence and increasing strain rate. Total elongation and reduction of area decreased with increasing fluence. The effect of increasing strain rate on the ductility properties was to decrease total elongation with little effect on reduction of area.

At an irradiation and test temperature of 593°C, little effect of increasing fluence or strain rate on strength properties was observed (Figure 18). Conversely, significant effects of both strain rate and fluence on total elongation and reduction of area were observed. At the lowest strain rate, both ductility properties decreased significantly with increasing fluence. Increasing strain rate to 1.0 sec^{-1} resulted in ductility of the irradiated material nearly identical to that of unirradiated material. Although uniform elongation data are not presented in this figure or Figure 17, the trends are consistent with total elongation behavior.

Since the strain rate dependence of the tensile properties of irradiated material was essentially identical to that for the unirradiated material, it appears that irradiation does not greatly alter the mechanisms controlling deformation in Inconel 718. Evidence to support this fact was obtained from the autographic records of the tests on irradiated materials.

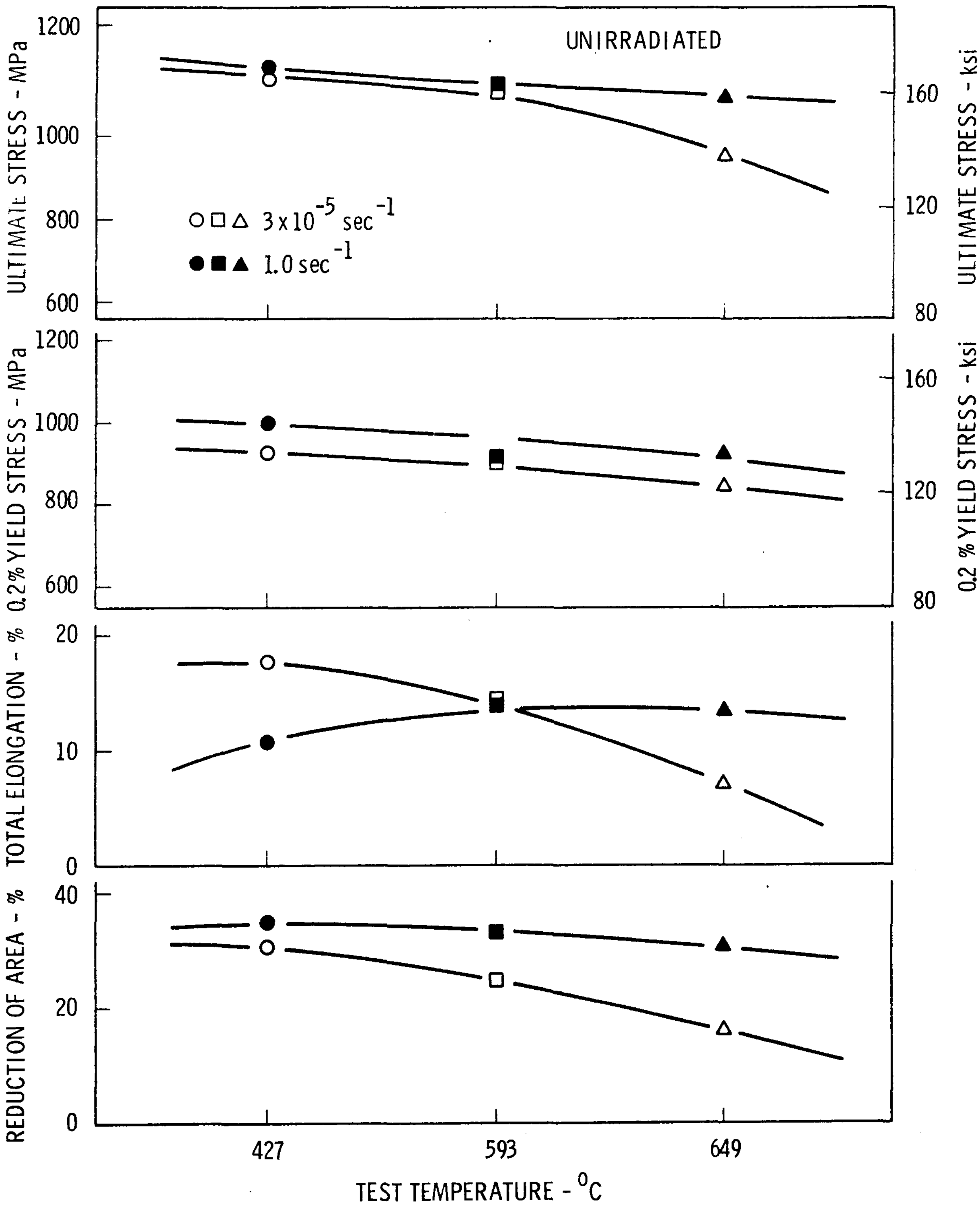

FIGURE 16. Tensile Properties of Unirradiated Inconel 718 at Temperatures of 427, 593, and 649°C.

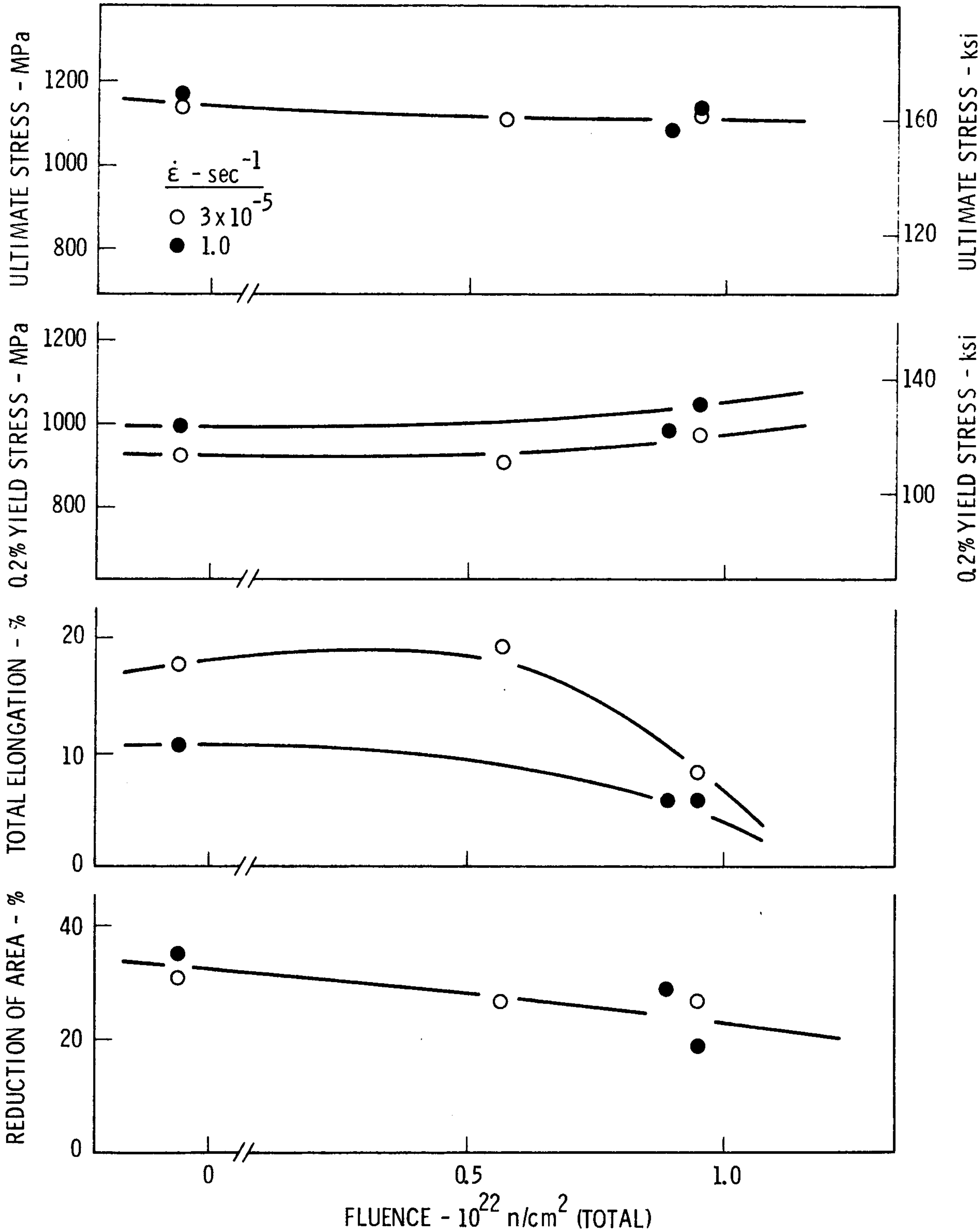

FIGURE 17. Effect of Fluence and Strain Rate on the Tensile Properties of Irradiated Inconel 718 -- Irradiated at ∿ 400°C and Tested at 427°C.

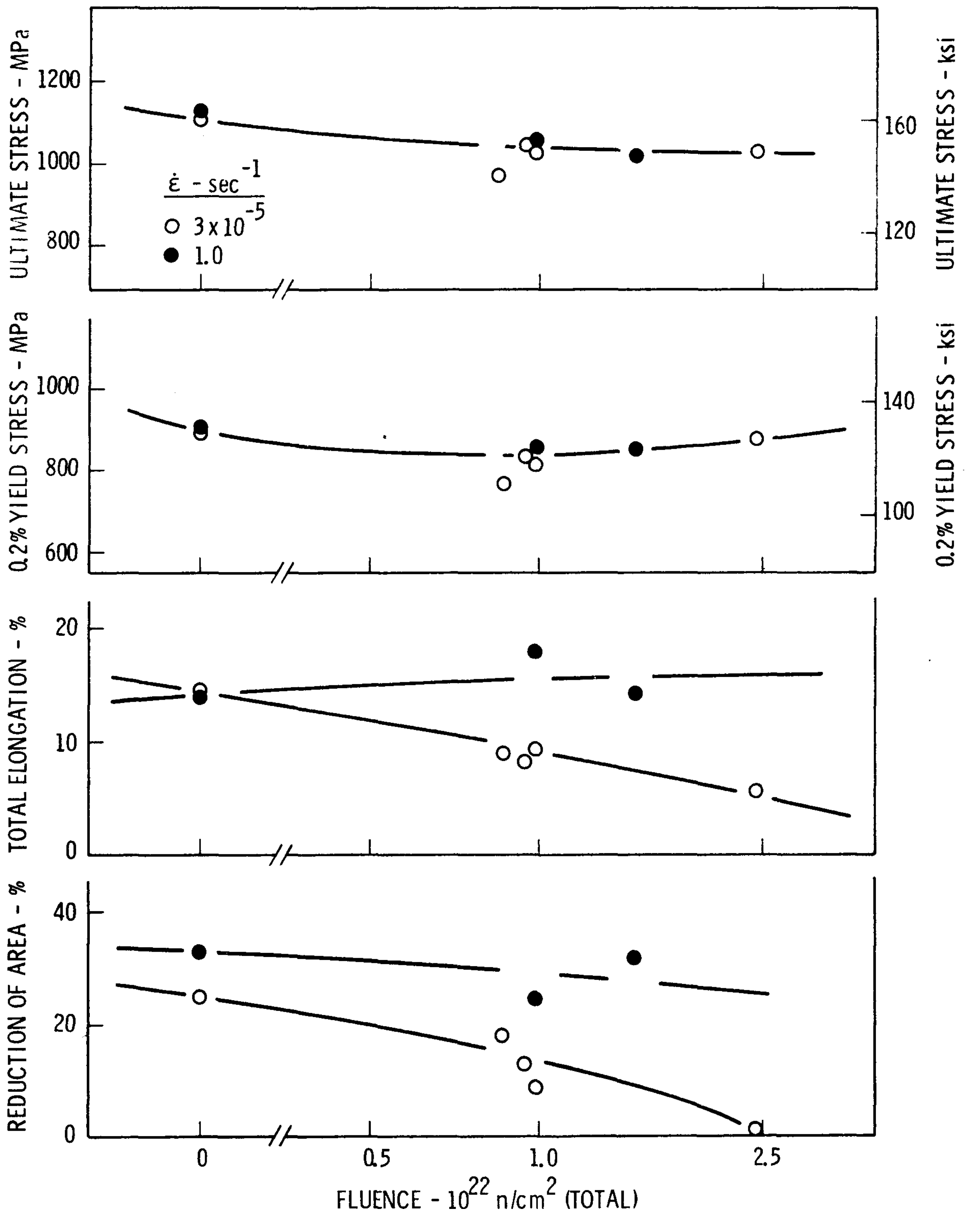

FIGURE 18. Effect of Fluence and Strain Rate on the Tensile Properties of Irradiated Inconel 718 -- Irradiated and Tested at 593°C.

Serrations were observed at the various test temperatures with similar shapes and magnitudes as compared to those in Figure 7. Also, increasing strain rate resulted in behavior of irradiated material which was consistent with that presented in Figure 8 for unirradiated material.

SUMMARY AND CONCLUSIONS

In the present study the effect of strain rate on the elevated temperature tensile properties of unirradiated and irradiated Inconel 718 were determined. Irradiation conditions included total neutron fluences to 1.0 x 10^{22} n/cm^2 at 400°C, to 2.4 x 10^{22} n/cm^2 at 593°C, and 3.4 x 10^{22} n/cm^2 at 649°C. Test parameters included temperatures to 649°C and strain rates to 1.0 sec^{-1}. The following conclusions can be made regarding the results of this study:

- The strength and ductility of unirradiated Inconel 718 are insensitive to strain rate for temperatures to 538°C. At temperatures above 538°C both properties significantly increased with strain rate.
- Neutron irradiation at $\sim$400°C did not alter this behavior since postirradiation properties were essentially unaffected by increasing strain rate.
- At irradiation temperatures of 593°C and above, strength properties were essentially consistent with unirradiated behavior. Ductility parameters were unaffected by strain rate for temperatures to 538°C. At higher temperatures ductility increased significantly with strain rate and approached unirradiated values.
- The severe ductility losses observed in all irradiated specimens at the lowest test rate (3 x 10^{-5} sec^{-1}) and higher test temperatures (593°C and above) is believed to result from helium embrittlement.

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