# Relationship of Mechanical Characteristics and Microstructural Features to the Time-Dependent Edge-Notch Sensitivity of Inconel 718 Sheet

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*Time-dependent notch sensitivity of Inconel 718 sheet was observed at 900 deg F to 1200 deg F (482–649 deg C). It occurred when edge-notched specimens were loaded below the yield strength and smooth specimen tests showed that small amounts of creep consumed large rupture life fractions. The severity of the notch sensitivity was reduced by decreasing the temperature of the solution treatments, increasing the time and/or temperature of aging and increasing the test temperature to 1400 deg F (760 deg C). Elimination of time-dependent notch sensitivity correlated with a change in dislocation motion mechanism from shearing to bypassing precipitate particles.*

## Introduction

The results presented were derived from a study of the severe time-dependent edge-notch sensitivity that has been observed for nickel-base superalloy sheet materials at temperatures from 900 to 1300 deg F (482–704 deg C). The research was carried out at The University of Michigan, Ann Arbor, Mich., under sponsorship of the National Aeronautics and Space Administration.

Extensive research [1, 2][1] established the scope and the cause of the problem for Waspaloy. In addition, heat treatments were defined which eliminated the time-dependent notch sensitivity. Continuing research is directed at broadening the applicability of the concepts developed for Waspaloy. To achieve this, the study is being extended to include other alloys. Reported are results obtained for Inconel 718. The composition of this alloy differs from that of Waspaloy. Of major significance, columbium is present in Inconel 718 but not in Waspaloy. This element has a marked influence on phase relationships and hence, on the metallurgical characteristics.

As part of an evaluation of the potential usefulness of sheet superalloys for air frame skin applications, Inconel 718 in three heat treated conditions was shown to exhibit time-dependent notch sensitivity at 1000 and 1200 deg F (538 and 649 deg C) [3]. The research presently reported was designed to extend the scope of these initial results. Heat treatments were selected to provide a wide range of microstructural features and mechanical characteristics. Tensile and creep-rupture tests of smooth and sharp-edged ($K_t > 20$) notched specimens were conducted at temperatures from 900 to 1400 deg F (482–760 deg C). The microstructural features, particularly the dislocation mechanisms in the tested specimens, were evaluated.

## Experimental Details

The Inconel 718 used in the investigation had the following reported composition (weight percent):

| Ni | C | Mn | Fe | S | Si | Cr |
|---|---|---|---|---|---|---|
| 53.97 | 0.05 | 0.12 | 16.50 | 0.007 | 0.22 | 18.98 |

| Al | Ti | Co | Mo | Cb | B |
|---|---|---|---|---|---|
| 0.52 | 01.4 | 0.05 | 3.15 | 5.25 | 0.002 |

The material was received as 0.030-in. (0.75 mm) thick cold reduced sheet. Specimen blanks were cut in the longitudinal direction prior to heat treatment as follows:

| | Solution treatment | | Aging treatment |
|---|---|---|---|
| 1 | 10 hr at 1950°F(1066°C) | + | 48 hr at 1350°F(732°C) |
| 2 | 1 hr at 1950°F(1066°C) | + | 48 hr at 1350°F(732°C) |
| 3 | 1 hr at 1950°F(1066°C) | + | 2 hr at 1550°F(843°C) |
| 4 | 1 hr at 1950°F(1066°C) | + | 24 hr at 1550°F(843°C) |
| 5 | 10 hr at 1800°F(982°C) | + | 48 hr at 1350°F(732°C) |
| 6 | 10 hr at 1700°F(927°C) | + | 3 hr at 1325°F(718°C) |
| 7 | 10 hr at 1700°F(927°C) | + | 48 hr at 1350°F(732°C) |
| 8 | 1 hr at 1700°F(927°C) | + | 3 hr at 1325°F(718°C) |
| 9 | 1 hr at 1700°F(927°C) | + | 2 hr at 1550°F(843°C) |

[1]Numbers in brackets designate References at end of paper.

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**Table 1 Tensile properties of 0.030 in. (0.75 mm) thick Inconel 718 sheet at 1000 deg and 1200 deg (538 deg and 649 deg C)**

| Heat Treatment | Smooth Specimen Properties: Test Temperature (°F) | Test Temperature (°C) | Tensile Strength (ksi) | Tensile Strength (MN/m²) | 0.2% Offset Yield Strength (ksi) | 0.2% Offset Yield Strength (MN/m²) | Y.S./T.S. | Elong. (%) | R.A. (%) | Notched Tensile Strength (ksi) | Notched Tensile Strength (MN/m²) | N/S Tensile Strength Ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 hrs. at 1950°F (1066°C) | 1000 | 538 | 145.4 | 1002 | 118.2 | 817 | 0.82 | 15.4 | 23 | 149.0 | 1027 | 1.02 |
| + 48 hrs. at 1350°F (732°C) | 1200 | 649 | 142.4 | 982 | 116.5 | 803 | 0.82 | 8.1 | 14 | 135.3 | 933 | 0.95 |
| 1 hr. at 1950°F (1066°C) | 1000 | 538 | 160.1 | 1104 | 129.5 | 893 | 0.81 | 22.5 | 30 | 152.4 | 1051 | 0.95 |
| + 48 hrs. at 1350°F (732°C) | 1200 | 649 | 157.5 | 1086 | 130.5 | 900 | 0.83 | 8.4 | 14 | 147.5 | 1017 | 0.94 |
| 1 hr. at 1950°F (1066°C) | 1000 | 538 | 134.9 | 930 | 90.5 | 624 | 0.67 | 27.0 | 34 | 113.6 | 783 | 0.84 |
| + 2 hrs. at 1550°F (843°C) | 1200 | 649 | 133.4 | 920 | 99.5 | 686 | 0.75 | 11.3 | 18 | 116.0 | 800 | 0.87 |
| 1 hr. at 1950°F (1066°C) | 1000 | 538 | 134.2 | 925 | | | | 32.8 | 30 | 102.1 | 704 | 0.76 |
| + 24 hrs. at 1550°F (843°C) | 1200 | 649 | 132.6 | 914 | 83.5 | 576 | 0.63 | 14.6 | 17 | 108.0 | 745 | 0.81 |
| 10 hrs. at 1800°F (982°C) | 1000 | 538 | 162.0 | 1117 | 122.0 | 841 | 0.75 | 19.6 | 23 | 135.9 | 937 | 0.84 |
| + 48 hrs. at 1350°F (732°C) | 1200 | 649 | 147.6 | 1018 | 120.5 | 831 | 0.82 | 16.7 | 15 | 140.8 | 971 | 0.95 |
| 10 hrs. at 1700°F (927°C) + 3 hrs. at 1325°F (718°C) | 1000 | 538 | 157.5 | 1086 | 116.0 | 800 | 0.75 | 15.5 | 24 | | | |
| 10 hrs. at 1700°F (927°C) | 1000 | 538 | 166.0 | 1144 | 116.5 | 803 | 0.71 | 15.9 | 23 | 125.1 | 863 | 0.75 |
| + 48 hrs. at 1350°F (732°C) | 1200 | 649 | 143.7 | 991 | 115.5 | 786 | 0.80 | 16.8 | 26 | 138.1 | 952 | 0.96 |
| 1 hr. at 1700°F (927°C) | 1000 | 538 | 165.2 | 1139 | 135.0 | 931 | 0.82 | 12.9 | 27 | 154.9 | 1068 | 0.94 |
| + 3 hrs. at 1325°F (718°C) | 1200 | 649 | 160.2 | 1105 | 136.0 | 938 | 0.85 | 8.3 | 22 | 140.3 | 967 | 0.88 |
| 1 hr. at 1700°F (927°C) | 1000 | 538 | 149.0 | 1027 | 101.5 | 700 | 0.68 | 19.8 | 27 | 121.9 | 841 | 0.82 |
| + 2 hrs. at 1550°F (843°C) | 1200 | 649 | 135.4 | 934 | 103.0 | 710 | 0.76 | 14.2 | 20 | 121.2 | 836 | 0.89 |

## Table 2 Smooth specimen creep-rupture properties at 900 deg to 1400 deg F (482–760 deg C)

| Heat Treatment | Test Temperature (°F) | Test Temperature (°C) | Stress (ksi) | Stress (MN/m²) | Rupture Time (hrs.) | Elong. (%) | R.A. (%) | Min. Creep Rate (% / hr.) | Intergranular Crack Length (%) |
|---|---|---|---|---|---|---|---|---|---|
| 10hr. 1950°F(1066°C) + 48hr. 1350°F(732°C) | 1000 | 538 | 145.4 | 1002 | Tensile | 15.4 | 23 | | 0 |
| | | | 130 | 896 | 21.5 | 7.4 | 13 | | 8 |
| | | | 115 | 793 | 333.7 | 3.4 | 9 | 0.00033 | 11 |
| | | | 105 | 724 | 3332.2ph | | | -ve | |
| | 1100 | 593 | 100 | 690 | 431.3 | 1.5 | 4 | 0.00041 | 18 |
| | | | 85 | 586 | 9691.4 | 1.0 | 3 | -ve | 26 |
| | 1200 | 649 | 142.4 | 982 | Tensile | 8.1 | 14 | | 0 |
| | | | 90 | 621 | 216.1 | 1.1 | 8 | 0.00067 | 26 |
| | | | 80 | 552 | 282.4ph | | | 0.00055 | |
| | | | 70 | 483 | 924.8 | 1.1 | 5 | 0.00014 | 34 |
| | | | 60 | 414 | 3564.0 | 1.3 | 4 | 0.000038 | 44 |
| | 1400 | 760 | 30 | 207 | 292.1 | 1.9 | 3 | 0.00091 | 60 |
| 1hr. 1950°F(1066°C) + 48hr. 1350°F(732°C) | 1000 | 538 | 160.1 | 1104 | Tensile | 22.5 | 30 | | 0 |
| | | | 140 | 965 | 385.0 | 2.7 | 11 | 0.00043 | 10 |
| | | | 130 | 896 | 2506.1 | 1.6 | 7 | 0.000022 | 14 |
| | 1100 | 593 | 120 | 827 | 1.4 | 4.2 | 10 | | 8 |
| | | | 110 | 758 | 1930.1 | 1.3 | 7 | 0.00015 | 22 |
| | | | 100 | 690 | 6833.6 | 1.6 | 6 | 0.000013 | 23 |
| | 1200 | 649 | 157.5 | 1086 | Tensile | 8.4 | 14 | | 0 |
| | | | 90 | 621 | 707.6 | 1.3 | 8 | 0.00028 | 24 |
| | | | 80 | 552 | 228.9ph | | | 0.00025 | |
| | | | 70 | 483 | 2469.5 | 0.8 | 2 | 0.000073 | 40 |
| | | | 60 | 414 | 6261.4 | 0.8 | 2 | -ve. | 40 |
| | | | 60 | 414 | 8168.8 | | 2 | 0.000026 | 48 |
| | 1400 | 760 | 30 | 207 | 384.0 | 2.1 | 5 | 0.00077 | 24 |
| + 2hr. 1550°F(843°C) | 1000 | 538 | 134.9 | 930 | Tensile | 27.0 | 34 | | 0 |
| | | | 130 | 896 | 63.5 | 18.7 | 19 | | 6 |
| | | | 120 | 827 | 154.1 | 11.9 | 14 | 0.00020 | 11 |
| | | | 115 | 793 | 4402.3 | 7.3 | 13 | 0.000005 | 17 |
| | 1100 | 593 | 110 | 758 | 138.2 | 7.8 | 13 | 0.00030 | 20 |
| | | | 100 | 690 | 385.2ph | | | <0.00047 | |
| | | | 85 | 586 | 18,470.5 | 1.1 | 5 | -ve | 30 |
| | 1200 | 649 | 133.4 | 920 | Tensile | 11.3 | 18 | | 1 |
| | | | 100 | 690 | 72.6 | 3.2 | 9 | 0.0025 | 26 |
| | | | 80 | 552 | 938.6 | 1.8 | 6 | 0.00021 | 39 |
| | | | 70 | 483 | 2094.6 | 1.6 | 5 | 0.00011 | 44 |
| | 1400 | 760 | 60 | 414 | 16.9 | 3.5 | 8 | | 43 |
| | | | 30 | 207 | 508.0 | 2.9 | 5 | 0.00091 | 98 |
| + 24 hr. 1550°F(843°C) | 1000 | 538 | 134.2 | 925 | Tensile | 32.8 | 10 | | 0 |
| | | | 125 | 862 | 40.9 | 24.9 | 23 | 0.090 | 3 |
| | | | 115 | 793 | 1856.7 | 10.2 | 12 | 0.00014 | 10 |
| | 1100 | 593 | 110 | 758 | 90.5 | 9.9 | 12 | 0.0034 | 15 |
| | | | 100 | 690 | 3528.1 | 4.7 | 6 | 0.000005 | 20 |
| | 1200 | 649 | 132.6 | 914 | Tensile | 14.6 | 17 | | 1 |
| | | | 100 | 690 | 11.6 | 6.9 | 13 | 0.17 | 19 |
| | | | 80 | 552 | 926.5 | 3.2 | 6 | 0.00037 | 23 |
| | | | 70 | 483 | 2480.9 | 2.0 | 5 | 0.000080 | 32 |
| | 1400 | 760 | 30 | 207 | 558.1 | 8.7 | 12 | 0.0011 | 92 |
| 10 hr. 1800°F(982°C) + 48 hr. 1350°F(732°C) | 1000 | 538 | 162.0 | 1117 | Tensile | 19.6 | 23 | | 0 |
| | | | 130 | 896 | 219.7 | 7.0 | 10 | 0.0175 | 9 |
| | | | 115 | 793 | 13437.5 | 3.1 | 6 | 0.000046 | 13 |
| | 1100 | 593 | 115 | 793 | 336.9 | 4.5 | 10 | 0.0052 | 12 |
| | | | 100 | 690 | 1266.5 | 3.0 | 8 | 0.00035 | 19 |
| | | | 90 | 621 | 5793.2 | 3.0 | 10 | 0.00010 | 26 |
| 10hr. 1800°F(982°C) + 48hr. 1350°F(732°C) | 1200 | 649 | 147.6 | 1018 | Tensile | 16.7 | 15 | | 1 |
| | | | 100 | 690 | 34.0 | 7.2 | 12 | 0.095 | 5 |
| | | | 80 | 552 | 410.4 | 6.2 | 11 | 0.027 | 26 |
| | | | 70 | 483 | 1420.9 | 6.0 | 13 | 0.00070 | 42 |
| | 1400 | 760 | 30 | 207 | 231.8 | 17.4 | 42 | 0.0056 | 52 |
| 10hr. 1700°F(927°C) + 3hr. 1325°F(718°C) | 1000 | 538 | 157.5 | 1086 | Tensile | 15.5 | 24 | | 0 |
| | | | 145 | 1000 | 26.5 | 21.6 | 22 | | 1 |
| | | | 130 | 896 | 391.1 | 9.0 | 11 | 0.0048 | 5 |
| | 1100 | 593 | 120 | 827 | 95.0 | 8.4 | 13 | 0.022 | 8 |
| | | | 90 | 621 | 2138.2 | 7.8 | 13 | 0.00024 | 11 |
| | 1200 | 649 | 85 | 586 | 79.4 | 6.0 | 18 | 0.012 | 65 |
| | | | 60 | 414 | 1061.8 | 12.6 | 16 | 0.0016 | |
| | | | 50 | 345 | 3766.9 | 15.8 | 16 | 0.00038 | |
| | 1400 | 760 | 20 | 137 | 506.9 | 32.3 | 50 | 0.0068 | |
| + 48hr. 1350°F(732°C) | 1000 | 538 | 166.0 | 1144 | Tensile | 15.9 | 23 | | 0 |
| | | | 130 | 896 | 125.7 | 11.7 | 14 | 0.050 | 2 |
| | | | 120 | 827 | 1382.8 | 5.6 | 8 | 0.0022 | 5 |
| | | | 115 | 793 | 1163.2 | 6.1 | 10 | 0.0023 | 6 |
| | 1100 | 593 | 100 | 690 | 192.2 | 11.7 | 14 | 0.036 | 10 |
| | | | 85 | 586 | 1574.0 | 2.7 | 6 | 0.00073 | 22 |
| | 1200 | 649 | 143.7 | 991 | Tensile | 16.8 | 26 | | 0 |
| | | | 85 | 586 | 42.5 | 9.2 | 20 | 0.087 | 15 |
| | | | 60 | 414 | 530.7 | 12.0 | 18 | 0.0045 | 30 |
| | | | 50 | 345 | 3378.9 | 12.4 | 21 | 0.00072 | 47 |
| | 1400 | 760 | 30 | 207 | 96.9 | 18.0 | 43 | 0.040 | 32 |
| | | | 20 | 137 | 439.0 | 32.7 | 45 | 0.013 | |
| 1 hr. 1700°F(927°C) + 3 hr. 1325°F(718°C) | 1000 | 538 | 165.2 | 1139 | Tensile | 12.9 | 27 | | 0 |
| | | | 145 | 1000 | 168.9 | 12.1 | 14 | 0.0048 | 2 |
| | | | 130 | 896 | 5613.4 | 3.5 | 12 | 0.000086 | 13 |
| | 1100 | 593 | 125 | 862 | 184.8 | 1.65 | 11 | 0.001 | 12 |
| | | | 115 | 793 | 406.6 | 1.6 | 6 | 0.00072 | 13 |
| | | | 100 | 690 | 2727.0 | 3.4 | 11 | 0.00017 | 26 |
| | 1200 | 649 | 160.2 | 1105 | Tensile | 8.3 | 22 | | 0 |
| | | | 100 | 690 | 53.0 | 1.75 | 9 | 0.0096 | 24 |
| | | | 85 | 586 | 291.1 | | 23 | | 18 |
| | | | 85 | 586 | 117.1 | 5.0 | 15 | 0.0061 | 23 |
| | | | 65 | 448 | 937.4 | 3.0 | 7 | 0.00096 | 36 |
| | | | 65 | 448 | 1501.2 | | 9 | | 32 |
| | 1400 | 760 | 30 | 207 | 144.0 | 10.8 | 27 | 0.013 | 60 |
| + 2 hr. 1550°F (843°C) | 1000 | 538 | 149.0 | 1027 | Tensile | 19.8 | 27 | | 0 |
| | | | 145 | 1000 | 2.0 | 24.3 | 32 | 1.7 | 1 |
| | | | 130 | 896 | 18.1 | 19.4 | 25 | | 1 |
| | | | 120 | 827 | 785.0 | 9.3 | 12 | 0.0016 | 7 |
| | | | 115 | 793 | 4385.2 | 2.6 | 6 | 0.000082 | 7 |
| | 1100 | 593 | 110 | 758 | 486.3 | 5.8 | 9 | 0.0018 | 9 |
| | | | 100 | 690 | 703.6 | 1.5 | 7 | 0.00056 | 19 |
| | | | 85 | 586 | 4078.6 | 2.2 | 4 | 0.00010 | 23 |
| | 1200 | 649 | 135.4 | 934 | Tensile | 14.2 | 20 | | 1 |
| | | | 100 | 690 | 21.9 | 9.3 | 15 | | 12 |
| | | | 85 | 586 | 154.3 | 4.0 | 9 | 0.0085 | 20 |
| | | | 65 | 448 | 1011.8 | 6.2 | 7 | 0.0013 | 20 |
| | 1400 | 760 | 30 | 207 | 160.1 | 21.4 | 34 | 0.030 | 33 |
| | | | 20 | 137 | 535.2 | 25.4 | 35 | 0.0053 | |

ph = failed at pinhole

It should be noted that although the higher temperature exposures are referred to as "solution treatments," the use of this designation does not necessarily signify complete solution of all constitutent phases. The heat treatment practice and the testing procedures were the same as those used previously [1].

Conventional methods were employed for microstructural examination. Samples for optical microscopy and replica electron microscopy were etched electrolytically in "G" etch [4]. Samples approximately 0.5-in. (1.3 cm) wide by 0.7-in. (1.8 cm) long for transmission electron microscopy were cut from the gauge lengths of tested smooth specimens, ground on wet silicon carbide papers and electropolished. This was carried out using 20 volts potential in conjunction with a chilled mixture of 83 percent methanol, 7.5 percent sulphuric acid, 3 percent nitric acid, 4.5 percent lactic acid, and 2 percent hydrofluric acid. The thin films were studied in a JEM electron microscope operated at 100 KV.

X-ray diffraction analysis was carried out on precipitate particles electrolytically extracted from the as-heat treated materials using a platinum cathode at 3–4 volts potential and a 10 percent phosphoric acid in water solution. X-ray exposures were conducted in a 144.6 mm dia Debye camera with nickel-filtered copper radiation.

## Experimental Observations

**Influence of Heat Treatment on the Mechanical Characteristics.** The heat treatments evaluated resulted in a range of mechanical characteristics (Tables 1 through 3). In particular, the severity of the notch sensitivity varied considerably. The results for the material heat treated 10 hr at 1950 deg F (1066 deg C) plus 48 hr at 1350 deg F (732 deg C) (Fig. 1), provide an example of severe time-dependent notch sensitivity. At the shorter times at the lower test temperatures, the rupture strengths for notched specimens were somewhat lower than for smooth specimens. The notched to smooth rupture strength ratios ($N/S$) were the same order as determined by tensile tests (Table 3). At varying time periods, the notched specimen rupture curves exhibited drastic increases in steepness (occurred at the approximate 0.2 percent offset yield stress) so that the $N/S$ ratios decreased with time to values considerably below those obtained in tensile tests, i.e., the material exhibited time-dependent notch sensitivity. Subsequently, with increasing test temperature and longer rupture times, the $N/S$ ratios increased until, at the highest temperature a value of about 1.0 was obtained.

The results for the material heat treated 10 hr at 1700 deg F (927 deg C) plus 48 hr at 1350 deg F (732 deg C) are in contrast to the foregoing behavior and are typical of the heat treated materials not susceptible to time-dependent notch sensitivity (Fig. 2). The $N/S$ rupture strength ratios were generally higher than those obtained in tensile tests (Table 3).

The severity of the time-dependent notch sensitivity for the heat treated conditions studied, including those evaluated previously [3], are tabulated below. Ratings of 2 and 1 correspond to severe and limited time-dependent notch sensitivity, respectively. Test conditions for which no time-dependent notch sensitivity was observed were rated 0.

| Solution treatment | | Aging treatment(s) | Test temperature °F / °C: 900 / 482 | 1000 / 538 | 1100 / 593 | 1200 / 649 | 1400 / 760 |
|---|---|---|---|---|---|---|---|
| 10 hr 1950°F(1066°C) | + | 48 hr 1350°F(732°C) | 2 | 2 | 2 | 2 | 0 |
| 1 hr 1950°F(1066°C) | + | 48 hr 1350°F(732°C) | 2 | 2 | 2 | 2 | 0 |
| | + | 2 hr 1550°F(843°C) | 2 | 2 | 2 | 1 | 0 |
| | + | 24 hr 1550°F(843°C) | | 0 | 0 | ? | 0 |
| 10 hr 1800°F(982°C) | + | 48 hr 1350°F(732°C) | 2 | 2 | 1 | ? | 0 |
| 10 hr 1700°F(927°C) | + | 3 hr 1325°F(718°C) | 2 | 1 | 0 | 0 | 0 |
| | + | 48 hr 1350°F(732°C) | 0 | 0 | 0 | 0 | 0 |
| 1 hr 1700°F(927°C) | + | 3 hr 1325°F(718°C) | 2 | 2 | ? | 0 | 0 |
| | + | 2 hr 1550°F(843°C) | | 0 | 0 | 0 | 0 |
| Cold worked 20% | + | "Multiple" 1[a] | | 2 | | 2 | |
| 1 hr 1950°F(1066°C) | + | "Multiple" 2[b] | | 2 | | 2 | |
| 1 hr 1750°F(954°C) | + | "Multiple" 1[a] | 2 | 2 | 1 | ? | |

[a] "Multiple" 1—1325°F(718°C)/8 hr, F. C. to 1150°F(621°C) in 10 hr, A. C.
[b] "Multiple" 2—1350°F(732°C)/8 hr, F. C. to 1200°F(649°C) in 12 hr, A. C.

The principal features evident were:

1 Decreasing the solution temperature decreased the susceptibility to time-dependent notch sensitivity.

2 Increasing the severity of the aging treatment (increasing time and/or temperature) reduced the susceptibility to time-dependent notch sensitivity.

3 The materials with the commonly used "multiple" aging treatments exhibited time-dependent notch sensitivity.

For all heat treated conditions, the rupture strengths decreased rapidly with increasing time and/or temperature for Larson-Miller parameter values above about 37,000 (Figs. 1 and 2). Extensive use is made of Inconel 718 for "high temperature" applications for which the parameter values are relatively low. Under these conditions, the smooth specimen rupture strengths are high, however, severe time-dependent notch sensitivity can occur. At the lower parameter values, the notched rupture strengths were below those for smooth specimens and varied considerably with heat treatment. (In contrast, the range of smooth specimen rupture strengths was relatively small.) Particularly important, was whether or not the material exhibited time-dependent notch sensitivity—those which did not have similar notched rupture strengths, while those which were notch sensitive had considerably lower strengths. It should also be noted that the commonly used multiple aging treatments evaluated previously, resulted in lower notched rupture strengths than obtained for a number of the heat treatments used in the present investigation. This occurred even though the heat treatments used were not selected to maximize notched rupture strengths.

**Fracture Characteristics.** The fracture characteristics of Inconel 718 were similar to those established for Waspaloy [1]. Consequently, this aspect is not reported in depth. Smooth and notched rupture tested specimens failed by initiation and relatively slow growth of intergranular cracks followed by transgranular fracture. (The lengths of the intergranular cracks, expressed as a percentage of specimen width, are included in Tables 2 and 3). The occurrence of time-dependent notch sensitivity was due to more rapid initiation of intergranular cracks in notched than in smooth specimens. This was associated with

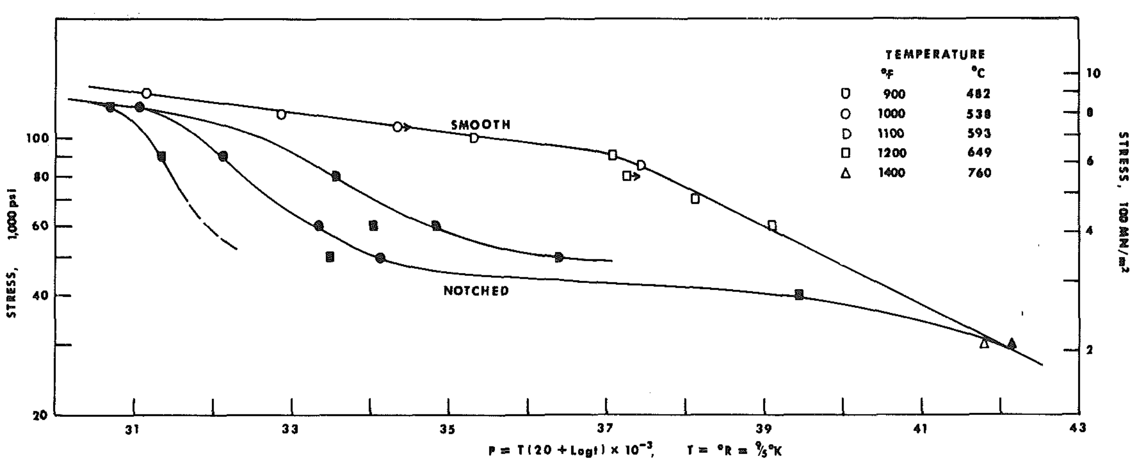


Fig. 1 Larson-Miller parameter curves showing the time-temperature dependence of the rupture strengths of smooth and notched specimens of Inconel 718 sheet heat treated 10 hr at 1950 deg F (1066 deg C) plus 48 hr at 1350 deg F (732 deg C). Time dependent notch sensitivity was evident at temperatures from 900 to 1200 deg F (482-649 deg C) but not at 1400 deg F(760 deg C).

**Table 3 Notched specimen ($K_t$ > 20) rupture properties at 900 deg to 1400 deg (482–760 deg C)**

| Heat treatment | Test Temperature (°F) | Test Temperature (°C) | Stress (ksi) | Stress (MN/m$^2$) | Rupture Time (hrs.) | Intergranular Crack Length (%) | N/S Strength Ratio |
|---|---|---|---|---|---|---|---|
| 10hr. 1950°F(1066°C) + 48hr. 1350°F(732°C) | 900 | 482 | 120 | 827 | 360.0 | 16 | |
| | | | 90 | 621 | 1075 1 | 27 | |
| | 1000 | 538 | 149.0 | 1027 | Tensile | 0 | 1.02 |
| | | | 120 | 827 | 18.7 | 6 | 0.92 |
| | | | 90 | 621 | 100.7 | 26 | 0.74 |
| | | | 60 | 414 | 682.7 | 54 | 0.53 |
| | | | 50 | 345 | 2342.4 | 38 | 0.47 |
| | 1100 | 593 | 80 | 552 | 31.6 | 35 | 0.71 |
| | | | 60 | 414 | 212.8 | | 0.58 |
| | | | 50 | 345 | 2121.8 | 39 | 0.55 |
| | 1200 | 649 | 135.3 | 933 | Tensile | 1 | 0.95 |
| | | | 60 | 414 | 3.1 | 32 | 0.46 |
| | | | 50 | 345 | 1.5 | 52 | 0.37 |
| | | | 40 | 276 | 5774.6 | 73 | 0.72 |
| | 1400 | 760 | 30 | 207 | 451.8 | 79 | 1.13 |
| 1hr. 1950°F(1066°C) + 48hr. 1350°F(732°C) | 900 | 482 | 130 | 896 | 34.6 | 6 | |
| | | | 90 | 621 | 1745.1 | 41 | |
| | 1000 | 538 | 152.4 | 1051 | Tensile | 0 | 0.95 |
| | | | 90 | 621 | 86.2 | 29 | 0.60 |
| | | | 70 | 483 | 221.2 | 41 | 0.49 |
| | | | 60 | 414 | 9262 Discontinued | | >0.49 |
| | 1100 | 593 | 80 | 552 | 10.8 | 30 | 0.55 |
| | | | 60 | 414 | 184.1 | 44 | 0.47 |
| | | | 50 | 345 | 8902 Discontinued | | >0.51 |
| | 1200 | 649 | 147.5 | 1017 | Tensile | 1 | 0.94 |
| | | | 50 | 345 | 46.3 | 45 | 0.41 |
| | | | 45 | 310 | 330.2 | 70 | 0.45 |
| | 1400 | 760 | 30 | 207 | 419.8 | 75 | 1.02 |
| + 2hr. 1550°F(843°C) | 900 | 482 | 80 | 552 | 5763.6 | 30 | |
| | 1000 | 538 | 113.6 | 783 | Tensile | 0 | 0.84 |
| | | | 90 | 621 | 173.8 | 29 | 0.72 |
| | | | 75 | 517 | 752.9 | 34 | 0.62 |
| | | | 65 | 448 | 1138.9 | 49 | 0.55 |
| | 1100 | 593 | 80 | 552 | 20.0 | 26 | 0.67 |
| | | | 60 | 414 | 704.8 | 59 | 0.61 |
| | 1200 | 649 | 116.0 | 800 | Tensile | 3 | 0.87 |
| | | | 80 | 552 | 4.1 | 29 | 0.66 |
| | | | 60 | 414 | 225.0 | 44 | 0.65 |
| | | | 50 | 345 | 5003.7 | 51 | 0.79 |
| | 1400 | 760 | 50 | 345 | 2.8 | 44 | 0.58 |
| | | | 40 | 276 | 148.3 | 59 | 1.05 |
| | | | 30 | 207 | 408.5 | 71 | 0.95 |
| | | | 30 | 207 | 493.8 | 73 | 1.00 |
| + 24hr. 1550°F(843°C) | 1000 | 538 | 102.1 | 704 | Tensile | 0 | 0.76 |
| | | | 90 | 621 | 253.5 | 14 | 0.76 |
| | | | 80 | 552 | 6862 Discontinued | | >0.73 |
| | | | 60 | 414 | 11000 Discontinued | | >0.55 |
| | 1100 | 593 | 85 | 586 | 40.6 | 23 | 0.70 |
| | | | 75 | 517 | 788.5 | 43 | 0.74 |
| | | | 60 | 414 | 9044 Discontinued | | >0.61 |
| | 1200 | 649 | 108.0 | 745 | Tensile | 4 | 0.81 |
| | | | 60 | 414 | 18.9 | 26 | 0.61 |
| | | | 60 | 414 | 40.3 | 30 | 0.63 |
| | | | 50 | 345 | 5588.8 | 48 | 0.81 |
| | 1400 | 760 | 30 | 207 | 373.8 | 53 | 0.88 |
| 10hr 1800°F(982°C) + 48hr 1350°F(732°C) | 900 | 482 | 90 | 621 | 980.3 | 17 | |
| | 1000 | 538 | 135.9 | 937 | Tensile | 0 | 0.84 |
| | | | 90 | 621 | 131.4 | 20 | 0.68 |
| | | | 75 | 517 | 238.4 | 26 | 0.58 |
| | | | 65 | 448 | 305.8 | 30 | 0.51 |
| | 1100 | 593 | 90 | 621 | 8.2 | 19 | 0.67 |
| | | | 75 | 517 | 105.2 | 31 | 0.64 |
| | | | 60 | 414 | 12867 Discontinued | | >0.68 |
| | 1200 | 649 | 140.8 | 971 | Tensile | 0 | 0.95 |
| | | | 90 | 621 | 14.0 | 32 | 0.85 |
| | | | 75 | 517 | .5.1 | 39 | 0.68 |
| | | | 60 | 414 | 1406.5 | 58 | 0.87 |
| | 1400 | 760 | 30 | 207 | 215.4 | 70 | 0.99 |
| 10hr. 1700°F(927°C) + 3hr. 1325°F (718°C) | 900 | 482 | 90 | 621 | 2639.1 | 12 | |
| | 1000 | 538 | 90 | 621 | 598.6 | 26 | 0.72 |
| | | | 75 | 517 | 7680 Discontinued | | >0.95 |
| | 1100 | 593 | 90 | 621 | 77.4 | 25 | 0.75 |
| | | | 80 | 552 | 951.2 | | 0.83 |
| | 1200 | 649 | 85 | 586 | 45.2 | 31 | 0.91 |
| | | | 60 | 414 | 1024.2 | 55 | 1.00 |
| | 1400 | 760 | 30 | 207 | 103.9 | 70 | 1.00 |
| + 48hr. 1350°F(732°C) | 900 | 482 | 90 | 621 | 13140 Discontinued | | |
| | 1000 | 538 | 125.1 | 863 | Tensile | 0 | 0.75 |
| | | | 90 | 621 | 299.2 | 20 | 0.72 |
| | | | 75 | 517 | 7656 Disco ntinued | | >0.70 |
| | 1100 | 593 | 90 | 621 | 167.8 | 28 | 0.89 |
| | | | 80 | 552 | 847.9 | 33 | 0.90 |
| | 1200 | 649 | 138.1 | 952 | Tensile | 1 | 0.96 |
| | | | 80 | 552 | 53.2 | 40 | 0.98 |
| | | | 60 | 414 | 468.2 | 52 | 0.94 |
| | | | 50 | 345 | 2422.0 | 65 | 0.97 |
| | 1400 | 760 | 35 | 241 | 57.0ph | 54 | 1.00 |
| | | | 30 | 207 | 103.0 | 57 | 1.00 |
| | | | 20 | 137 | 483.0 | 67 | 1.02 |
| 1hr. 1700°F(927°C) + 3hr. 1325°F (718°C) | 900 | 482 | 90 | 621 | 2547.2 | 30 | |
| | 1000 | 538 | 154.9 | 1068 | Tensile | 0 | 0.94 |
| | | | 130 | 896 | 17.5 | 7 | 0.86 |
| | | | 90 | 621 | 152.6 | 23 | 0.62 |
| | | | 75 | 517 | 239.4 | 39 | 0.53 |
| | | | 65 | 448 | 1561.3 | 51 | 0.49 |
| | 1100 | 593 | 90 | 621 | 30.7 | 28 | 0.60 |
| | | | 80 | 552 | 131.4 | 26 | 0.59 |
| | 1200 | 649 | 140.3 | 967 | Tensile | 1 | 0.88 |
| | | | 85 | 586 | 2.6 | 35 | 0.63 |
| | | | 75 | 517 | 109.8 | 37 | 0.83 |
| | | | 65 | 448 | 1031.9 | 52 | 0.99 |
| | 1400 | 760 | 30 | 207 | 105.9 | 61 | 0.94 |
| + 2hr. 1550°F(843°C) | 1000 | 538 | 121.9 | 841 | Tensile | 0 | 0.82 |
| | | | 90 | 621 | 3205.7 | 23 | 0.78 |
| | | | 75 | 517 | 5133 Discontinued | | >0.66 |
| | 1100 | 593 | 90 | 621 | 748.4 | 28 | 0.92 |
| | 1200 | 649 | 121.2 | 836 | Tensile | 0 | 0.89 |
| | | | 65 | 448 | 223.3 | 42 | 0.80 |
| | | | 50 | 345 | 1677 | 59 | 0.82 |
| | 1400 | 760 | 30 | 207 | 92.5 | 61 | 0.85 |

ph = failed at pin hole

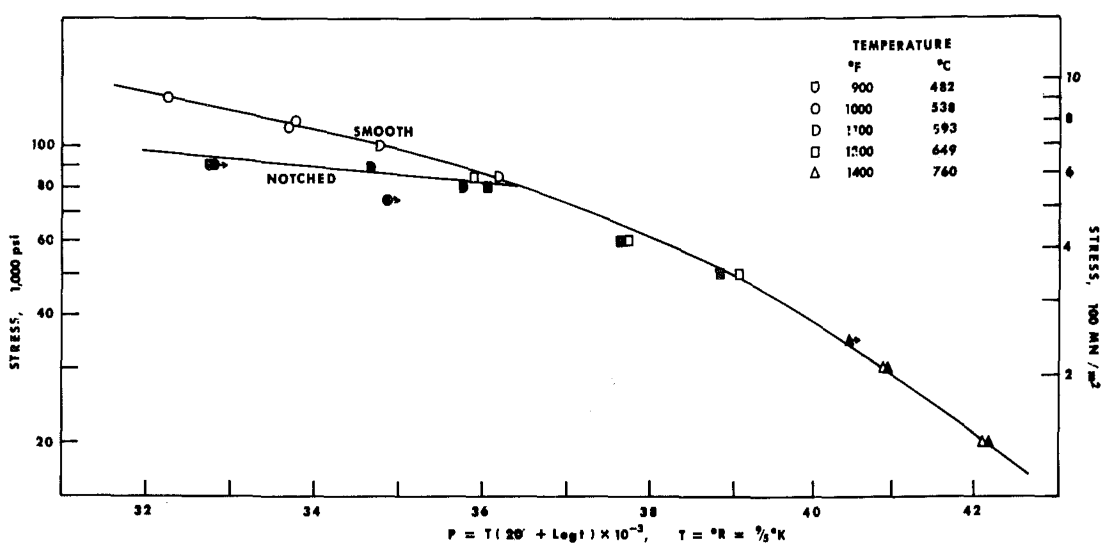


Fig. 2 Larson-Miller parameter curves showing the time-temperature dependence of the rupture strengths of smooth and notched specimens of Inconel 718 sheet heat treated 10 hr at 1700 deg F (927 deg C) plus 48 hr at 1350 deg F (732 deg C). No time-dependent notch sensitivity was evident.

local deformation at the base of the notches accompanying the relaxation of the stress concentrations.

**Stress Relaxation.** Relaxation of stress concentrations can occur by "yielding" on loading (time-independent deformation) and by subsequent creep (time-dependent deformation). No time-dependent notch sensitivity was observed for notched specimens loaded above the approximate 0.2 percent offset yield strengths (established by smooth specimen tests). In these tests, yielding on loading reduced the stresses across the specimens at the base of the notches to approximately the nominal stresses.

For Waspaloy, time-dependent notch sensitivity occurred when notched specimens were loaded below the yield strength and when smooth specimen tests showed that small amounts of creep consumed large fractions of creep-rupture life [1]. In other words, when the relaxation by creep of the stress concentrations at notches caused excessive damage and thus premature initiation of intergranular cracks. The smooth specimen deformation characteristics of Inconel 718 were examined to determine whether this correlation occurred. Iso-creep strain curves were constructed for each temperature on plots of life fraction versus test stress. Curves were derived for 0.1, 0.2 (the order of deformation necessary to ensure relaxation of elastic stresses from the approximate yield stresses to the nominal stresses), and also for 0.5, 1, and 2 percent creep strain.

For the material heat treated 10 hr at 1950 deg F (1066 deg C) plus 48 hr at 1350 deg F (732 deg C), with decreasing stress the life fractions for small amounts of creep strain, increased drastically at 1000 and 1100 deg F (538 and 593 deg C), increased and subsequently decreased at 1200 deg F (649 deg C) (Fig. 3). These changes are consistent with the observed variations in the severity of notch sensitivity (Fig. 1). For the material heat treated 10 hr at 1700 deg F (927 deg C) plus 48 hr at 1350 deg F (732 deg C), the life fractions for small amounts of creep strain were at low levels for all test conditions (Fig. 4). In accordance with this, no time-dependent notch sensitivity was observed (Fig. 2).

Data for the other heat treated materials exhibited similar correlations between the time-dependent notch sensitivity and the characteristics of the iso-creep strain curves.

**Microstructural Features Contributing To Time-Dependent Notch Sensitivity.** Many nickel-base superalloys (including Waspaloy) age harden by precipitation of an $LI_2$-ordered fcc phase-$Ni_3(Al, Ti)$, called gamma prime. Inconel 718 differs in that

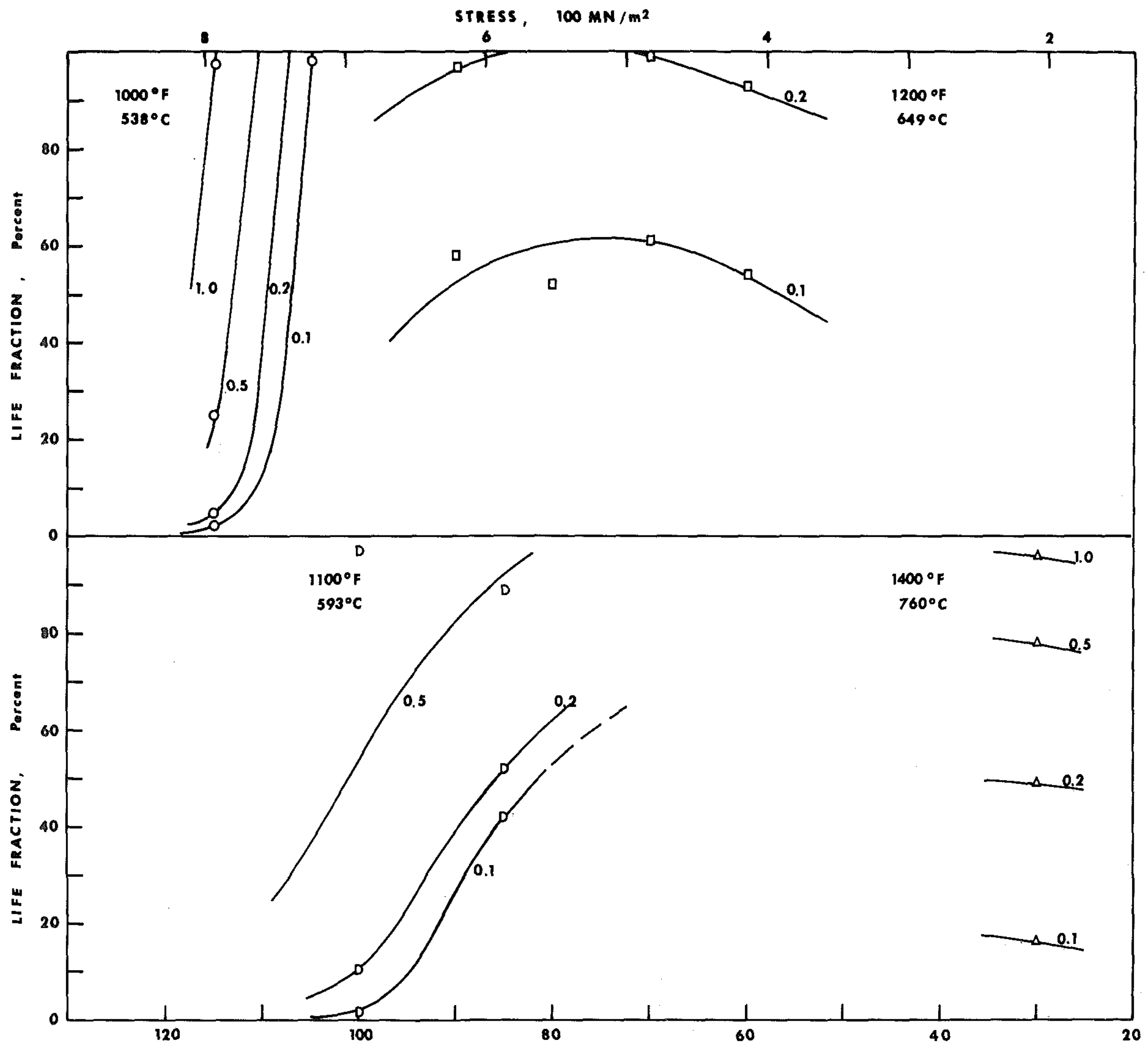


Fig. 3 Iso-creep strain curves of life fraction versus stress at temperatures from 1000 F to 1400 deg F (538 – 760 deg C) for Inconel 718 heat treated 10 hr at 1950 deg F (1066 deg C) plus 48 hr at 1350 deg F (732 deg C). Time-dependent notch sensitivity occurred under test conditions where large amounts of rupture life were utilized for small percent creep strains at test temperatures 1000 F, 1100 F, and 1200 deg F (538, 593, and 649 deg C).

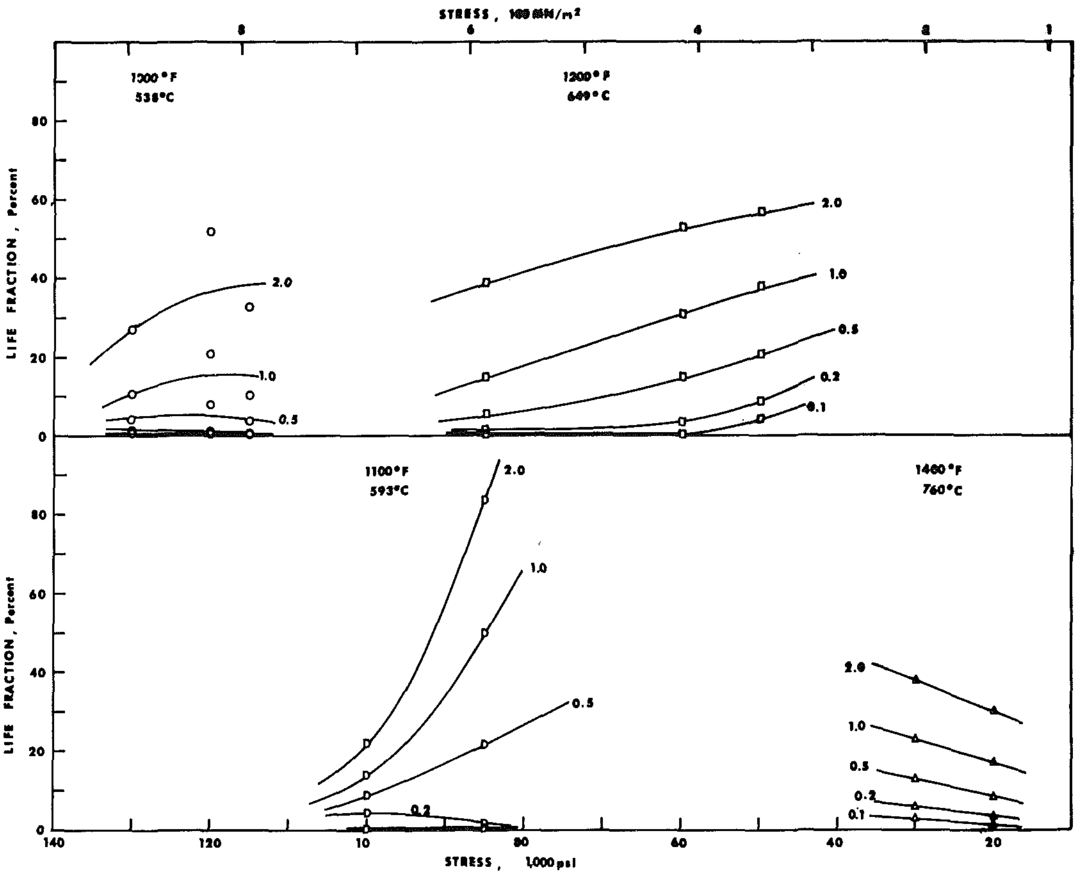


**Fig. 4 Iso-creep strain curves of life fraction versus stress at temperatures from 1000 to 1400 deg F (538 – 760 deg C) for Inconel 718 heat treated 10 hr at 1700 deg F (927 deg C) plus 48 hr at 1350 deg F (732 deg C). Little rupture life was utilized for small amounts of creep under all test conditions and no time-dependent notch sensitivity was observed.**

hardening is primarily due to precipitation of $Ni_3Cb$ [5]. This phase, designated $\gamma''$, has a $DO_{22}$-ordered bct structure. The $\gamma''$ phase is metastable so that it is replaced on thermal exposure by the $\beta$ phase which is also $Ni_3Cb$, but it has a $Cu_3Ti$-ordered orthorhombic structure.

The microstructural features of Inconel 718 were studied primarily to determine whether a correlation existed between the dislocation motion mechanism and the notch sensitive behavior.

***Materials Solution Treated 1 and 10 Hours at 1950 Deg F (1066 Deg C)* and Aged 48 Hours at 1350 Deg F (732 Deg C).** X-ray diffraction of extracted residues indicated the presence of Cb,Ti(C, N), $\gamma'$ and/or[2] $\gamma''$ (Table 4). The Ti(C, N) was a relatively large, randomly dispersed precipitate (Fig. 5(*a*)). Cb(C, N) particles in grain boundaries were "plate-like" in appearance (Fig. 5(*b*)). The $\gamma'$ and/or $\gamma''$ were intragranular precipitates about 300 Å in diameter. The $\gamma''$ was identified by electron diffraction [6]. The presence of $\gamma'$ was inferred from subsequently reported observations where these particles were large. (In cases such as this where the $\gamma'$ and the $\gamma''$ could not be distinguished visibly, the precipitate will be referred to as $\gamma'/\gamma''$.)

Specimens of the material heat treated 1 hr at 1950 deg F (1066 deg C) plus 48 hr at 1350 deg F (732 deg C) were examined after testing. [Similar structures were expected for the material heat treated 10 hr at 1950 deg F (1066 deg C) and aged which differed in that it had a larger grain size (0.06 mm compared to 0.03 mm).] For the specimen tested at 1100 deg F (593 deg C) [at 120 ksi (827MN/m²) ruptured in 1.4 hr] the most obvious feature was {111} planar slip banding (Fig. 6(*a*)). This reflects shearing of the coherently precipitated $\gamma'/\gamma''$ by dislocations [5, 7]. This dislocation motion mechanism would occur in other specimens tested at temperatures low enough to cause little or no growth of $\gamma'/\gamma''$.

It was evident from microstructures of the specimen tested at 1400 deg F (760 deg C) [at 30 ksi (207MN/m²) ruptured in 384 hr] that structural changes had occurred during the test exposure. $Ni_3Cb$ needles precipitated. The $\gamma'$ increased in size to spherical particles about 750 Å in diameter. The $\gamma''$ also grew so that it was clearly resolvable as plates approximately 500 Å thick and 4000 Å long. Contrast effects [8] indicated that, despite the large particle sizes, both the $\gamma'$ and $\gamma''$ were coherent with the matrix. The deformation was not localized in slip bands (Fig. 6(*b*)). Dislocations were observed entangled with $\gamma''$ and, in some cases, as loops around $\gamma'$ particles. The observations indicated that the dislocations bypassed the precipitate particles. This mechanism results in homogeneous deformation. It must be assumed that in the early part of the test when the particles were small, the dislocations sheared the particles.

The foregoing observations are analogous to those reported for Waspaloy [2]. In this case, dislocations sheared $\gamma'$ particles smaller than a critical size. When the particles were larger than the critical, they were bypassed by dislocations. These mechanisms resulted in localized and homogeneous deformation, respectively.

[2]The $\gamma''$ and $\gamma'$ phases are difficult to distinguish using X-ray diffraction. The "*d*" values are similar. Differences do occur in the superlattic reflections but these are not readily resolvable [5].

**Table 4 X-ray diffraction data of extracted residues of Inconel 718 in the heat treated conditions**

| Solution Treatment | 10 hrs. at 1950°F (1066°C) | 1 hr. at 1950°F (1066°C) | 1 hr. at 1950°F (1066°C) | 1 hr. at 1950°F (1066°C) | 10 hrs. at 1800°F (982°C) | 10 hrs. at 1700°F (927°C) | 10 hrs. at 1700°F (927°C) | 1 hr. at 1700°F (927°C) | 1 hr. at 1700°F (927°C) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Aging Treatment | 48 hrs. at 1350°F (732°C) | 48 hrs. at 1350°F (732°C) | 2 hrs. at 1550°F (843°C) | 24 hrs. at 1550°F (843°C) | 48 hrs. at 1350°F (732°C) | 3 hrs. at 1325°F (718°C) | 48 hrs. at 1350°F (732°C) | 3 hrs. at 1325°F (718°C) | 2 hrs. at 1550°F (843°C) | Indicated Phases |
| | d(A) I | d(A) I | d(A) I | d(A) I | d(A) I | d(A) I | d(A) I | d(A) I | d(A) I | |
| | 3.25 vw | 3.26 vvw | 3.25 vw | 3.25 w | 3.25 vw | 3.26 vvw | 3.26 vvw | | 3.25 w | γ'' |
| | | | | | 2.643vvw | 2.646w | 2.659vvw | | 2.644w | ? |
| | 2.552w | 2.57 vw | 2.564w | 2.561w | 2.555w | | 2.567vvw | 2.552w | 2.553w | MC |
| | | | | | 2.385vvw | 2.394vvw | | 2.388vvw | | L? |
| | | | | | | | | 2.330w | | ? |
| | | | 2.266vvw | | 2.257vw | 2.272w | 2.272vw | | 2.264vvw | β |
| | | | | | | 2.231m | 2.232m | 2.232m | | β |
| | 2.214w | 2.226vw | 2.223w | 2.217w | 2.219w | | 2.222vw | | 2.221w | MC, L? |
| | 2.116 to* | 2.123 to* | 2.111vs | 2.108vs | 2.104vs | 2.117s | 2.116s | 2.118m | 2.108vs | β |
| | 2.078vs | 2.087vs | 2.080vw | 2.080m | 2.083vs | 2.08 vw | 2.081s | 2.080w | 2.079s | γ'/γ'' |
| | | | | 2.040vvw | 2.033vw | 2.033vvw | | 2.043w | 2.038vw | L? |
| | | | 1.994w | 1.992vw | 1.992m | 2.000m | 2.000s | 2.003m | 1.996m | β, L? |
| | | | 1.969w | 1.948w | 1.965s | 1.977s | 1.973s | 1.975s | 1.968s | β |
| | 1.850vw | | 1.854vw | 1.846w | | | | | 1.855w | γ'/γ'' |
| | 1.809s | 1.813m | 1.818w | 1.808s | 1.805s | | 1.807m | 1.807vvw | 1.809m | γ'/γ'' |
| | 1.568w | 1.575vvw | 1.569vw | 1.567w | 1.567vw | 1.573vvw | 1.573vvw | 1.574w | 1.566vw | MC |
| | | | | | 1.545vvw | 1.548vvw | 1.549vw | | 1.546vvw | ? |
| | | | 1.535vw | | 1.530w | 1.536m | 1.534w | 1.536w | 1.535w | ? |
| | 1.337w | 1.339vw | 1.338vw | 1.337w | 1.338w | | 1.337vvw | 1.344vvw | 1.338w | MC |
| | 1.292w | 1.296vvw | 1.298vw | 1.294m | 1.300w | 1.302w | 1.302w | 1.303vvw | 1.300w | β, γ'/γ'' |
| | 1.278m | 1.280w | 1.280vw | 1.280m | 1.278m | 1.281w | 1.280w | 1.281vvw | 1.280w | MC, ? |
| | | | | | 1.195w | 1.195w | | 1.199w | | L? |
| | | | 1.193vw | 1.188vvw | 1.189w | 1.191w | 1.193w | 1.193vvw | 1.192w | ? |
| | 1.110vw | 1.110w | 1.107vw | 1.110m | 1.106w | 1.108w | 1.109w | 1.111w | 1.108w | β, ? |
| Phases | | | | | | | | | | |
| MC | w | w | w | w | w | w | w | w | w | |
| γ'/γ'' | s | s | s | vs | s | w | m | w | s | |
| β | 0 | 0 | w | w | m | s | s | s | m | |

* Values at extremes of wide reflection

**Intensities** I: s = Strong, m = Medium, w = Weak, v = Very

**Phases:** MC = Cb, Ti(C, N), γ' = $Ni_3$(Al, Ti), γ'' = $Ni_3$Cb(bct), β = $Ni_3$Cb(orthorhombic)

L = "Laves", $Fe_2$(Ti, Cb).

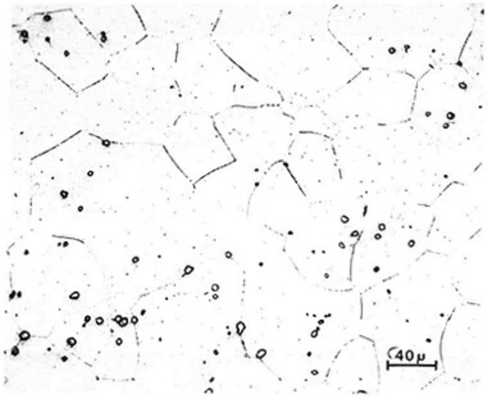


Fig. 5(*a*) 10 hr 1950 deg F (1066 deg C) + 48 hr 1350 deg F (732 deg C)

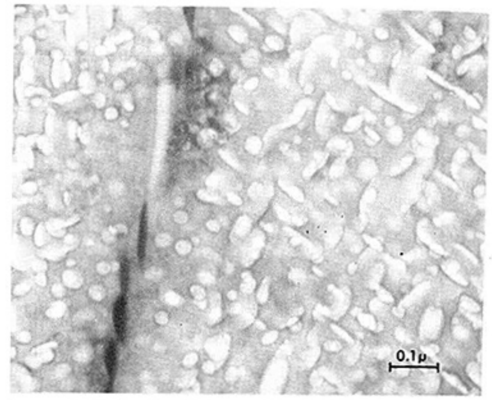


Fig. 5(*b*) 1 hr 1950 deg F (1066 deg C) + 48 hr 1350 deg F (732 deg C)

**Fig. 5 Optical and transmission electron micrographs showing micro-structural features of Inconel 718 solution treated at 1950 deg F (1066 deg C) and aged**

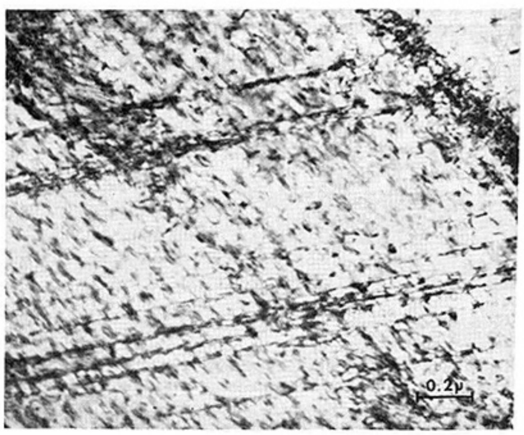


Fig. 6(*a*)

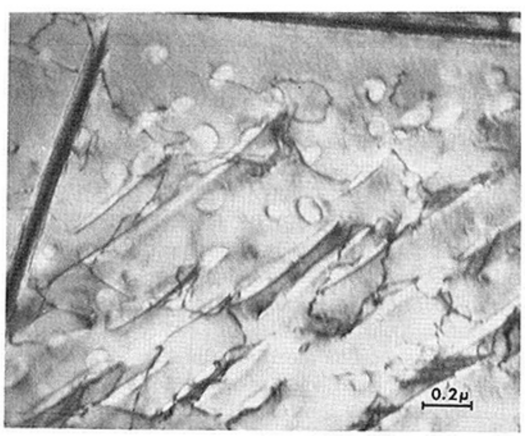


Fig. 6(*b*)

***Fig. 6 Transmission electron micrographs of Inconel 718 heat treated* 1 hr at 1950 deg F (1066 deg C) plus 48 hr at 1350 deg F (732 deg C) and creep-rupture tested (*a*) at 120 ksi (827MN/m²) at 1100 deg F (593 deg C) (ruptured in 1.4 hr at 4.2 percent elongation), (*b*) at 30 ksi (207 MN/m²) at 1400 deg F (760 deg C) (ruptured in 384 hr at 2.1 percent elongation). In the lower temperature tests, the $\gamma'/\gamma''$ were sheared by dislocations and the deformation was localized. In the test at 1400 deg F (760 deg C) $\gamma'/\gamma''$ growth occurred causing the dislocation to bypass the particles *and the deformation to be homo*geneous.**

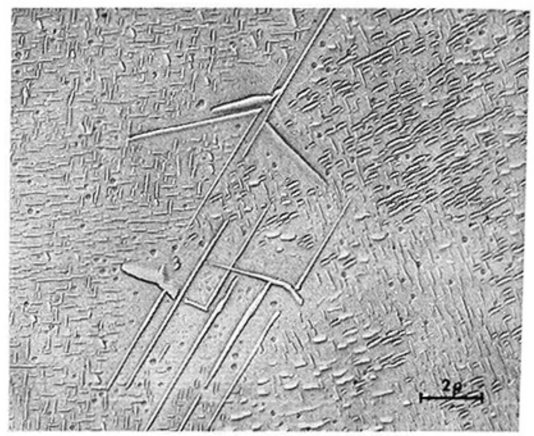


**Fig. 7 Electron micrograph of a replica of Inconel 718 heat treated 1 hr 1950 deg F (1066 deg C) plus 24 hr at 1550 deg F (843 deg C). The phases present are $\gamma'$ (spherical particles), $\gamma''$ (plates), and $\beta$ (needles).**

**Materials Heat Treated 1 Hour at 1950 Deg F (1066 Deg C) and Aged 2 and 24 Hours at 1550 Deg F (843 Deg C).** X-ray diffraction indicated that small amounts of $\beta$ phase formed during the aging treatments (Table 4). In micrographs, this phase was evident as needles, predominately alongside grain boundaries. The areas adjacent to grain boundaries and the $\beta$ phase were depleted of $\gamma''$ (Fig. 7). A relatively small amount of $\gamma'$ was present as particles about 450 Å and 1100 Å in diameter for the 2 and 24 hr treatments, respectively. The majority of the precipitate particles were plates of $\gamma''$ (precipitates coherently with the *c*-axis normal to the plane of the plates and along any of the three $\{110\}$ fcc directions—reference [5]). The approximate average thickness and length of the plates were, respectively, 200 Å and 1000 Å for the 2 hr treatment and 500 Å and 4000 Å for the 24 hr treatment.

The dislocation structures in tested specimens indicated that after aging 2 and 24 hr at 1500 deg F (843 deg C), the $\gamma'/\gamma''$ were smaller and larger than the critical size, respectively.

**Material Solution Treated 1 and 10 Hours at 1700 Deg F (927 Deg C) and Aged 3 Hours at 1325 Deg F (718 Deg C) and 48 Hours at 1350 Deg F (732 Deg C).** All of the heat treated materials contained Cb, Ti(C, N), $\gamma'/\gamma''$ and $\beta$ phases (Table 4). $Ni_3Cb$ needles precipitated during heat treatment at 1700 deg F (927 deg C). A

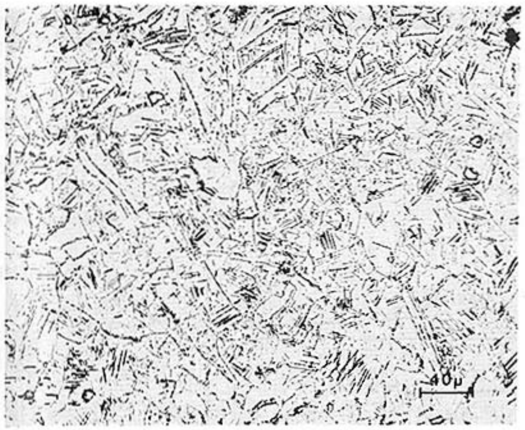


Fig. 8(*a*) 10 hr 1700 deg F (927 deg C)

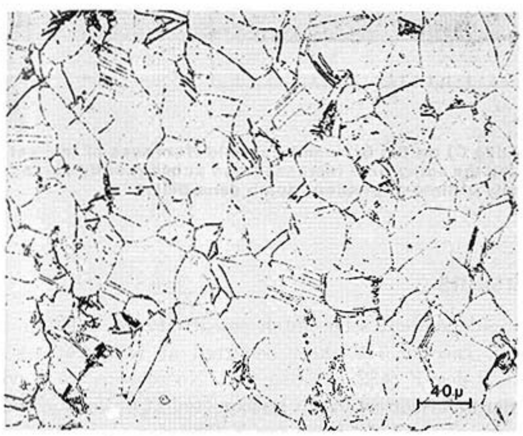


Fig. 8(*b*) 1 hr 1700 deg F (927 deg C)

**Fig. 8 Optical micrographs of Inconel 718 showing the $\beta$ phase that precipitated during the 1700 deg F (927 deg C) "solution" treatments**

much larger amount of $\beta$ phase was present after the 10 hr exposure than the 1 hr treatment (Fig. 8). Aging 3 hr at 1325 deg F (718 deg C) and 48 hr at 1350 deg F (732 deg C) after solution treatment at 1700 deg F (927 deg C) resulted in $\gamma'/\gamma''$ particles about 60 Å and 200 Å in diameter, respectively. [These $\gamma'/\gamma''$ particles are smaller than those produced by similar aging treatments after solution treatment at 1950 deg F (1066 deg C).]

For the material heat treated 1 hr at 1700 deg F (927 deg C) plus 3 hr at 1325 deg F (718 deg C) and tested at 1000 deg F (538 deg C), [at 130 ksi (896 MN/m$^2$) ruptured in 5613 hr] the deformation was localized (Fig. 9). In many cases, the dislocations in pileups were dissociated to form stacking fault ribbons. This type of deformation was not expected, because in the presence of $\gamma''$, it requires coplanar motion of multiple dislocations. Four whole dislocations must move along the same plane to restore order for all three orientations of $\gamma''$ [7]. (The presence of $\gamma''$ was confirmed by electron diffraction.) Growth of $\gamma'/\gamma''$ occurred during exposure of the specimen tested at 1200 deg F (649 deg C) [at 65 ksi (448MN/m$^2$) ruptured in 937 hr]. As a result, the dislocations bypassed the $\gamma'/\gamma''$ particles (about 250 Å in diameter).

Similar dislocation structures were evident for tested specimens of the material heat treated 10 hr at 1700 deg F (927 deg C) plus 3 hr at 1325 deg F (718 deg C).

Results indicated that after heat treatment 10 hr at 1700 deg F (927 deg C) plus 48 hr at 1350 deg F (732 deg C) the $\gamma'/\gamma''$ particle (200 Å in diameter) were larger than the critical size.

The foregoing observations indicate that the critical sizes for these materials were smaller than for those solution treated at 1950 deg F (1066 deg C). This could reflect different $\gamma'/\gamma''$ volume fractions. Reportedly, decreasing the amount of precipitate lowers the critical size [9]. Extensive precipitation of $\beta$ phase must decrease the amount of Cb available to from $\gamma''$. Therefore less $\gamma'/\gamma''$ was probably present in the materials aged after solution treatment at 1700 deg F (927 deg C) than those aged after heat treatment at 1950 deg F (1066 deg C).

**Correlation of the Time-Dependent Notch Sensitivity With the Dislocation Structure.** A correlation existed between the dislocation motion mechanism and the time-dependent notch sensitivity. The relationship was the same as evident for Waspaloy [2]. Shearing the precipitate particles by dislocations resulted in greater susceptibility to time-dependent notch sensitivity than when they were bypassed. For the materials heat treated 1 hr at 1950 deg F (1066 deg C) plus 48 hr at 1350 deg F (732 deg C), 1 hr at 1950 deg F (1066 deg C) plus 2 hr at 1550 deg F (843 deg C), 1 hr at 1700 deg F (927 deg C) plus 3 hr at 1325 deg F (718 deg C) and 10 hr at 1700 deg F (927 deg C) plus 3 hr at 1325 deg F (718 deg C), time-dependent notch sensitivity was observed at the lower test temperatures. During these tests, the $\gamma'/\gamma''$ particles were sheared by dislocations and the deformation was localized. During the higher temperature tests, growth of the $\gamma'$ and $\gamma''$ precipitates occurred. This resulted in a change of dislocation motion mechanism to "bypassing" so that a homogeneous distribution of dislocations resulted. This correlates with the elimination of time-dependent notch sensitivity with increasing test temperature.

For the materials heat treated 1 hr at 1950 deg F (1066 deg C) plus 24 hr at 1550 deg F (843 deg C) and 10 hr at 1700 deg F (927 deg C) plus 48 hr at 1350 deg F (732 deg C), the dislocations were homogeneously distributed for all test conditions and no time-dependent notch sensitivity was observed.

There was no evidence to indicate that the other heat treated materials, for which tested specimens were not studied, would not follow the foregoing correlation.

It is of interest to compare the behavior of materials with a given aging treatment, e. g., 48 hr at 1350 deg F (732 deg C). The time-dependent notch sensitivity was severe for the material solution treated at 1950 deg F (1066 deg C). Decreasing

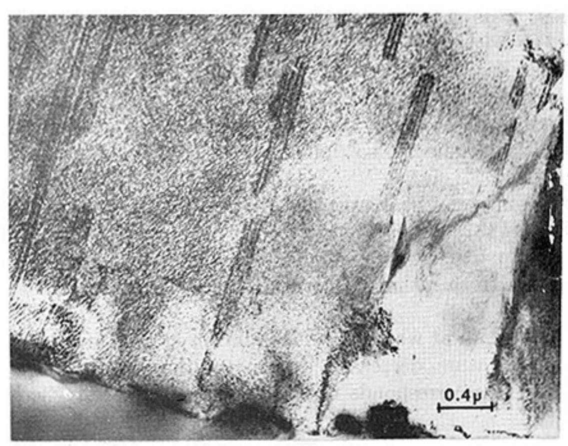


**Fig. 9 Transmission electron micrograph of Inconel 718 heat treated 1 hr at 1700 deg F (927 deg C) plus 3 hr at 1325 deg F (718 deg C) and creep-rupture tested at 130 ksi (896 MN/m$^2$) at 1000 deg F (538 deg C) (ruptured in 5613 hr at 3.5 percent elongation). The deformation was localized. The dislocation sheared the $\gamma'/\gamma''$ particles and were, in many cases, extended to form stacking fault ribbons.**

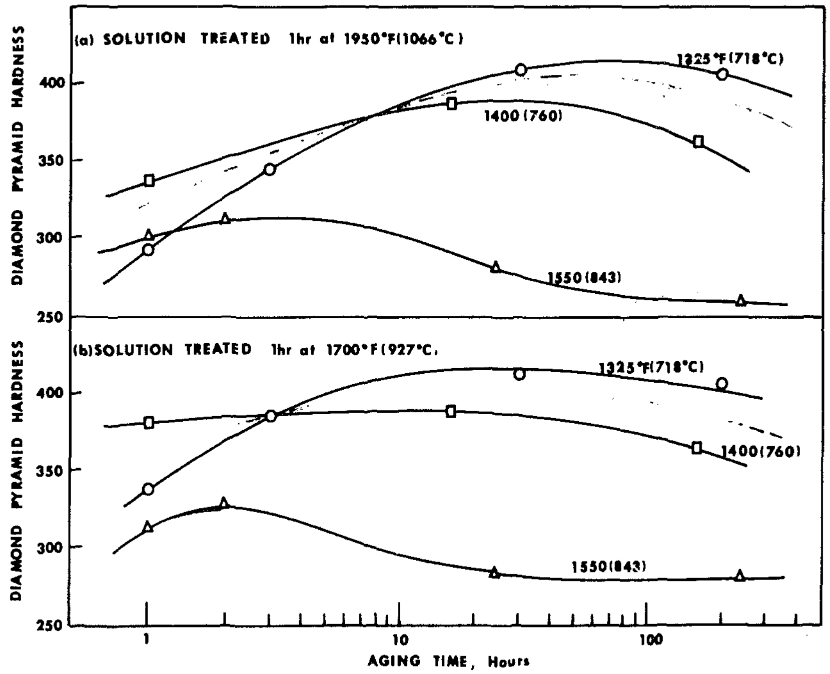


**Fig. 10 Effect of aging exposures at 1325, 1400, and 1550 deg F (718, 760, and 843 deg C) on the Diamond Pyramid Hardness of Inconel 718 *sheet solution treated at 1950 deg F and at 1700 deg F (1066 and 927 deg C). Increasing the aging time increased and subsequently decreased* the hardness. This corresponds to an increase followed by a decrease in severity of time-dependent notch sensitivity.**

the solution temperature to 1800 deg F (982 deg C) decreased the notch sensitivity, until for the 1700 deg F (927 deg C) treatment, none was observed. This is consistent with the metallographic observation that the "critical" size decreased with decreasing solution temperature.

Any influence of variations in the grain boundary characteristics on notch sensitivity was not evident from the results. Nor was there in the study of Waspaloy [2]. As previously discussed [2], this suggests that the strong dependence of notch sensitive behavior on the morphology of the $\gamma''$ and/or $\gamma'$ precipitates overshadows effects from variations in grain boundary characteristics.

**Hardness Testing.** Results for Waspaloy indicated that room temperature hardness tests could be used to monitor $\gamma'$ size relative to the critical (maximum hardness) and hence to indicate probable notch sensitive behavior [2]. This was also evident from hardness tests conducted for a range of heat treatments of Inconel 718 (Fig. 10).

1 The hardness values of the material heat treated 1 hr at 1950 deg F (1066 deg C) plus 24 hr at 1550 deg F (843 deg C) indicated that the $\gamma'/\gamma''$ particles were larger than the critical size. Correspondingly, no time-dependent notch sensitivity was observed.

2 For material heat treated 1 hr at 1700 deg F (927 deg C) plus 3 hr at 1325 deg F (718 deg C), hardness tests indicated that the $\gamma'/\gamma''$ particles were smaller than the critical size. In accordance with this, the material exhibited time-dependent notch sensitivity.

3 The times at which the maximum in hardness occurred at each temperature decreased as the solution temperature decreased. This corresponds to the observed decrease in "critical size."

4 For some heat treated materials, the hardness tests indicated that the $\gamma'/\gamma''$ sizes were near the critical and, therefore, it would not be possible to predict the time-dependent notch sensitive behavior. In no case did the hardness values incorrectly indicate the notch sensitive behavior.

## Conclusions

1 Time-dependent edge-notch sensitivity of 0.030-in. (0.75 mm) thick Inconel 718 sheet occurred at temperatures from 900 to 1200 deg F (482–649 deg C). No reasons were evident why similar behavior could not be expected at prolonged times at lower temperatures. At 1400 deg F (760 deg C) no notch sensitivity was observed.

2 Time-dependent notch sensitivity occurred when (i) the notched specimen loads were below the approximate 0.2 percent smooth specimen offset yield strength; and (ii) test data from smooth specimens indicated that small amounts of creep consumed large fractions of creep-rupture life.

3 Decreasing the solution temperature or increasing the time and/or temperature of the aging treatment decreased the susceptibility to the time-dependent notch sensitivity. None was observed for materials heat treated 1 hr at 1950 deg F (1066 deg C) plus 24 hr at 1550 deg F (843 deg C), 10 hr at 1700 deg F (927 deg C) plus 48 hr at 1350 deg F (732 deg C) and 1 hr at 1700 deg F (927 deg C) plus 2 hr at 1550 deg F (843 deg C).

Commonly used aging treatments: 1350 deg F (732 deg C)/8 hr, F. C. to 1200 deg F (649 deg C) in 12 hr, A. C. [after solution treatment at 1950 deg F (1066 deg C)] and 1325 deg F (718 deg C)/8 hr, F. C. to 1150 deg F (621 deg C) in 10 hr, A. C. [after solution treatment at 1750 deg F (954 deg C)] result in notch sensitive behavior.

4 Variations in notch sensitivity were correlated with changes in the dislocation motion mechanism. $Ni_3Cb$(bct) particles (and gamma prime) smaller than a critical size were sheared by dislocations. This gave rise to localized deformation and time-dependent notch sensitive behavior. Larger particles were bypassed by dislocations. Under these conditions, the deformation was homogeneous and no time-dependent notch sensitivity was observed.

5 Hardness tests indicate particle size relative to the critical and are, therefore, useful in the prediction of notch sensitive behavior.

6 Most important, the results showed that the notch sensi-

tive behavior of Inconel 718 could be correlated with the same mechanical characteristics and similar microstructural features as evident for Waspaloy [1, 2]. This would suggest even wider applicability of the results.

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