# NIMONIC® alloy PE16

NIMONIC® alloy PE16 is a wrought nickel-chromium-iron-base alloy strengthened by additions of molybdenum, titanium and aluminum. It was developed for service mainly in the temperature range 500-750°C, and combines the high strength of the age hardening nickel-base alloys with excellent fabricational characteristics.

The alloy is used in gas turbine flame tubes, nuclear reactor parts, missile hot components, superheater tubing, and aircraft ducting systems.

## Composition, %

| | |
|---|---|
| Carbon | 0.04-0.08 |
| Silicon | 0.5 max. |
| Manganese | 0.2 max. |
| Sulfur | 0.015 max. |
| Silver | 0.0005 max. |
| Aluminum | 1.1-1.3 |
| Boron | 0.005 max. |
| Bismuth | 0.0001 max. |
| Cobalt | 2.0 max. |
| Chromium | 15.5-17.5 |
| Copper | 0.5 max. |
| Molybdenum | 2.8-3.8 |
| Nickel + Cobalt | 42.0-45.0 |
| Lead | 0.0015 max. |
| Titanium | 1.1-1.3 |
| Zirconium | 0.02-0.04 |
| Iron | Balance* |

*Reference to the ‘balance’ of a composition does not guarantee this is exclusively of the element mentioned but that it predominates and others are present only in minimal quantities.

## Physical Properties

Table 1- Physical Properties

| | |
|---|---|
| Density, $Mg/m^3$ | 8.00 |
| $lb/in^3$ | 0.289 |
| Melting Range | |
| Liquidus Temperature, °C | 1355 |
| Solidus Temperature, °C | 1310 |
| Specific Heat, (20-400°C), J/kg•°C | 544 |

The exact density of NIMONIC alloy PE16 is dependent on compositional variation within the release specification, on form and on heat treatment.

## Heat Treatment

The heat treatment recommended for NIMONIC alloy PE16 is dependent on the intended service condition. Two are recommended, namely:

(a) 4 h/1040°C/AC + 1 h/900°C/AC + 8 h/750°C/AC
(b) 2 h/1040°C/AC + 2 h/800°C/AC + 16 h/700°C/AC

Data shows that heat treatment (b) gives slightly higher creep-rupture properties at longer times. Heat treatment (a) gives material of greater metallurgical stablility, and is recommended for general applications. If high proof stress up to 600°C is the sole criterion then heat treatment (b) should be applied.

For both the above heat treatments, the first stage at 1040°C should be for 5-15 minutes for thin section material such as sheet.

### *WELDING*

Welding should be carried out in the solution-treated condition. Post-weld heat treatments of either

1 h/900°C/AC + 8 h/750°C/AC or
2 h/800°C/AC + 16h/700°C/AC

should then be applied, depending on the intended service condition. This practice will generally yield good properties in both the weld metal and weld area.

Details of welding practice are given subsequently under Fabrication.

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## Physical Properties (continued)

**Table 2** - Thermal Conductivity and Electrical Resistivity

| °C | Thermal Conductivity W/m °C | Electrical Resistivity at 20°C = 1.1 MΩm |
|---|---|---|
| | | Relative Resistance |
| 20 | 11.72 | 1.000 |
| 100 | 13.82 | 1.022 |
| 200 | 15.07 | 1.047 |
| 300 | 16.75 | 1.073 |
| 400 | 18.42 | 1.094 |
| 500 | 19.68 | 1.109 |
| 600 | 21.35 | 1.121 |
| 700 | 23.03 | 1.132 |
| 800 | 25.12 | 1.129 |
| 900 | 26.80 | 1.129 |
| 1000 | 28.47 | 1.139 |

**Table 3** - Mean Coefficient of Linear Thermal Expansion

| °C | μm/m - °C |
|---|---|
| 20-100 | 13.8 |
| 20-200 | 14.6 |
| 20-300 | 14.9 |
| 20-400 | 15.1 |
| 20-500 | 15.5 |
| 20-600 | 16.0 |
| 20-700 | 16.4 |
| 20-800 | 17.2 |
| 20-900 | 18.0 |
| 20-1000 | 18.5 |

## Dynamic Moduli

**Table 4** - Dynamic Moduli

| °C | Dynamic Young's Modulus GPa | Dynamic Torsional Modulus GPa |
|---|---|---|
| 20 | 198 | 74 |
| 100 | 193 | 73 |
| 200 | 187 | 71 |
| 300 | 180 | 69 |
| 400 | 175 | 66 |
| 500 | 168 | 62 |
| 600 | 161 | 59 |
| 700 | 153 | 55 |
| 800 | 144 | 53 |
| 900 | 134 | 48 |
| 1000 | 122 | 42 |

## Tensile Properties

The data given in Tables 5 and 6, and presented graphically in Figures 1 and 2, are for extruded and subsequently cold stretched bar after application of the two recommended heat treatments.

Strain rate 0.005/min to proof stress (at room temperature), 0.002/min to proof stress (at elevated temperatures) and 0.1/min thereafter.

**Table 5** - Tensile Properties of Bar

| Heat treatment 4 h/1040°C/AC + 1 h/900°C/AC + 8 h/750°C/AC | | | | |
|---|---|---|---|---|
| °C | 0.2% Proof Stress MPa | Tensile Strength MPa | Elongation on 5.56 √So, % | Reduction of Area % |
| 20 | 450 | 830 | 29 | 55 |
| 100 | 425 | 810 | 29 | 54 |
| 200 | 395 | 780 | 30 | 54 |
| 300 | 380 | 770 | 31 | 54 |
| 400 | 365 | 750 | 31 | 55 |
| 500 | 380 | 730 | 31 | 55 |
| 600 | 410 | 680 | 30 | 51 |
| 700 | 410 | 590 | 28 | 35 |
| 800 | 290 | 350 | 37 | 52 |
| 900 | 100 | 140 | 74 | 96 |
| 1000 | 50 | 80 | >100 | 98 |

**Table 6** - Tensile Properties of Bar

| Heat treatment 2 h/1040°C/AC + 2 h/800°C/AC + 16 h/700°C/AC | | | | |
|---|---|---|---|---|
| °C | 0.2% Proof Stress MPa | Tensile Strength MPa | Elongation on 5.56 √So, % | Reduction of Area % |
| 20 | 525 | 880 | 37 | 54 |
| 100 | 500 | 850 | 35 | 55 |
| 200 | 480 | 810 | 33 | 55 |
| 300 | 470 | 800 | 29 | 55 |
| 400 | 465 | 780 | 27 | 54 |
| 500 | 470 | 750 | 26 | 53 |
| 600 | 475 | 730 | 27 | 51 |
| 700 | 445 | 620 | 33 | 51 |
| 800 | 290 | 380 | 53 | 63 |
| 900 | 100 | 140 | >100 | 94 |
| 1000 | 50 | 90 | >100 | 99 |

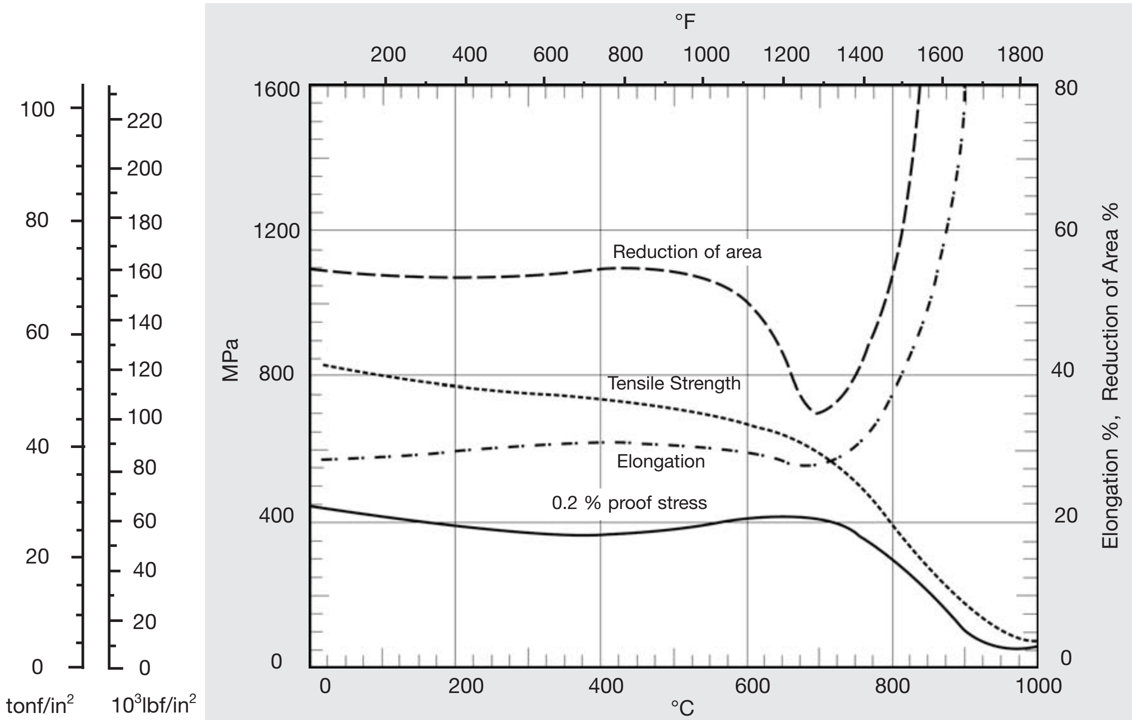


**Figure 1.** Tensile properties of bar
Heat treatment 4 h/1040°C/AC + 1 h/900°C/AC + 8 h/750°C/AC

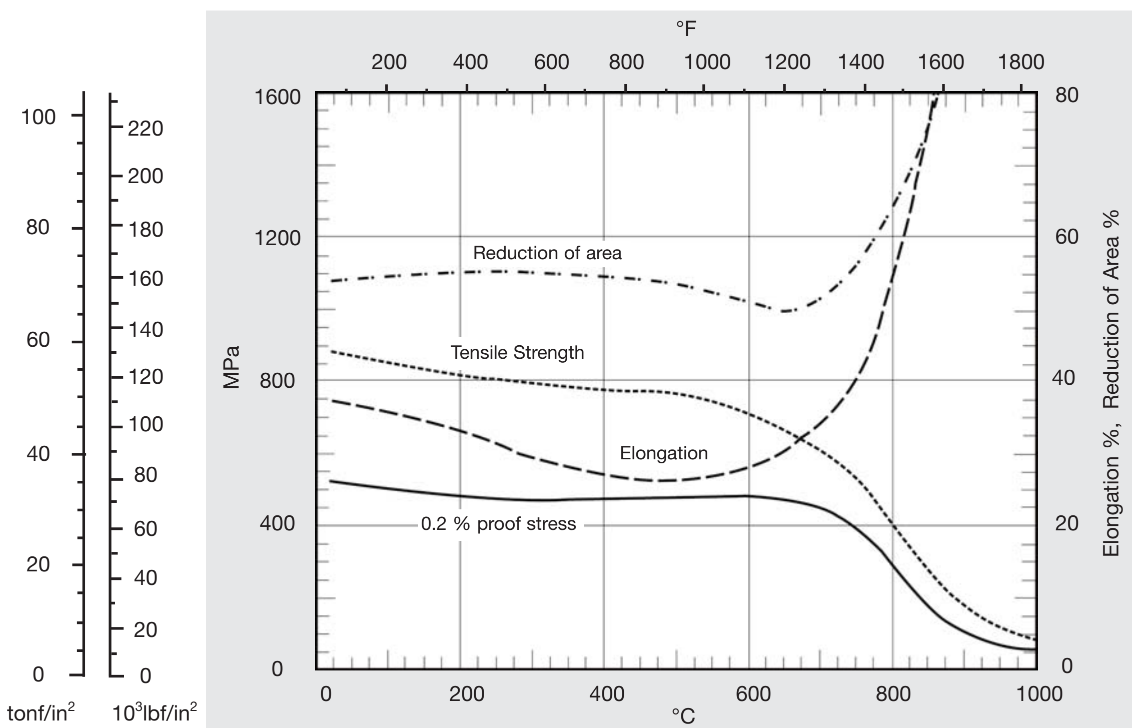


**Figure 2.** Tensile properties of bar
Heat treatment 2 h/1040°C/AC + 2 h/800°C/AC + 16 h/700°C/AC

# Tensile Properties (continued)

**Table 7** - Tensile Properties of Sheet

| Heat treatment 15 min/1040°C/AC + 1 h/900°C/AC + 8 h/750°C/AC | | | |
|---|---|---|---|
| °C | 0.2% Proof Stress MPa | Tensile Strength MPa | Elongation on 50 mm, % |
| 20 | 539 | 950 | 26.9 |
| 100 | 507 | 902 | 26.5 |
| 200 | 483 | 881 | 23.2 |
| 300 | 481 | 857 | 24.8 |
| 400 | 479 | 833 | 26.8 |
| 500 | 476 | 809 | 24.3 |
| 600 | 483 | 806 | 24.5 |
| 700 | 489 | 672 | 36.8 |
| 800 | 306 | 380 | 46.1 |
| 900 | 86 | 136 | 111.1 |
| 1000 | 45 | 73 | 101.6 |

**Table 8** - Tensile Properties of Sheet

| Heat treatment 15 min/1040°C/AC + 2 h/800°C/AC + 16 h/700°C/AC | | | |
|---|---|---|---|
| °C | 0.2% Proof Stress MPa | Tensile Strength MPa | Elongation on 50 mm, % |
| 20 | 607 | 993 | 25.2 |
| 400 | 585 | 892 | 21.4 |
| 500 | 565 | 871 | 20.4 |
| 600 | 565 | 848 | 18.4 |
| 700 | 522 | 666 | 33.8 |
| 800 | 309 | 392 | 54.1 |

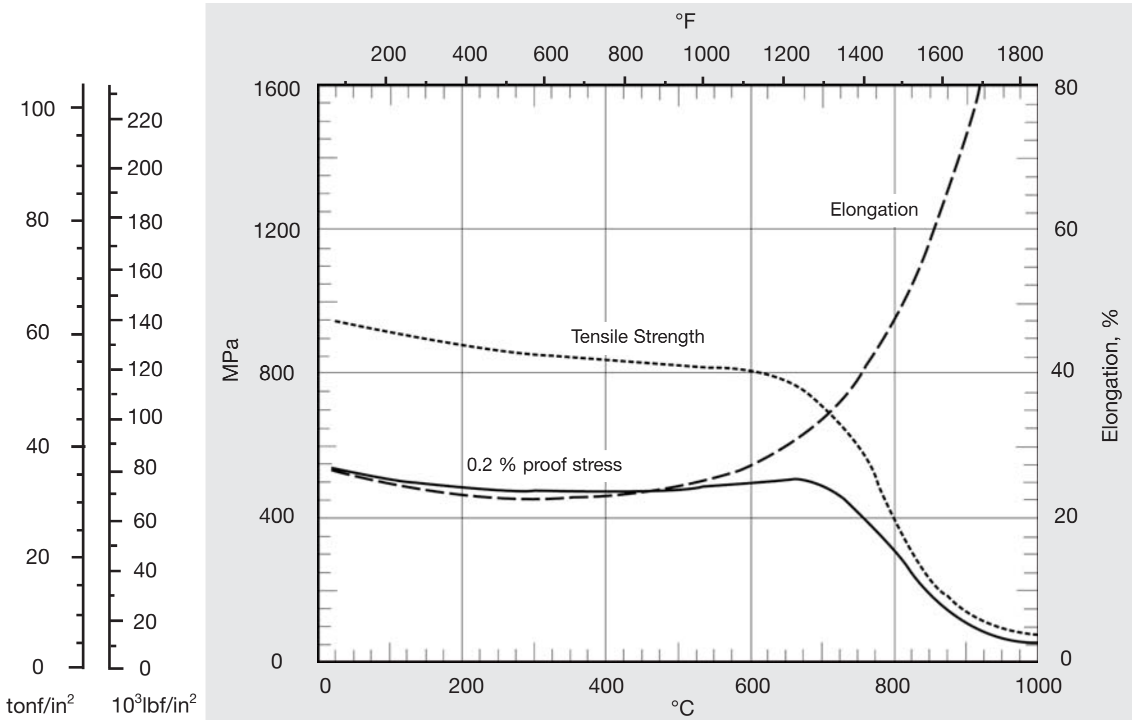


**Figure 3.** Tensile properties of sheet
Heat treatment 15 min/1040°C/AC + 1 h/900°C/AC + 8 h/750°C/AC

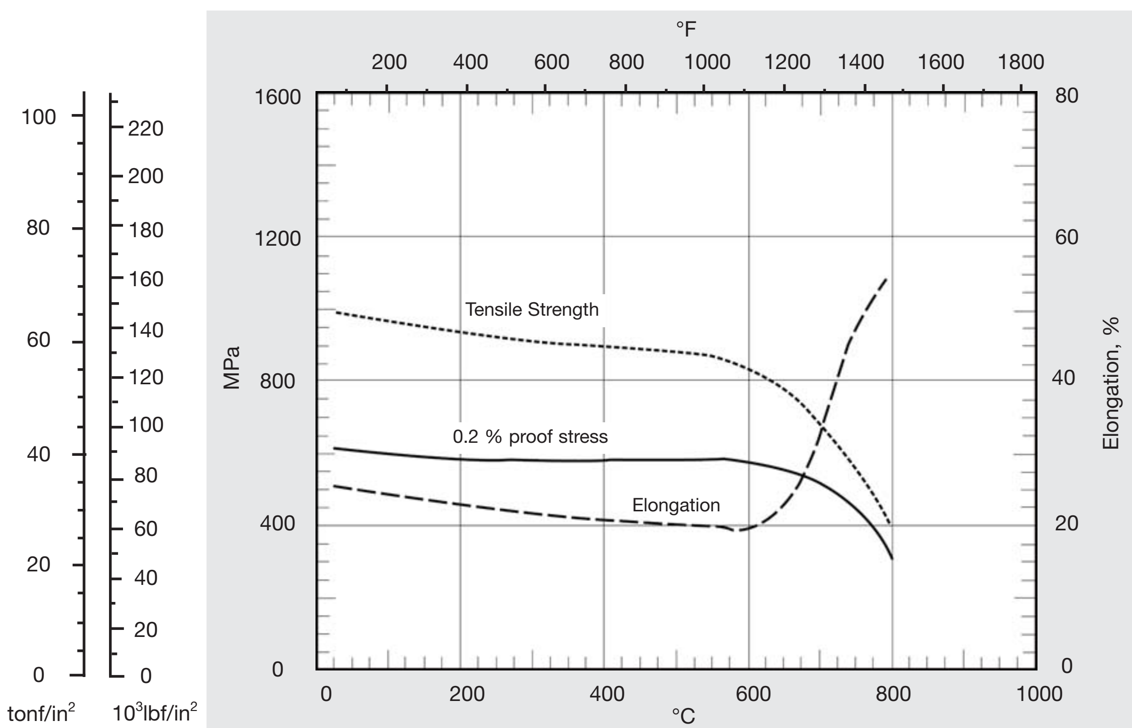


**Figure 4.** Tensile properties of sheet
Heat treatment 15 min/1040°C/AC + 2 h/800°C/AC + 16 h/700°C/AC

**Table 9** - Tensile Properties of Welded Sheet

| Hounsfield Tensometer tests for plain and welded cold-rolled sheet 1.6 mm thick | | | | | | | |
|---|---|---|---|---|---|---|---|
| Type of sample | Test Temperature °C | Post-weld heat treatment or aging treatment | | | | | |
| | | 1 h/900°C/AC + 8 h/750°C/AC | | | 2 h/800°C/AC + 16 h/700°C/AC | | |
| | | Tensile Strength MPa | Elongation on 25 mm % | Location of Fracture | Tensile Strength MPa | Elongation on 25 mm % | Location of Fracture |
| Plain | 550 | 800 | 25 | — | 860 | 24 | — |
| | | 800 | 28 | — | 830 | 20 | — |
| | 650 | 710 | 33 | — | 760 | 32 | — |
| | | 700 | 34 | — | 760 | 30 | — |
| Autogenous weld | 550 | 700 | 13 | W | 790 | 9 | W |
| | | 700 | 13 | W | 790 | 13 | W |
| | 650 | 670 | 11 | W | 710 | 10 | W |
| | | 640 | 9 | W | 730 | 16 | W |
| NIMONIC alloy PE16 filler metal weld, not dressed | 550 | 750 | 16 | W | 830 | 17 | PM |
| | | 790 | 20 | PM | 850 | 21 | PM |
| | 650 | 700 | 27 | PM | 760 | 29 | PM |
| | | 730 | 27 | PM | 760 | 24 | PM |
| NIMONIC alloy PE16 filler metal weld, surface ground | 550 | 600 | 9 | W | 760 | 10 | W |
| | | 620 | 9 | W | 750 | 8 | W |
| | 650 | 620 | 8 | W | 730 | 11 | W |
| | | 590 | 8 | W | 680 | 7 | W |

W= weld metal    Cross head speed= 1.6 mm/min
PM= parent metal    Equivalent strain rate= 0.005/min

## Creep Properties

The creep properties are given for bar, sheet and tube after the two recommended heat treatments. Test data at 600°C have deliberately been excluded because the creep-stresses involved are generally in the region of proof stress. Under these conditions the creep characteristics are markedly influenced by the method of applying the stress and the amount of strain on loading. In addition the significant increase in test data scatter at around proof stress calls for greater caution in the interpretation of the results so far obtained.

### *Sheet*

Creep-rupture properties for cold-rolled sheet are shown as a double curve by Larson-Miller presentation in Figure 7, and by log stress-log time curves in Figure 8. Again the Larson-Miller curves should not be used for extrapolations much outside the test conditions indicated by the corresponding derived creep-rupture properties given in Tables 14 and 15.

Total plastic strain data for both heat treatments, carried out on sheet 1.2 mm thick made from the same cast, are given in Tables 16 and 17.

### *Bar*

Creep-rupture properties for NIMONIC alloy PE16 bar, by Larson-Miller presentation, are shown in Figure 5, and by log stress-log time curve in Figure 6. The difference in the effect of the two recommended heat treatments on the creep-rupture properties of bar cannot clearly be delineated by two curves on the Larson-Miller diagram. A single mean curve is therefore given.

Derived creep-rupture properties and total plastic strain data are shown for both heat treatments in Tables 10 to 13 inclusive.

The Larson-Miller diagram should not be used for extra-polations much outside the range of temperature and time indicated by the derived creep-rupture properties shown in Tables 10 and 11.

Total plastic strain data are shown for both heat treatments in Tables 12 and 13.

### *Tube*

Creep-rupture data for cold-drawn tube are shown by log stress-log time curves in Figure 9. Derived creep-rupture properties are given in Tables 18 and 19.

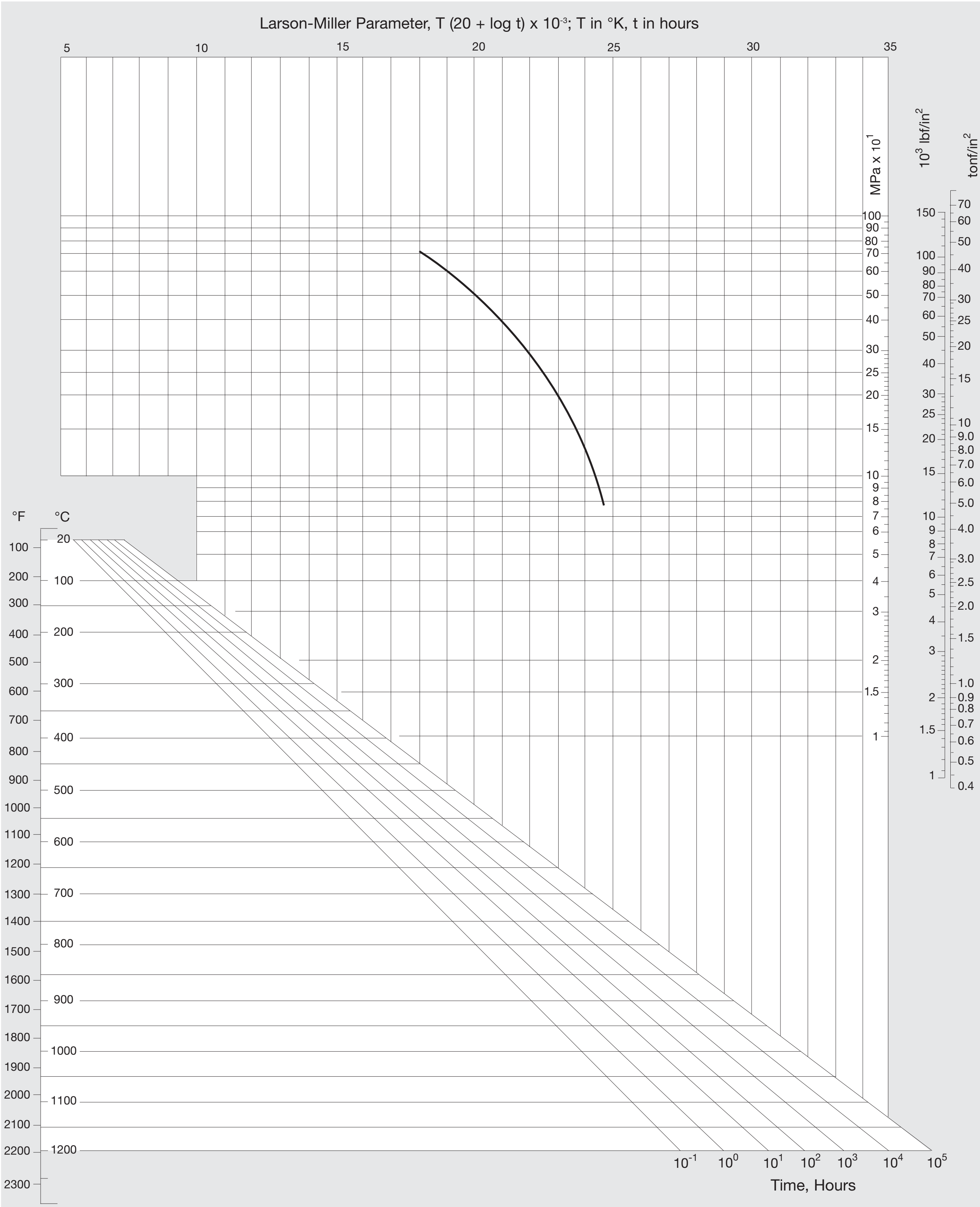


**Figure 5.** Creep-rupture properties of bar. Heat treatment: 4 h/1040°C/AC + 1 h/900°/AC + 8 h/750°/AC.

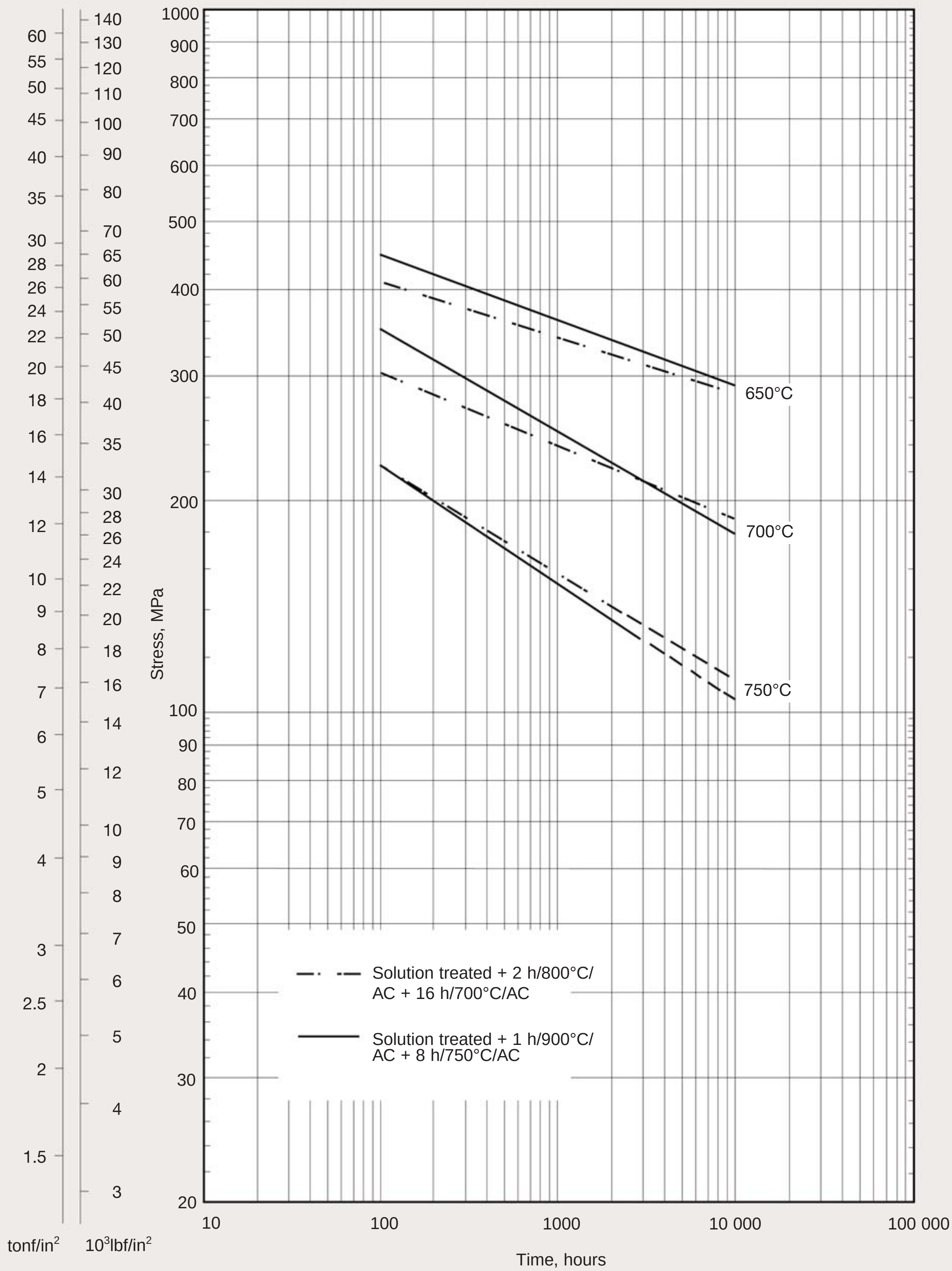


**Figure 6.** Creep-rupture properties for bar.

**Table 10** - Creep-Rupture Properties of Bar

| Solution treated and then aged 1 h /900°C/AC + 8 h/750°C/AC | | | | | |
|---|---|---|---|---|---|
| °C | Stress, MPa, to produce rupture in | | | | Elongation at fracture on 5.65 √So % |
| | 300 h | 1000 h | 3000 h | 10 000 h | |
| 650 | — | 363 | 332 | 285 | 13-20 |
| 700 | 301 | 255 | 217 | 178 | 21-28 |
| 750 | 185 | 155 | 128 | 100 | 13-27 |

**Table 11** - Creep-Rupture Properties of Bar

| Solution treated and then aged 2 h /800°C/AC + 16 h/700°C/AC | | | | | | |
|---|---|---|---|---|---|---|
| °C | Stress, MPa, to produce rupture in | | | | | Elongation at fracture on 5.65 √So, % |
| | 100 h | 300 h | 1000 h | 3000 h | 10 000 h | |
| 650 | — | 371 | 340 | 317 | 279 | 15-19 |
| 700 | 301 | 271 | 243 | 217 | 178 | 26-29 |
| 750 | — | 185 | 162 | 132 | (108) | — |

( ) Extrapolated data

**Table 12** - Total Plastic Strain Data for Bar

| Solution treated and then aged 1 h/900°C/AC + 8 h/750°/AC | | | | | | |
|---|---|---|---|---|---|---|
| **Test Temperature °C** | **Strain, %** | **Stress, MPa, to give total plastic strain in** | | | | |
| | | **100 h** | **300 h** | **1000 h** | **3000 h** | **10 000 h** |
| **650** | 0.1 | 332 | 293 | 255 | 217 | (170) |
| | 0.2 | 355 | 317 | 279 | 239 | 201 |
| | 0.5 | 386 | 347 | 309 | 271 | 231 |
| | 1.0 | 394 | 355 | 317 | 285 | 247 |
| **700** | 0.1 | 209 | 185 | 155 | 132 | — |
| | 0.2 | 239 | 209 | 178 | 148 | 115 |
| | 0.5 | 263 | 231 | 201 | 170 | 137 |
| | 1.0 | 279 | 247 | 209 | 185 | 155 |
| **750** | 0.1 | 132 | 116 | 89 | 70 | 53 |
| | 0.2 | 151 | 131 | 108 | 86 | 64 |
| | 0.5 | 162 | 145 | 124 | 105 | 85 |
| | 1.0 | 170 | 153 | 131 | 113 | 92 |

( ) Extrapolated data

**Table 13** - Total Plastic Strain Data for Bar

| Solution treated and then aged 2 h/800°C/AC + 16 h/700°/AC | | | | | | |
|---|---|---|---|---|---|---|
| **Test Temperature °C** | **Strain, %** | **Stress, MPa, to give total plastic strain in** | | | | |
| | | **100 h** | **300 h** | **1000 h** | **3000 h** | **10 000 h** |
| **650** | 0.1 | 317 | 285 | 247 | 216 | 185 |
| | 0.2 | 332 | 305 | 279 | 239 | 209 |
| | 0.5 | 347 | 332 | 293 | 263 | 224 |
| | 1.0 | 355 | 332 | 309 | 271 | 231 |
| **700** | 0.1 | 209 | 178 | 150 | 124 | (93) |
| | 0.2 | 231 | 201 | 170 | 145 | 115 |
| | 0.5 | 255 | 224 | 193 | 170 | 137 |
| | 1.0 | 263 | 239 | 209 | 178 | 151 |
| **750** | 0.1 | 124 | 99 | 77 | 60 | 46 |
| | 0.2 | 151 | 128 | 104 | 78 | 57 |
| | 0.5 | 162 | 145 | 124 | 105 | (85) |
| | 1.0 | 180 | 155 | 131 | 113 | 93 |

( ) Extrapolated data

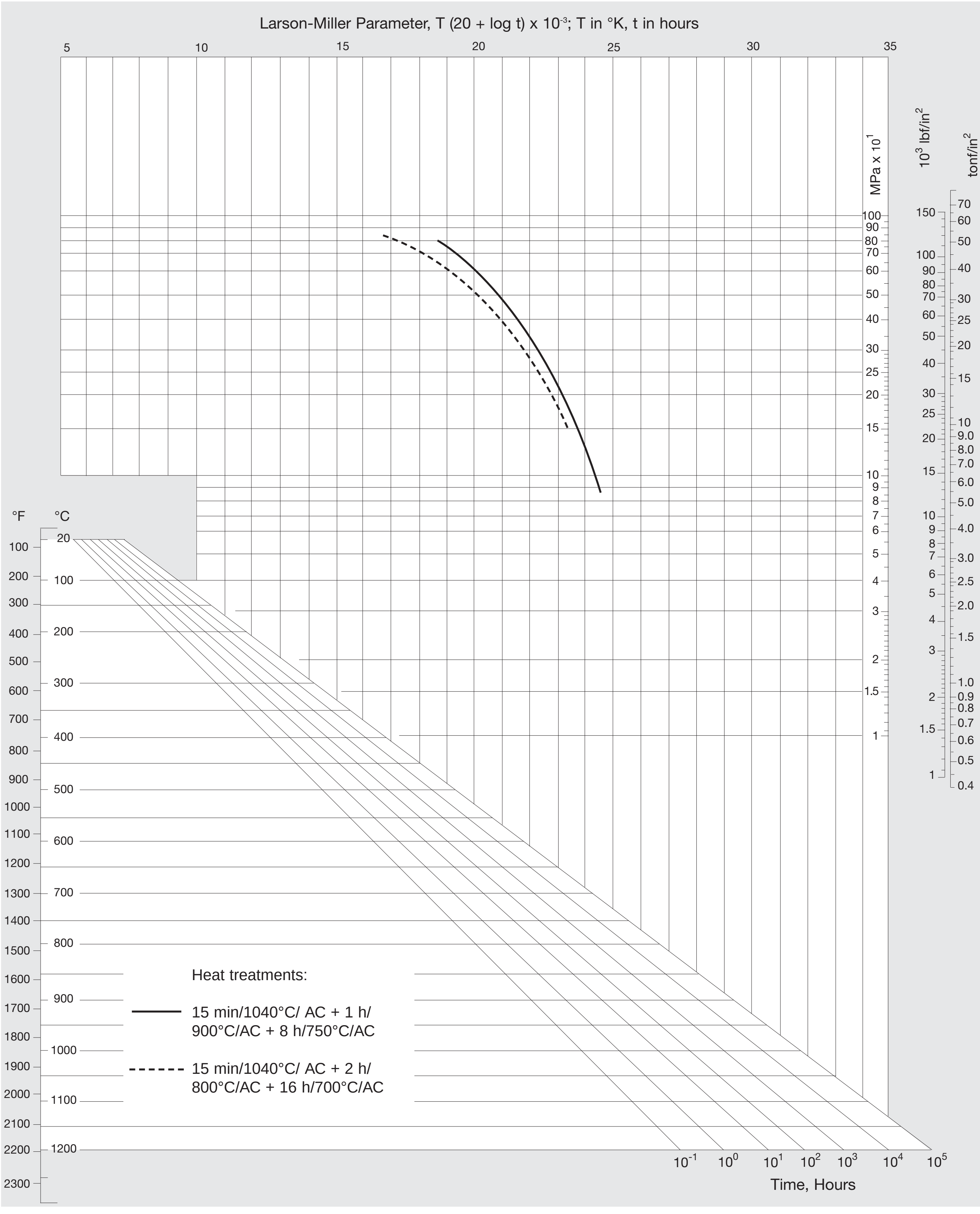


**Figure 7.** Creep-rupture properties of sheet.

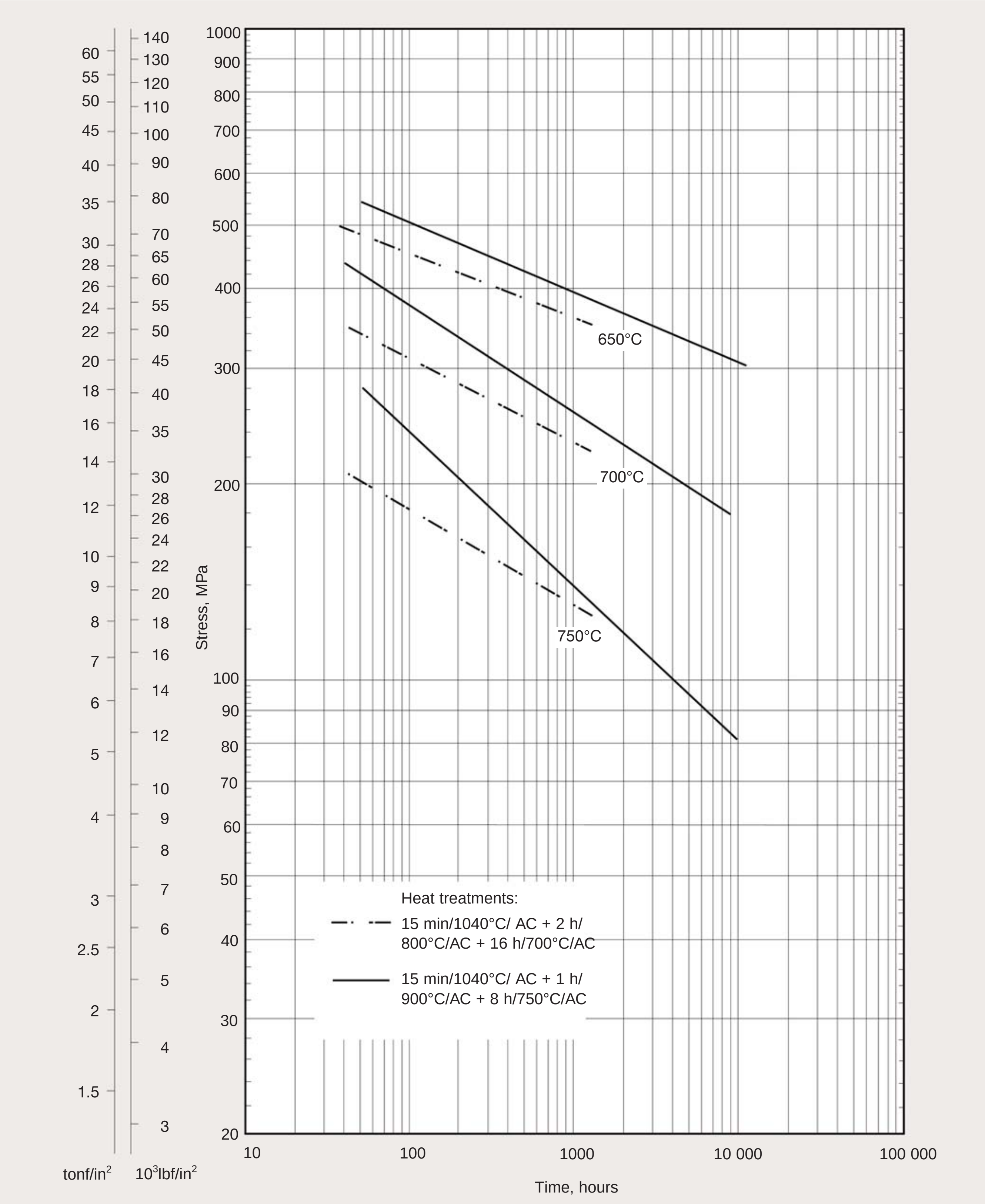


**Figure 8.** Creep-rupture properties of sheet.

**Table 14** - Creep-Rupture Properties of Sheet

| Heat treatment 15 min/1040°C/AC + 1 h/900°C/AC + 8 h/750°C/AC | | | | | | | |
|---|---|---|---|---|---|---|---|
| °C | Stress, MPa, to give rupture in | | | | | | Elongation at fracture on 50 mm, % |
| | 50 h | 100 h | 300 h | 1000 h | 3000 h | 5000 h | |
| 650 | 530 | 510 | 460 | 400 | 340 | 320 | 12-14 |
| 700 | 400 | 370 | 325 | 260 | 217 | 185 | 11-20 |
| 750 | 280 | 250 | 185 | 142 | 110 | 94 | 14-20 |

**Table 15** - Creep-Rupture Properties of Sheet

| Heat treatment 15 min/1040°C/AC + 2 h/800°C/AC + 16 h/700°C/AC | | | | | |
|---|---|---|---|---|---|
| °C | Stress, MPa, to give rupture in | | | | Elongation at fracture on 50 mm, % |
| | 50 h | 100 h | 300 h | 1000 h | |
| 650 | 480 | 450 | 400 | 360 | 9-21 |
| 700 | 340 | 310 | 270 | 230 | 16-23 |
| 750 | 200 | 185 | 155 | 131 | 28-41 |

**Table 16** - Total Plastic Strain Data for Sheet

| Heat treatment 15 min/1040°C/AC + 1 h/900°/AC + 8 h/750°C/AC | | | | | | | |
|---|---|---|---|---|---|---|---|
| °C | Strain, % | Stress, MPa, to give total plastic strain in | | | | | |
| | | 50 h | 100 h | 300 h | 1000 h | 3000 h | 5000 h |
| 650 | 0.1 | 370 | 340 | 260 | 180 | — | — |
| | 0.2 | 430 | 390 | 320 | 280 | 200 | 170 |
| | 0.5 | 460 | 430 | 370 | 320 | 260 | 250 |
| | 1.0 | 490 | 460 | 400 | 340 | 290 | 280 |
| 700 | 0.1 | 200 | 170 | 127 | 78 | — | — |
| | 0.2 | 235 | 220 | 170 | 124 | 78 | — |
| | 0.5 | 290 | 260 | 220 | 170 | 129 | 110 |
| | 1.0 | 310 | 290 | 250 | 200 | 151 | 131 |
| 750 | 0.1 | 93 | 70 | 31 | <30 | <30 | <30 |
| | 0.2 | 131 | 97 | 62 | 37 | <30 | <30 |
| | 0.5 | 170 | 147 | 96 | 64 | 48 | 43 |
| | 1.0 | 185 | 170 | 131 | 81 | 62 | 54 |

**Table 17** - Total Plastic Strain Data for Sheet

| Heat treatment 15 min/1040°C/AC + 2 h/800°/AC + 16 h/700°C/AC | | | | | |
|---|---|---|---|---|---|
| °C | Strain, % | Stress, MPa, to give total plastic strain in | | | |
| | | 50 h | 100 h | 300 h | 1000 h |
| 650 | 0.1 | 330 | 310 | 280 | 240 |
| | 0.2 | 355 | 340 | 300 | 260 |
| | 0.5 | 390 | 360 | 330 | 285 |
| | 1.0 | 420 | 390 | 355 | 310 |
| 700 | 0.1 | 180 | 155 | 116 | 93 |
| | 0.2 | 210 | 185 | 147 | 116 |
| | 0.5 | 270 | 230 | 180 | 139 |
| | 1.0 | 310 | 270 | 210 | 162 |
| 750 | 0.1 | 54 | 38 | 24 | 16 |
| | 0.2 | 83 | 62 | 38 | 24 |
| | 0.5 | 124 | 100 | 70 | 46 |
| | 1.0 | 162 | 131 | 93 | 70 |

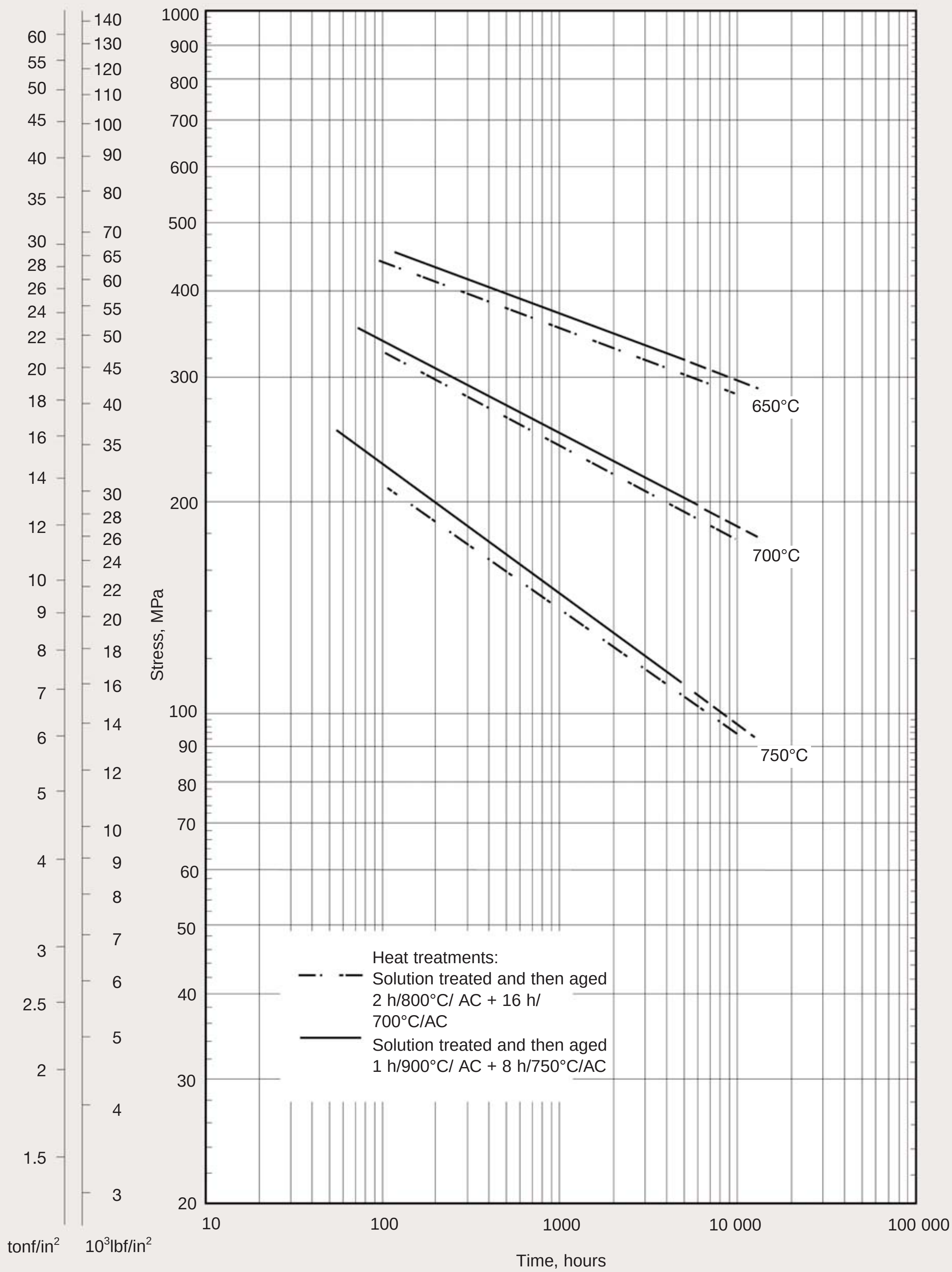


**Figure 9.** Creep-rupture properties of tube.

**Table 18** - Creep-Rupture Properties of Tube

| Solution treated and then aged 1 h /900°C/AC + 8 h/750°C/AC | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| °C | Stress, MPa, to produce rupture in | | | | | | | Elongation at fracture on 5.65 √So, % |
| | 50 h | 100 h | 300 h | 1000 h | 3000 h | 5000 h | 10 000 h | |
| 650 | — | 450 | 420 | 390 | 340 | 325 | (290) | 31-39 |
| 700 | 360 | 340 | 290 | 255 | 220 | 200 | (180) | 25-38 |
| 750 | 250 | 220 | 185 | 155 | 116 | 108 | (93) | 23-25 |

( ) Extrapolated data

**Table 19** - Creep-Rupture Properties of Tube

| Solution treated and then aged 2 h /800°C/AC + 16 h/700°C/AC | | | | | | |
|---|---|---|---|---|---|---|
| °C | Stress, MPa, to produce rupture in | | | | | Elongation at fracture on 5.65 √So, % |
| | 100 h | 300 h | 1000 h | 3000 h | 10 000 h | |
| 650 | 440 | 390 | 355 | 320 | 285 | 17-25 |
| 700 | 325 | 280 | 240 | 210 | 170 | 23-38 |
| 750 | 210 | 170 | 139 | 108 | 93 | 33-48 |

( ) Extrapolated data

## Impact Data

The room-temperature Charpy impact strength for NIMONIC alloy PE16 extruded and subsequently cold-stretched is in the region of 108 J after either of the recommended heat treatments.

Long term embrittlement of this alloy has been investigated by Charpy impact testing at room and elevated temperatures of material heat treated for 8 h/1040°C/AC + 1 h/900°C/AC + 8 h/750°C/AC, namely before finalization of the two currently recommended heat treatments. The data ginen in Tables 20 and 21 represent the finding of these investigations, and in general show the results of duplicate tests.

**Table 20** - Impact Values, J, at Room Temperature

| Soaking time h | Soaking Temperature, °C | | | | |
|---|---|---|---|---|---|
| | 500 | 600 | 650 | 700 | 800 |
| 30 | 133 : 109 | 103 : 98 | 95 : 98 | 98 : 100 | 128 : 125 |
| 100 | 110 : 104 | 95 : 90 | 88 : 95 | 88 : 84 | 123 : 117 |
| 300 | 110 : 111 | 91 : 94 | 81 : 85 | 79 : 71 | 106 : 110 |
| 1000 | 96 : 95 | 84 | 65 : 64 | 54 : 52 | 80 : 60 |
| 3000 | — | 75 : 79 | 46 : 48 | 35 : 29 | 57 : 54 |
| 10 000 | 117 : 102 | 57 : 62 | 34 : 52 | 26 : 29 | 58 : 61 |

**Table 21** - Impact Values, J, at Elevated Temperature

| Soaking time h | Soaking and Test Temperature, °C | | | | |
|---|---|---|---|---|---|
| | 500 | 600 | 650 | 700 | 800 |
| 30 | 95 : 100 | 100 : 92 | 76 | 81 : 81 | 109 : 114 |
| 100 | 109 : 103 | 80 : 87 | 76 : 76 | 76 : 79 | 113 : 110 |
| 300 | 95 : 96 | 80 : 77 | 71 : 72 | 73 : 71 | 111 : 103 |
| 1000 | 95 : 92 | 72 : 71 | 60 : 60 | 62 : 66 | 84 : 91 |
| 3000 | — | 62 : 73 | 57 : 49 | 50 : 52 | 65 : 75 |
| 10 000 | 106 : 109 | 65 : 62 | 58 : 56 | 46 : 38 | 84 : 79 |

## Nuclear Properties

NIMONIC alloy PE16 has been extensively used in nuclear reactors, particularly the advanced gas-cooled reactor and sodium-cooled fast breeder reactor systems.

A major application in the advanced gas-cooled reactor is the tie bars from which the fuel assemblies are suspended. The average thermal neutron absorption cross-section has therefore been calculated from the composition as 3.5 barns. Based on research and development, chiefly by the UKAEA, NIMONIC alloy PE16 is highly regarded as a fuel sub-assembly and core structural material for the sodium-cooled fast breeder reactor, particularly for sub-assembly hexagon wrappers, fuel pins and spacers. The main reasons for the success of NIMONIC alloy PE16 are its resistance to corrosion by liquid sodium (see Figure 12), and its outstanding resistance to swelling by void formation in fast neutron environments as shown in Figures 10 and 11.

Figures 10, 11 and 12 are produced respectively from References 1, 2 and 3 from which acknowledgement is made to the United Kingdom Atomic Energy Authority and the British Nuclear Energy Society.

**References:**

1. 'The Significance of Fast Neutron Induced Voids in the Design of Fast Reactors', J.F.W. Bishop, UKAEA, Risley. Paper to the British Nuclear Energy Society Conference 'Voids Formed by Irradiation of Reactor Materials', Reading, 1971.

2. 'Performance Development of the PFR Fuel and the Use of PFR as a Fuel Development Facility', J.F.W. Bishop, UKAEA, Risley. Paper to the British Nuclear Energy Society Conference, 'Fast Reactor Power Stations', London, 1974.

3. 'Corrosion and Mass Transport of Steel and Nickel Alloys in Sodium Systems', A.W. Thorley and C. Tyzack, UKAEA, Risley. Paper 41 to the British Nuclear Energy Society Conference 'Liquid Alkali Metals', Nottingham, 1973.

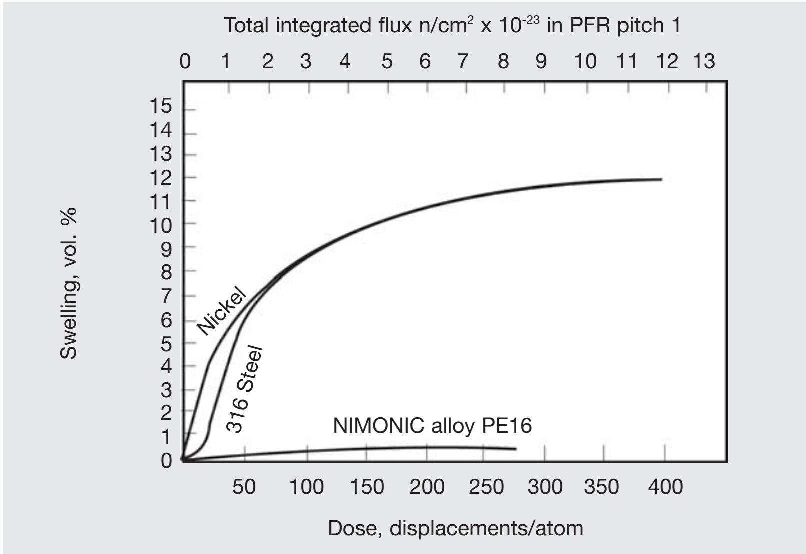


**Figure 10.** Dose dependence of swelling by void formation produced at 525°C by irradiation by carbon ions in the UKAEA variable energy cyclotron to simulate fast-neutron-induced void formation experienced in PFP. The swelling of NIMONIC alloy PE16 is low.

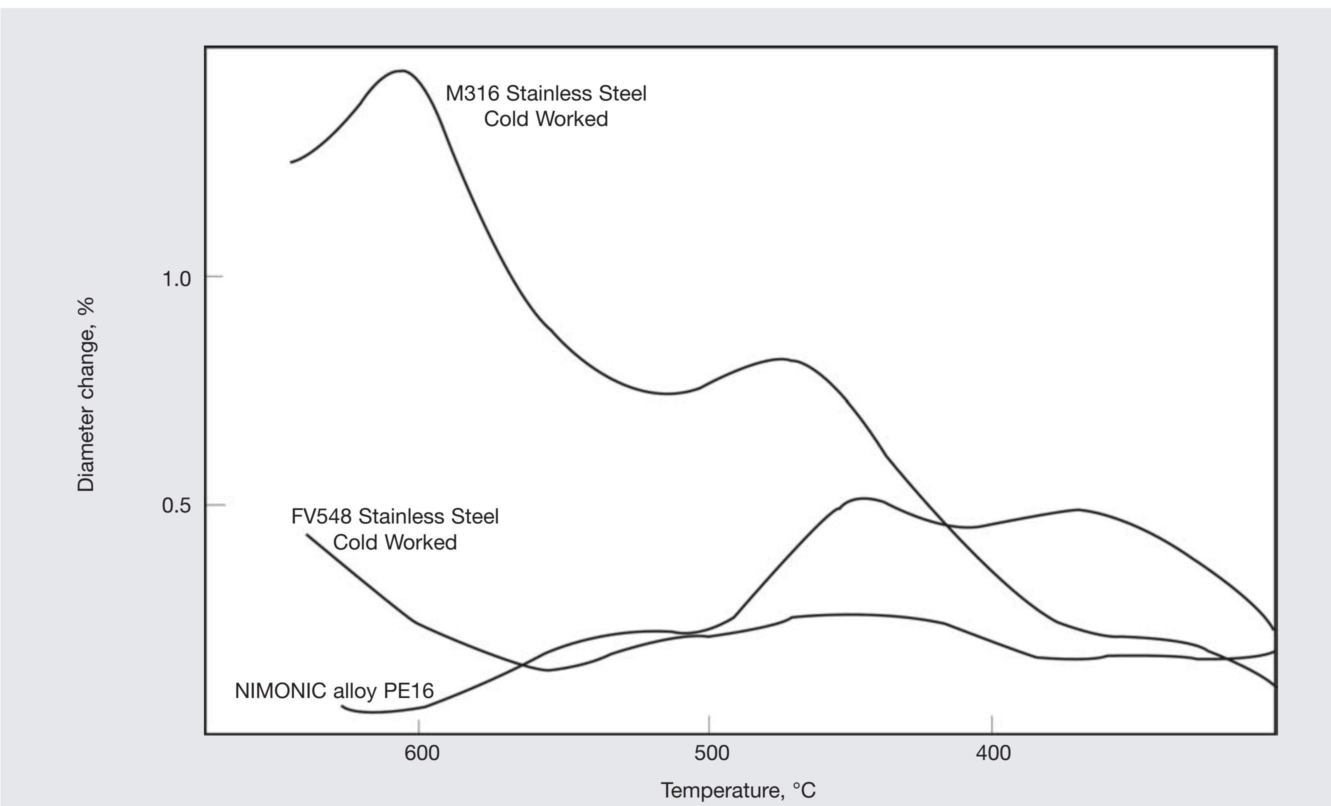


**Figure 11.** Dimensional changes, due chiefly to void swelling in fuel pins from a sub-assembly exposed to 11.2% peak burn-up in the UKAEA Dounreay Fast Reactor (DFR) confirming the low void swelling in heat treated NIMONIC alloy PE16 by carbon ion irradiation shown in Figure 10.

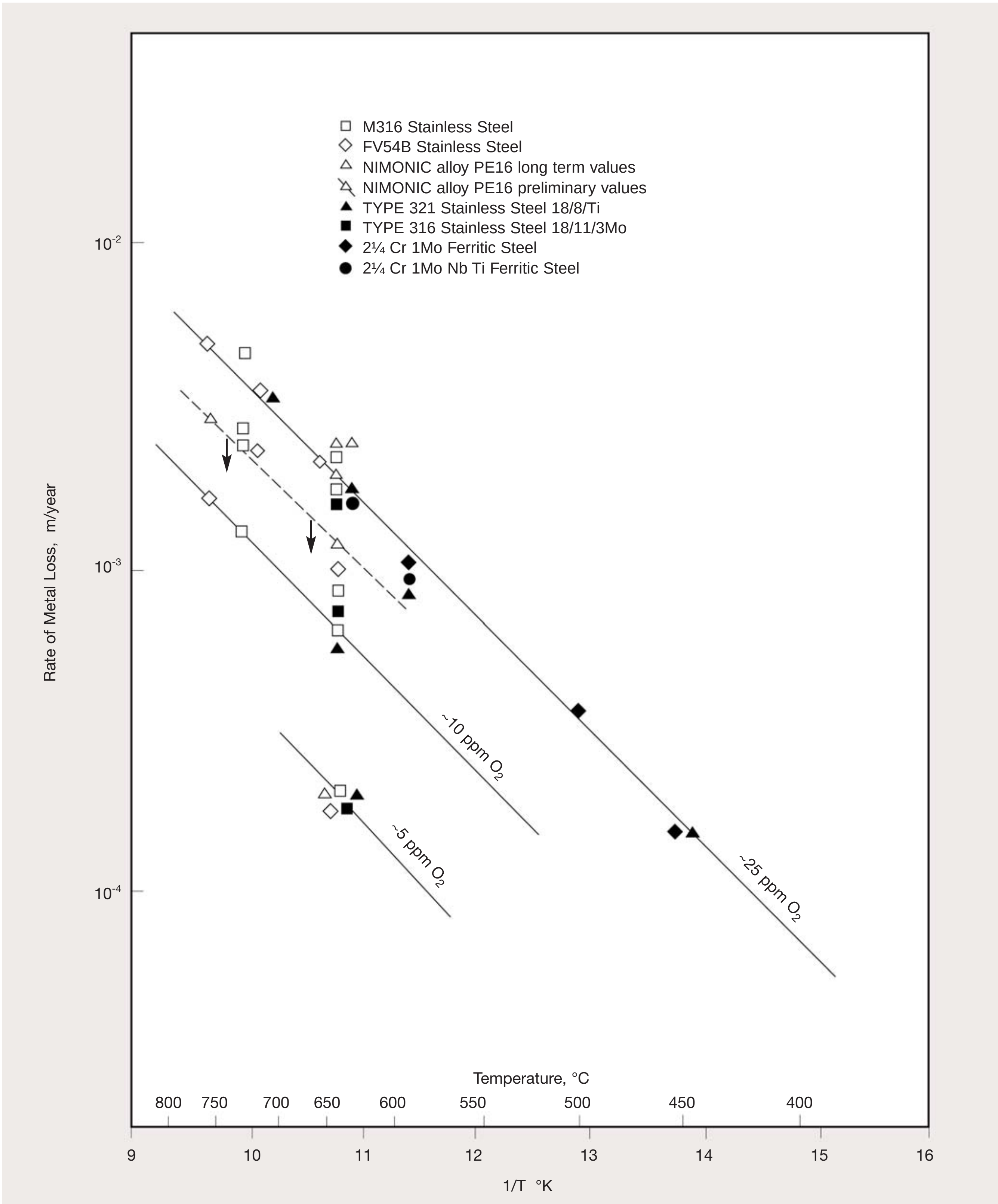


**Figure 12.** Exposure of NIMONIC alloy PE16 and other materials to flowing liquid sodium.

## Corrosion Resistance

Laboratory corrosion testing of NIMONIC alloy PE16 has been defined in molten salt tests, using the following mixtures:

Salt mixture
A 0.5% NaCl + 99.5% $Na_2SO_4$
B 25.0% NaCl + 75.0% $Na_2SO_4$
C 20.0% $V_2O_5$ + 80.0% $Na_2SO_4$
D 80.0% $V_2O_5$ + 20.0% $Na_2SO_4$
E 20.0% $V_2O_5$ + 60.0% $Na_2SO_4$ + 20.0% NaCl

Results of these tests are tabulated and compared with an austenitic stainless steel of typical composition 15.0% Cr, 10.0% Ni, 6.0% Mn, 1.0% Nb, 1.0% Mo, 0.5% Si.

**Table 22** - Corrosion Resistance to Salt Mixtures

| Material | °C | Weight loss, mg/cm², after 300 h exposure | | | | |
|---|---|---|---|---|---|---|
| | | Salt Mixture | | | | |
| | | A | B | C | D | E |
| NIMONIC alloy PE16 | 700 | 22.6 | 192 | 104.4 | 515 | 100.5 |
| | 800 | 26 | 777 | 1630 | 1449 | 64 |
| | 900 | 6.0 | 183 | 1310 | >2000 | 44.7 |
| Austenitic stainless steel | 700 | 13.5 | 53.6 | 167 | 624 | 203 |
| | 800 | 35.7 | 382 | 74.1 | 1730 | 186.7 |
| | 900 | 23.9 | 835 | 21.9 | >2000 | 200 |

Except for salt mixture C, these results show comparable corrosion resistance with the austenitic stainless steel.

## Fabrication

### Hot Working

NIMONIC alloy PE16 may be hot worked in the temperature range 950-1180°C. Further advice on specific hot working conditions may be obtained from the Marketing Department.

### Cold Working

Average mechanical properties pertinent to cold forming operations for sheep annealed 15 min/1040°C/AC and of 0.7-0.9 mm thickness are given below.

**Table 23** - Average Mechanical Properties

| | |
|---|---|
| 0.1 % proof stress | 242 MPa |
| 0.2 % proof stress | 255 MPa |
| 0.5 % proof stress | 272 MPa |
| Tensile strength | 678 MPa |
| Percentage elongation on 50 mm | 42.0 |
| Hardness | 163 HV |
| Mean grain size | ASTM 8.5 |
| Erichsen value | 12.0 mm |
| Typical plastic anisotropy, $\bar{R}$ value † | 0.85 |
| Shear strength | 518 MPa |
| Ratio of shear to tensile strength | 0.76 |

† Mean value of plastic anisotropy ratio R for tests at 0°, 45° and 90° to the final rolling direction using the formula $\bar{R} = ¼(R_{0°} + 2R_{45°} + R_{90°})$.

### Annealing

Interstager annealing of NIMONIC alloy PE16 should be carried out at 1040°C, followed by air cooling. The recommended time at temperature depends on the form and section thickness as indicated:

**Table 23**

| | |
|---|---|
| Bar | 1/2 - 1 h/1040°C/AC |
| Sheet | 5 - 15 min/1040°C/AC |
| Cold-drawn tube | 1/4 - 4 h/1040°C/AC |

Additional information on the effects of annealing conditions for 0.9 mm NIMONIC alloy PE16 sheet is shown in Figures 13 and 14. The very rapid softening of thin sheet is clearly indicated in Figure 13, and the effect of high temperature annealing on grain growth is demonstrated by Figure 14.

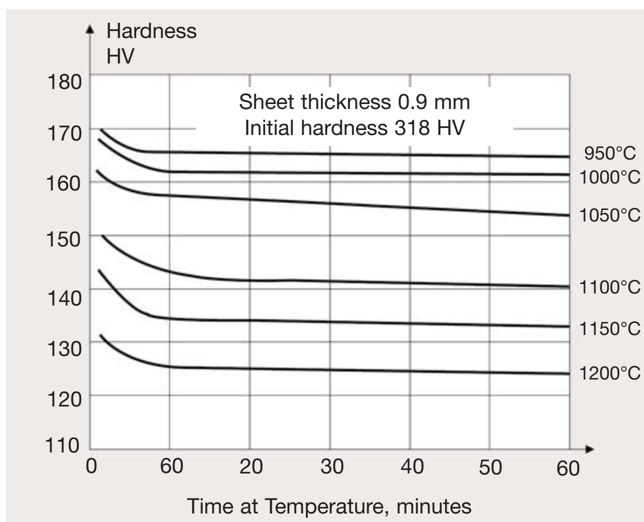


**Figure 13.** Softening curve for NIMONIC alloy PE16 sheet air cooled from temperature.

## Welding

NIMONIC alloy PE16 can be welded both to itself and to a variety of other materials using many of the normal welding processes. In practice, however, manual argon-arc welding (T.I.G.) or M. I. G. welding with dip-transfer conditions are the most commonly employed.

### Metallic-Arc Welding

Metallic-arc welding using flux-coated electrodes can be used, but electrodes that will develop matching mechanical properties to the parent material have not been developed. However, for possible dissimilar metal joints involving steels or non-precipitation hardening nickel-base alloys, metallic-arc welding can be usefully employed. Special Metals Welding Products Company (website: www.specialmetalswelding.com) should be consulted for specific advice.

### Argon Shielded Process

Material up to 1.5 mm thick can be fusion welded without the addition of filler wire, although the properties of such joints are slightly below those of the parent material. Above this thickness NIMONIC filler metal PE16 should be added to the joint, which will then develop properties matching those of the parent material. Where the material is sufficiently thick to allow M.I.G. welding to be employed, dip-transfer conditions should be used with either 0.8 or 1.1 mm diameter wire. Welding with spray transfer conditions results in cracking in both the weld metal and the heat-affected zone.

These processes can also be used for joining the alloy to a variety of other materials, and the criterion is in the selection of a suitable filler material. The Special Metals Welding Products Company (www.specialmetalswelding.com) should be consulted for specific advice.

### Other Joining Processes

NIMONIC alloy PE16 can also be joined by such processes as flash butt welding; resistance, spot, stitch and seam welding; electron-beam welding, and high temperature brazing. The choice of any one particular process will, of course, depend on the application and form of the material.

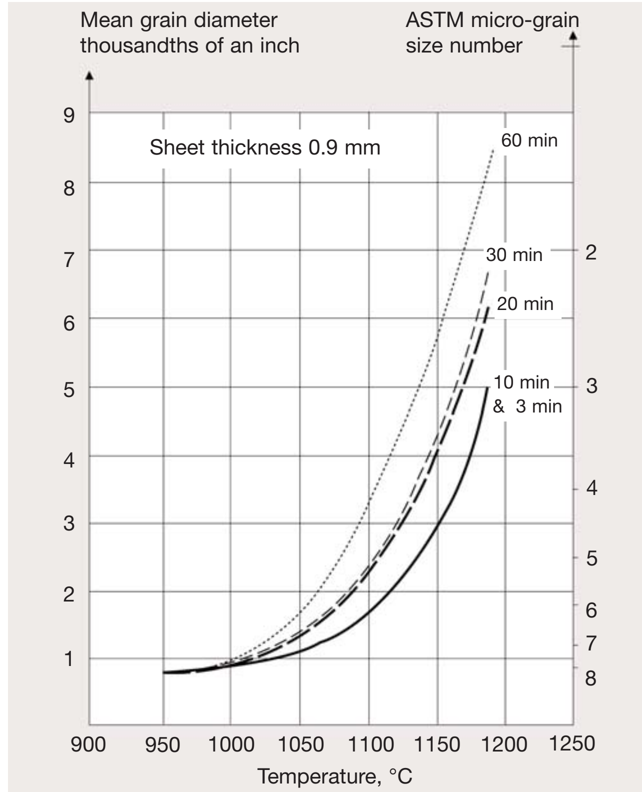


**Figure 14.** Grain size - annealing condition curves for NIMONIC alloy PE16 sheet.

## Heat Treatment

Whichever welding process is being employed, the material to be welded should be in the annealed or solution treated condition. If forming operations prior to welding induce a large amount of cold work into the material, then annealing is recommended prior to welding. After welding the two-stage heat treatment of either:

1 h/900°C/AC + 8 h/750°C/AC or
2 h/800°C/AC + 16 h/700°C/AC

is necessary to develop the good properties in the weld and heat-affected zone. The choice of heat treatment is dependent on the intended service condition as discussed under the ‘Heat Treatment’ section on page 1.

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