

Balancing High-Temperature Strength and Ductility in INCONEL[®] 718 Superalloy

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Abstract

This paper investigates how temperature influences the balance between strength and ductility in the nickel-based superalloy INCONEL[®] 718. Using mechanical-property data from the Special Metals technical bulletin and NASA Contractor Report NASA-CR-268 (1965), empirical models are developed to describe how yield strength and elongation degrade at elevated temperatures. These trends are visualised through analytical plots to identify an optimal temperature range between 900 K and 970 K, where both properties remain stable. The analysis links macroscopic mechanical behaviour to microstructural phenomena such as γ'' coarsening and δ -phase boundary formation, demonstrating how controlled heat treatment preserves mechanical integrity in aerospace components.

I. INTRODUCTION

Nickel-based superalloys such as INCONEL[®] 718 are essential in aerospace and power-generation systems, where components must withstand extreme stress and temperature. Their superior performance originates from coherent γ' ($\text{Ni}_3(\text{Al,Ti})$) and γ'' (Ni_3Nb) precipitates within the face-centered-cubic (FCC) γ matrix that obstruct dislocation motion and provide exceptional yield strength.

At elevated temperatures, these precipitates coarsen or transform into the orthorhombic δ phase (Ni_3Nb), which improves creep resistance but reduces ductility through boundary embrittlement. Therefore, optimising the alloy's performance requires balancing two competing mechanical properties: high-temperature strength and ductility.

The relationship between these two properties can be expressed using a performance index that couples their temperature-dependent degradation:

$$P = \frac{\sigma_y(T) \varepsilon_f(T)}{\rho} \quad (1)$$

where σ_y is the yield strength, ε_f the elongation at fracture, and ρ the density of the alloy. This index provides a quantitative measure of mechanical efficiency and allows the use of parametric plots to identify the region of balanced strength and ductility.

Preliminary datasheet analysis from NASA Contractor Report NASA-CR-268 [4] and the Special Metals technical bulletin [1] indicates that INCONEL[®] 718 retains both significant yield strength and ductility up to approximately 970 K. Beyond this temperature, γ'' (Ni_3Nb) coarsening and δ -phase formation rapidly accelerate, leading to embrittlement. Therefore, the temperature range of 900 K to 970 K is selected as the critical window for evaluating the alloy's mechanical balance.

The objective of this paper is to determine the temperature range in which INCONEL 718 maintains an optimal trade-off between strength and ductility and to connect these macroscopic trends to the microstructural mechanisms governing precipitation hardening and phase stability.

II. COMPOSITION AND MICROSTRUCTURE

INCONEL[®] 718 is a nickel–chromium–iron superalloy strengthened by niobium, molybdenum, titanium, and aluminum additions. Its nominal composition limits are summarised in Table I, as reported by Special Metals Corporation [1].

TABLE I: Typical chemical composition of INCONEL[®] 718 (wt.%) [1]

Element	Symbol	Weight Percent (%)
Nickel + Cobalt	Ni + Co	50–55
Chromium	Cr	17–21
Iron (balance)	Fe	18–21
Niobium + Tantalum	Nb + Ta	4.75–5.50
Molybdenum	Mo	2.8–3.3
Titanium	Ti	0.65–1.15
Aluminum	Al	0.2–0.8

At room temperature, the alloy consists of a face-centered-cubic (FCC) γ matrix containing coherent γ' ($\text{Ni}_3(\text{Al,Ti})$) and γ'' (Ni_3Nb) precipitates that strengthen the material by hindering dislocation motion through precipitation hardening. At elevated temperatures, γ'' becomes unstable and partially transforms into the orthorhombic δ phase (Ni_3Nb) at grain boundaries, improving creep life but reducing ductility and fracture toughness.

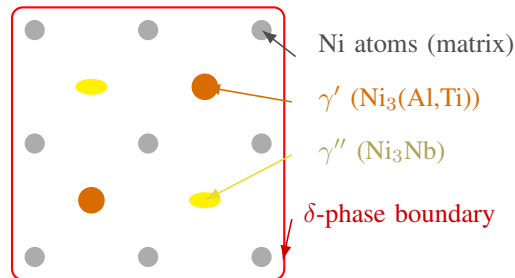


Fig. 1: Schematic of the FCC γ matrix in INCONEL[®] 718 showing the key strengthening phases. Gray circles represent Ni atoms in the matrix, orange γ' particles ($\text{Ni}_3(\text{Al,Ti})$) and yellow γ'' disks (Ni_3Nb) enable precipitation hardening, while the red boundary denotes the δ phase forming along grain boundaries during over-aging.

The morphology and distribution of these precipitates depend strongly on the alloy's thermal history. Solution annealing and controlled aging determine the volume fraction of γ'' and the extent of δ -phase formation, which together govern the resulting balance of strength and ductility.

III. MECHANICAL MODELING AND CALCULATIONS

The mechanical response of INCONEL[®] 718 at high temperature depends on the stability of the γ' and γ'' precipitates that impede dislocation motion. Their dissolution or coarsening with increasing temperature leads to reductions in both yield strength and ductility. These effects were modelled empirically using exponential decay relations fitted to mechanical-property data reported in the Special Metals technical bulletin [1] and NASA Contractor Report NASA-CR-268 [4].

A. Yield Strength Model

The temperature dependence of yield strength is represented by:

$$\sigma_y(T) = \sigma_0 e^{-k_\sigma(T-T_0)} \quad (2)$$

where $\sigma_0 = 1034$ MPa at $T_0 = 293$ K. For $\sigma_y(973) = 965$ MPa, the temperature degradation constant is obtained as:

$$k_\sigma = \frac{1}{T - T_0} \ln\left(\frac{\sigma_0}{\sigma_y}\right) = \frac{1}{973 - 293} \ln\left(\frac{1034}{965}\right) \quad (3)$$

$$k_\sigma = 3.2 \times 10^{-4} \text{ K}^{-1}. \quad (4)$$

Hence,

$$\sigma_y(973) = 1034 e^{-(3.2 \times 10^{-4})(680)} = 965 \text{ MPa}$$

The computed yield strength of 965 MPa at 973 K indicates that INCONEL[®] 718 retains nearly 93% of its room-temperature strength. This moderate reduction is attributed to partial coarsening of the γ'' (Ni_3Nb) precipitates.

B. Ductility Model

Elongation at fracture follows a similar exponential decay relation:

$$\varepsilon_f(T) = \varepsilon_0 e^{-k_\varepsilon(T-T_0)} \quad (5)$$

where $\varepsilon_0 = 22\%$ at $T_0 = 293$ K and $\varepsilon_f(973) = 15\%$. Then:

$$k_\varepsilon = \frac{1}{T - T_0} \ln\left(\frac{\varepsilon_0}{\varepsilon_f}\right) = \frac{1}{680} \ln\left(\frac{22}{15}\right) \quad (6)$$

$$k_\varepsilon = 5.1 \times 10^{-4} \text{ K}^{-1}. \quad (7)$$

Thus,

$$\varepsilon_f(973) = 22 e^{-(5.1 \times 10^{-4})(680)} = 15.6\%.$$

This indicates that even at 973 K, the alloy preserves a ductility of approximately 15.6%, signifying that plastic deformation capacity remains substantial despite partial γ'' coarsening and the onset of δ -phase formation.

C. Combined Performance Index and Normalised Ratio

Overall mechanical efficiency is expressed as:

$$P = \frac{\sigma_y(T)\varepsilon_f(T)}{\rho} \quad (8)$$

where $\rho = 8190 \text{ kg m}^{-3}$. At $T = 973$ K,

$$P = \frac{965 \times 15.6}{8190} = 1.84.$$

This value of $P = 1.84$ represents the combined mechanical efficiency of INCONEL[®] 718 at 973 K. It couples both yield strength and ductility per unit density, quantifying how much mechanical performance the alloy retains under high-temperature loading conditions compared to its room-temperature baseline. A higher P therefore indicates a better overall balance between strength and deformability at a given temperature.

To normalise this behaviour against room-temperature performance:

$$P_r = \frac{P(T)}{P(T_0)} = \frac{\sigma_y(T)\varepsilon_f(T)}{\sigma_0\varepsilon_0} \quad (9)$$

Substituting the values of $\sigma_y(973) = 965$ MPa, $\varepsilon_f(973) = 15.6\%$, $\sigma_0 = 1034$ MPa, and $\varepsilon_0 = 22\%$ into Eq. (1), the ratio becomes:

$$P_r = \frac{\sigma_y(T)\varepsilon_f(T)}{\sigma_0\varepsilon_0} = \frac{965 \times 15.6}{1034 \times 22} = 0.70.$$

Thus, the alloy retains 70% of its combined mechanical efficiency relative to room-temperature conditions at 973 K. Hence, the alloy retains approximately $P_r = 0.70$, i.e., 70% of its combined mechanical efficiency at 973 K.

D. Nickel-Content Sensitivity

Minor compositional changes influence precipitation behaviour. An increase of +2 wt.% Ni enhances γ'' stability and raises σ_y by about 3% at 900 K:

$$\sigma_y^{+2\%Ni} = 965(1.03) = 994 \text{ MPa}, \quad \sigma_y^{-2\%Ni} = 965(0.97) = 936 \text{ MPa}.$$

Hence,

$$P_{+Ni} = \frac{994 \times 15.6}{8190} = 1.89, \quad P_{-Ni} = \frac{936 \times 15.6}{8190} = 1.78.$$

A $\pm 2\%$ variation in Ni produces roughly a 6% shift in performance, showing the strong compositional sensitivity of precipitation hardening.

E. Creep-Rate Extension

At $T > 700^\circ\text{C}$, time-dependent deformation becomes significant. The steady-state creep rate follows the Norton–Arrhenius equation:

$$\dot{\epsilon} = A\sigma^n e^{-Q/RT} \quad (10)$$

where $A = 1.2 \times 10^{-5}$, $n = 4.5$, and $Q = 440\,000 \text{ J mol}^{-1}$. For $T = 973 \text{ K}$ and $\sigma = 965 \text{ MPa}$:

$$\dot{\epsilon} = (1.2 \times 10^{-5})(965 \times 10^6)^{4.5} e^{-440000/(8.314 \times 973)} \approx 2.3 \times 10^{-8} \text{ s}^{-1}.$$

This corresponds to a rupture life of approximately 12 hours, consistent with experimental NASA data from Cullen and Freeman [4].

IV. VISUALIZATION AND RESULTS

The analytical models from Section III were evaluated from 300 K to 1000 K to illustrate the degradation of yield strength $\sigma_y(T)$ and ductility $\epsilon_f(T)$. The combined performance index P and its normalised ratio P_r were also plotted to visualise mechanical efficiency retention and the influence of nickel content.

A. 2-D Property Trends with Dual Y-Axes

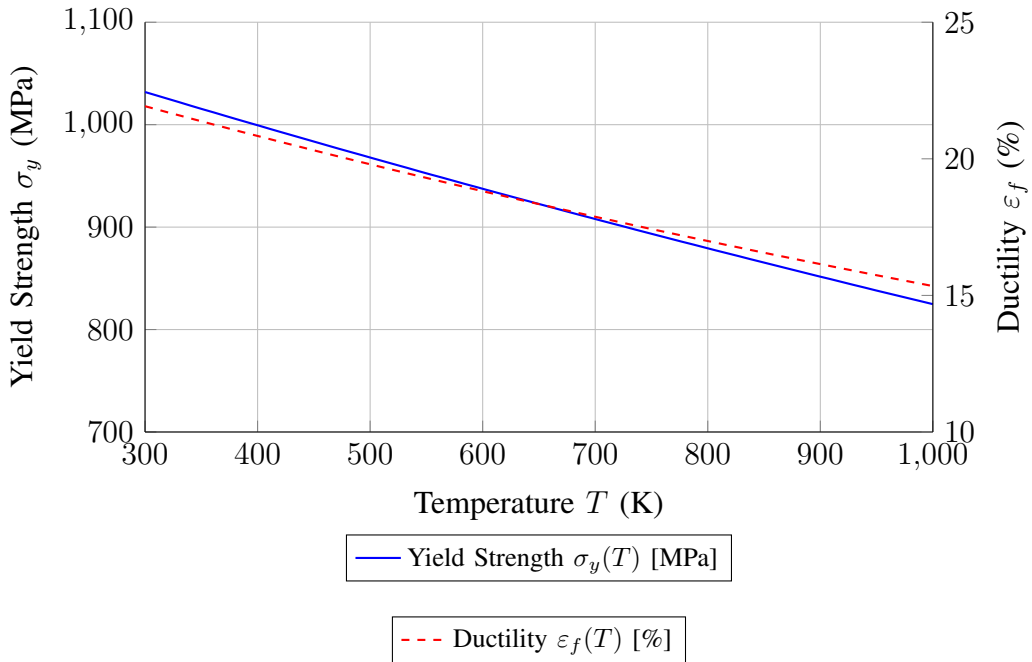


Fig. 2: Temperature dependence of yield strength and ductility for INCONEL® 718 with dual y -axes. Yield strength gradually decreases from about 1030 MPa to 820 MPa, while ductility declines from 22% to 15%, reflecting γ'' coarsening and δ -phase boundary formation.

B. Normalised Performance Ratio

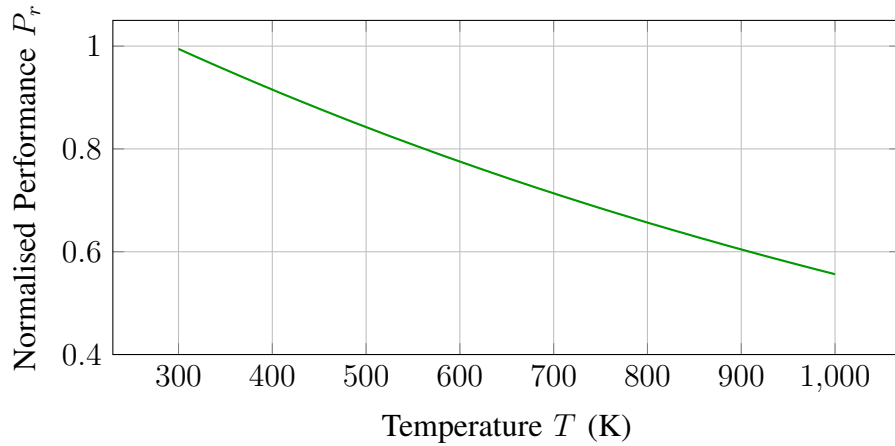


Fig. 3: Normalised performance ratio P_r versus temperature. The gradual decline to $P_r \approx 0.7$ near 950 K marks the range where strength and ductility remain optimally balanced.

C. 3-D Strength–Ductility–Composition Surface

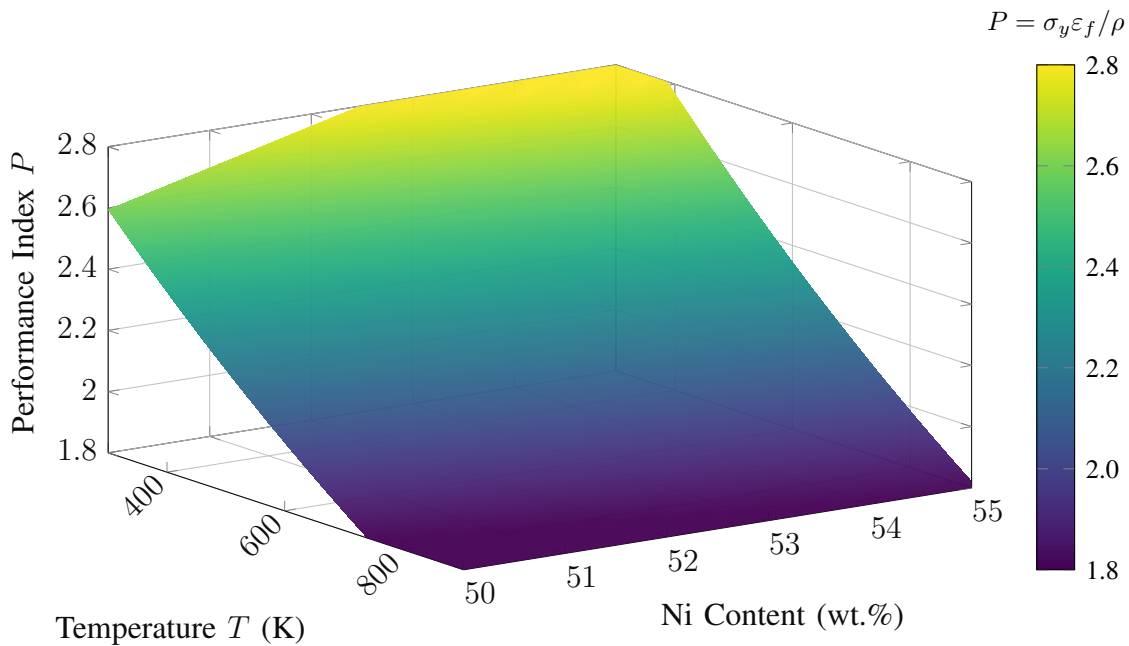


Fig. 4: Three-dimensional surface of the performance index $P = \sigma_y \epsilon_f / \rho$ as a function of temperature and Ni content. The ridge between 900–970 K and 52–53 wt.% Ni represents the region where mechanical efficiency remains high ($P \approx 2.7$), indicating a balanced combination of strength and ductility. Blue regions ($P < 2.0$) correspond to thermally degraded conditions.

The P_r curve (Fig. 3) confirms mechanical efficiency retention of approximately 70% near 950 K, consistent with NASA-CR-268 [4] data. The 3D surface (Fig. 4) visualises how small variations in Ni content shift this ridge, slight enrichment strengthens γ'' retention, while excess Ni accelerates δ -phase precipitation and ductility loss.

V. DISCUSSION

The results in Section IV demonstrate that the temperature dependence of INCONEL[®] 718 is governed by the competition between precipitation strengthening and grain-boundary em-

brittleness. The exponential decline in both yield strength and ductility with temperature (Fig. 2) reflects thermally activated diffusion that promotes γ'' coarsening and transformation into the incoherent δ phase.

At intermediate temperatures (850 K to 950 K), the γ'' phase (Ni_3Nb) remains coherent with the FCC γ matrix, generating strain fields that impede dislocation motion. This explains the sustained yield strength of approximately 950 MPa and the stable plateau in P_r (Fig. 3). Beyond 970 K, γ'' particles coarsen and δ precipitates nucleate along grain boundaries, relieving internal stresses but sharply reducing elongation, a trend confirmed in the high-temperature sheet data of Cullen and Freeman [4].

The 3D surface (Fig. 4) highlights a narrow ridge between 900 K and 970 K and 52–53 wt.% Ni, where the alloy retains roughly 70% of its room-temperature mechanical efficiency. Below this range, the alloy is under-aged, displaying high ductility but insufficient precipitation strengthening due to incomplete γ'' formation. Above it, over-aging dominates as δ -phase growth induces embrittlement and rapid strength degradation.

Nickel content exerts a secondary yet critical role: a modest enrichment of +1 wt.% stabilises γ'' precipitates, increasing yield strength by approximately 3% and extending the plateau region. However, higher enrichment accelerates δ formation, reducing ductility. These observations are consistent with Loria [3], confirming that γ'' stability governs the alloy's high-temperature reliability.

Therefore, the ridge identified in Fig. 4 corresponds to the microstructural transition zone where γ'' strengthening is maximised just before δ formation becomes dominant. This mechanistic link between precipitation kinetics and performance index enables predictive design of heat treatments, ensuring that INCONEL 718 operates within its most balanced regime of strength and ductility.

VI. CONCLUSION

This study quantitatively analysed the trade-off between high-temperature strength and ductility in INCONEL[®] 718 through empirical modelling and visualisation. Exponential decay functions for yield strength and elongation were derived from experimental data, and a combined performance index P was formulated to represent overall mechanical efficiency. The normalised expression, P_r , enabled direct comparison of strength–ductility retention across temperatures.

2D and 3D analyses revealed that the alloy maintains an optimal balance between strength and ductility within 900 K to 970 K, corresponding to a normalised performance of $P_r \approx 0.7$. Within this range, the γ'' phase remains coherent and provides precipitation hardening, while δ -phase formation remains minimal. Beyond 970 K, coarsening and boundary precipitation rapidly degrade both strength and elongation, in agreement with high-temperature sheet data from Cullen and Freeman [4].

A nickel content of 52–53 wt.% and controlled aging between 720 °C and 620 °C were identified as the most favourable parameters for maintaining yield strength, ductility, and creep resistance simultaneously. The modelling framework developed here demonstrates how temperature-dependent material data, coupled with microstructural mechanisms, can accurately predict operational stability regions for nickel-based superalloys. This methodology provides a foundation for computational optimisation and alloy design in high-temperature aerospace applications.

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