Nickel-based superalloys

Description

Image

Caption

1. Hair dryer with a Nichrome heating element. an alloy of nickel and chromium. © Granta Design 2. Toaster with a Nichrome heating element. an alloy of nickel and chromium. © Granta Design

The material

With a name like "superalloy" there has to be something special here. There is. Superalloy is a name applied to nickel-based, iron-based and cobalt-based alloys that combine exceptional high-temperature strength with excellent corrosion and oxidation resistance. Without them, jet engines would not be practical: they can carry load continuously at temperatures up to 1200 C. The nickel-based superalloys are the ultimate metallic cocktail: nickel with a good slug of chromium and lesser shots of cobalt, aluminum, titanium, molybdenum, zirconium and iron. The data in this record span the range of high-performance nickel-based superalloys.

Composition (summary)

Ni + 10 to 25% Cr + Ti, Al, Co, Mo, Zr, B and Fe in varying proportions.

General properties

Density	484	-	540	lb/ft^3
Price	* 9.47	-	10.4	USD/lb
Date first used	1944			

Mechanical properties

Young's modulus	21.8	-	35.5	10^6 psi
Shear modulus	7.98	-	14.5	10^6 psi
Bulk modulus	16	-	29.7	10^6 psi
Poisson's ratio	0.26	-	0.325	
Yield strength (elastic limit)	43.5	-	276	ksi
Tensile strength	58	-	305	ksi
Compressive strength	43.5	-	276	ksi
Elongation	0.5	-	60	% strain
Hardness - Vickers	200	-	600	HV
Fatigue strength at 10^7 cycles	* 19.6	-	131	ksi
Fracture toughness	59.2	-	100	ksi.in^0.5
Mechanical loss coefficient (tan delta)	* 9e-5	-	0.001	

Thermal properties

Melting point	2.33e3	-	2.58e3	°F
Maximum service temperature	* 1.65e3	-	2.19e3	°F
Minimum service temperature	-458	-	-456	°F

Thermal conductor or insulator?	Good conductor			
Thermal conductivity	4.62	-	9.82	BTU.ft/h.ft^2.F
Specific heat capacity	0.0908	-	0.117	BTU/lb.°F
Thermal expansion coefficient	5	-	8.89	µstrain/°F

Electrical properties

Electrical conductor or insulator?	Poor conductor			
Electrical resistivity	84	-	240	µohm.cm

Optical properties

Transparency	Opaque

Processability

Castability	3		
Formability	3	-	4
Machinability	3		
Weldability	4	-	5
Solder/brazability	5		

Durability: water and aqueous solutions

Water (fresh)	Excellent
Water (salt)	Excellent
Soils, acidic (peat)	Excellent
Soils, alkaline (clay)	Excellent
Wine	Excellent

Durability: acids

Acetic acid (10%)	Excellent
Acetic acid (glacial)	Excellent
Citric acid (10%)	Excellent
Hydrochloric acid (10%)	Acceptable
Hydrochloric acid (36%)	Excellent
Hydrofluoric acid (40%)	Excellent
Nitric acid (10%)	Acceptable
Nitric acid (70%)	Unacceptable
Phosphoric acid (10%)	Excellent
Phosphoric acid (85%)	Excellent
Sulfuric acid (10%)	Excellent
Sulfuric acid (70%)	Excellent

Durability: alkalis

Sodium hydroxide (10%)	Acceptable
Sodium hydroxide (60%)	Acceptable

Durability: fuels, oils and solvents

Amyl acetate	Excellent
Benzene	Excellent
Carbon tetrachloride	Excellent
Chloroform	Excellent
Crude oil	Excellent
Diesel oil	Excellent
Lubricating oil	Excellent
Paraffin oil (kerosene)	Excellent
Petrol (gasoline)	Excellent
Silicone fluids	Excellent

Toluene	Excellent
Turpentine	Excellent
Vegetable oils (general)	Excellent
White spirit	Excellent

Durability: alcohols, aldehydes, ketones

Acetaldehyde	Excellent
Acetone	Excellent
Ethyl alcohol (ethanol)	Excellent
Ethylene glycol	Excellent
Formaldehyde (40%)	Excellent
Glycerol	Excellent
Methyl alcohol (methanol)	Excellent

Durability: halogens and gases

Chlorine gas (dry)	Acceptable
Fluorine (gas)	Acceptable
O2 (oxygen gas)	Excellent
Sulfur dioxide (gas)	Acceptable

Durability: built environments

Industrial atmosphere	Excellent
Rural atmosphere	Excellent
Marine atmosphere	Excellent
UV radiation (sunlight)	Excellent

Durability: flammability

Flammability	Non-flammable

Durability: thermal environments

Tolerance to cryogenic temperatures	Excellent
Tolerance up to 150 C (302 F)	Excellent
Tolerance up to 250 C (482 F)	Excellent
Tolerance up to 450 C (842 F)	Excellent
Tolerance up to 850 C (1562 F)	Excellent
Tolerance above 850 C (1562 F)	Excellent

Geo-economic data for principal component

Annual world production	1.41e6	ton/yr
Reserves	6.99e7	l. ton

Primary material production: energy, CO2 and water

Embodied energy, primary production	*	2.39e4	-	2.64e4	kcal/lb
CO2 footprint, primary production	*	13	-	14.4	lb/lb
Water usage	*	39.3	-	43.4	gal(US)/lb
Eco-indicator 95		5.2e3			millipoints/kg
Eco-indicator 99		2.83e3			millipoints/kg

Material processing: energy

Casting energy	*	1.08e3	-	1.19e3	kcal/lb
Extrusion, foil rolling energy	*	868	-	960	kcal/lb
Rough rolling, forging energy	*	450	-	497	kcal/lb
Wire drawing energy	*	3.17e3	-	3.51e3	kcal/lb
Metal powder forming energy	*	3.42e3	-	4.13e3	kcal/lb
Vaporization energy	*	1.25e6	-	1.38e6	kcal/lb

Coarse machining energy (per unit wt removed)	* 114	-	127	kcal/lb
Fine machining energy (per unit wt removed)	* 679	-	751	kcal/lb
Grinding energy (per unit wt removed)	* 1.31e3	-	1.44e3	kcal/lb
Non-conventional machining energy (per unit wt removed)	1.25e4	-	1.38e4	kcal/lb

Material processing: CO2 footprint

Casting CO2	* 0.748	-	0.826	lb/lb
Extrusion, foil rolling CO2	* 0.601	-	0.664	lb/lb
Rough rolling, forging CO2	* 0.311	-	0.344	lb/lb
Wire drawing CO2	* 2.2	-	2.43	lb/lb
Metal powder forming CO2	* 2.52	-	3.05	lb/lb
Vaporization CO2	* 860	-	950	lb/lb
Coarse machining CO2 (per unit wt removed)	* 0.0791	-	0.0874	lb/lb
Fine machining CO2 (per unit wt removed)	* 0.47	-	0.52	lb/lb
Grinding CO2 (per unit wt removed)	* 0.905	-	1	lb/lb
Non-conventional machining CO2 (per unit wt removed)	8.6	-	9.5	lb/lb

Material recycling: energy, CO2 and recycle fraction

Recycle	✓			
Embodied energy, recycling	* 3.93e3	-	4.34e3	kcal/lb
CO2 footprint, recycling	* 2.85	-	3.15	lb/lb
Recycle fraction in current supply	22	-	26	%
Downcycle	✓			
Combust for energy recovery	✗			
Landfill	✗			
Biodegrade	✗			
Toxicity rating	Slightly toxic			
A renewable resource?	✗			

Environmental notes

About 10% of the population is sensitive to nickel, causing them to react even to the nickel in stainless steel watch straps. Compounds of nickel can be more toxic; nickel carbonyl, used in the extraction of nickel, is deadly.

Supporting information

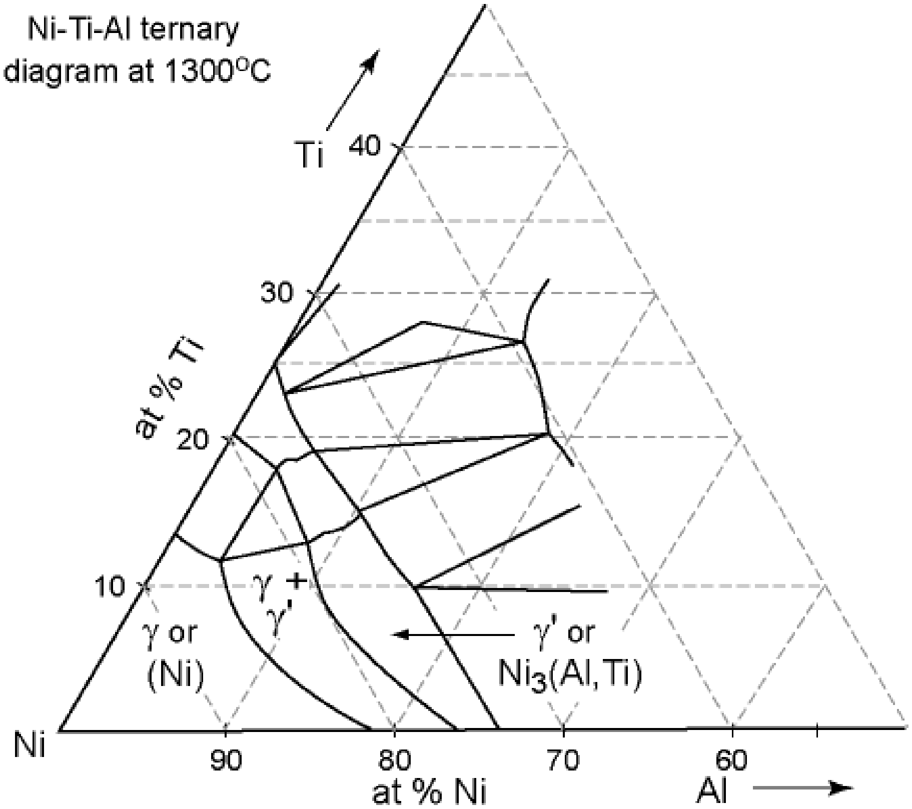
Design guidelines

Superalloys are expensive and, at room temperature, too hard to forge or roll; this can only be done hot. Those of highest strength are initially shaped by casting or by powder methods such as hot isostatic pressing, then finished by machining or grinding to give the final tolerance. High performance turbine blades, often of complex shape like the one in the photograph, are investment-cast. Their high temperature performance is further enhanced by causing the casting to solidify directionally, giving large oriented grains or a single crystal, increasing its resistance to creep.

Technical notes

All superalloys are age-hardened -- heated to dissolve the alloying elements, quenched to trap them in solution and then reheated (aged) to make them precipitate as a fine dispersion of particles. The precipitates are intermetallics such as Ni3Al and Ni3Ti. It is these that give the strength. The chromium adds to this, and also imparts resistance to hot gasses by creating a surface film of Cr203.

Phase diagram



Phase diagram description

Nickel based superalloys are alloys of nickel with aluminum, titanium and chromium. This is the nickel-rich corner of the nickel (Ni), aluminum (Al) titanium (Ti) phase diagram.

Typical uses

Blades, disks, and combustion chambers in turbines and jet engines; rocket engines; general structural aerospace applications; light springs, high temperature chemical engineering equipment; bioengineering and medical.

Tradenames

Inconel, Nimonic, Udimet, Haynes alloy, Hastalloy.

Links

Reference

ProcessUniverse

Producers