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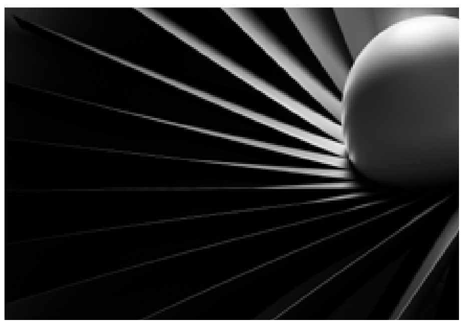
Solution treatment, quenching, and aging are involved to optimize high-temperature strength, creep resistance, and ductility.

Heat treatment of nickel-based superalloys

Heat treatment of nickel-based superalloys is designed to control precipitation, dissolution, and coarsening of strengthening phases, primarily the ordered γ' phase in an FCC γ matrix, along with carbides and other intermetallics. These treatments tailor microstructure for creep resistance, fatigue strength, and environmental stability in extreme turbines and aerospace environments.

Nickel-based superalloys are complex, multi-component FCC alloys built on a face-centered-cubic γ Ni-rich matrix with coherent ordered $L1_2$ γ' precipitates, typically $Ni_3(Al, Ti)$. The presence of the γ' precipitates provide the high temperature strength by impeding dislocation motion. There are two different classes of nickel-based super alloys. Polycrystalline and directionally solidified (DS) alloys rely significantly on grain-boundary strengthening and carbide distributions, whereas single crystal (SX) alloys eliminate grain boundaries and depend more heavily on optimized γ/γ' morphology and rafting behavior under service conditions [1] [2].



Nickel-based superalloys, often used in jet engines, are the largest class of superalloys due to excellent high-temperature strength and oxidation resistance. (Courtesy: Shutterstock)

Typical heat-treating cycles for nickel-based super alloys involve solution heat treatment, quenching, and multiple aging steps. The solution heat treatment consists of heating to approximately 980-1,200°C (depending on alloy) to just below the incipient melting point to dissolve non-equilibrium γ', carbides, and segregated phases, followed by quenching or rapid cooling to retain a supersaturated γ matrix [2] [3]. After quenching, or controlled cooling, aging is accomplished in either a single or multi-step process. The alloy is heated to a lower temperature than the solution heat-treatment temperature to nucleate and grow a controlled population of γ' and secondary carbides [2] [3].

There are two different methods for the solution heat treatment of nickel-based superalloys. The first method is a full solution heat treatment, where the temperature is raised to above the γ' solvus for a sufficient time to dissolve nearly all primary γ' and eutectic constituents. This maximizes homogenization but risks incipient melting in segregated regions [2] [4]. Partial solution heat treatment involves heating to slightly below the γ' solvus. This leaves a small fraction of residual primary γ' but eliminates the risk of incipient melting. By selecting the proper time and temperature, segregation gradients can be reduced, and incipient melting is avoided. Proper control of grain size is also achieved.

After solution treatment and quenching, the supersaturated γ matrix is metastable and will precipitate γ' on aging. The aging parameters of time, temperature, and cooling rate control the γ' morphology (spherical, cuboidal, plate-like), and the γ' volume fraction and size distribution. Typically, two-stage aging is used [1] [4]. In the first stage aging (about 1,080-1,150°C, depending on alloy) the primary γ' nucleates heterogeneously and grows into cuboidal precipitates, establishing a course, coherent matrix. A lower temperature (850-900°C) age step follows where secondary and tertiary γ' form within the remaining supersaturated matrix, producing a refined γ' distribution that enhances yield strength and low-cycle fatigue resistance [1] [5] [6].

The nucleation and growth of γ' are governed by classical precipitation kinetics in a supersaturated γ matrix. Nucleation rates are maximized at intermediate aging temperatures and growth driven by solute diffusion. This is like the aging of precipitation hardening of aluminum alloys [7]. Coarsening follows Ostwald ripening, with a cube-root time dependence of precipitate radius under diffusion-controlled conditions, though elastic interactions and coherency strains modify coarsening behavior in high-volume-fraction γ' systems [1].

In general, the goal is to have a γ' volume fraction of approximately 60-70 percent, depending on the application. The primary cuboidal γ' precipitate size is typically on the order of 100–500 nm, and for secondary/tertiary γ', the spacing is 40-60 nm. The cuboidal precipitates minimize coherency strain in the matrix [1] [5] [3]. Over-aging at either primary or secondary aging temperatures leads to coarsening of γ' and reduced precipitation strengthening. At the same time, the matrix may contain a greater fraction of very fine γ' that can coarsen rapidly under service, causing unstable mechanical response [3].

Additively manufactured nickel-based superalloy parts produced with laser or electron beam powder-bed fusion start with very fine microstructures, high dislocation densities, and high residual stresses. Multiple stress-relief operations are often needed, followed by hot isostatic pressing (HIP) to remove porosity. The part is then processed normally using conventional solution-aging sequences to develop a γ/γ' microstructure comparable to cast or wrought material [3].

CONCLUSION

In this article, I reviewed the basic steps necessary to heat treat nickel-based superalloys. The solution heat treatment brings everything into solution, but care must be taken to avoid the onset of incipient melting. This is followed by quenching or controlled cooling to produce a supersaturated γ matrix. Two-step aging is used to control the size and morphology and distribution of γ' in the matrix.

Should you have any comments or question regrading this article, or have suggestions for further articles, please contact the editor or myself.

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