Ni-Based Superalloys for Turbine Discs

David Furrer and Hans Fecht

Superalloys have been developed for specific, specialized properties and applications. One of the main applications for nickel-based superalloys is gas-turbine-engine disc components for land-based power generation and aircraft propulsion. Turbine engines create harsh environments for materials due to the high operating temperatures and stress levels. Hence, as described in this article, many alloys used in the high-temperature turbine sections of these engines are very complex and highly optimized.

INTRODUCTION

Gas turbines are complex machines, being employed in both aircraft engines or land-based power-generation applications. Small, intermediate, and large gas turbines are being developed rapidly for mobile land-based power units[1] and large commercial aircraft applications (Figure 1).[2]

The various parts within this type of power-generation system have specific and unique requirements. For example, the high-pressure turbine section reaches the highest temperature and is one of the highest stress parts of the engine, requiring very specialized nickel-based superalloy materials. The operating temperatures for the rim sections (near the gas-flow path) of high-pressure turbine discs have continued to challenge materials and design engineers as temperatures now approach 760°C and even 815°C for military applications.[3]

In addition to high temperature concerns, materials for modern turbine applications are driven by ever-growing commercial pressures. These pressures can be seen as demands for lower component costs,[4] life-cycle costs, and maintenance costs. For lower acquisition costs, avenues such as alloys with reduced cobalt and alloys that result in higher processing yields are being pursued. For lower life-cycle costs, alloys are being designed with longer service lives. Alloys with good stability and very low crack-growth rates that are readily inspectable by nondestructive means are desired. Fuel efficiency and emissions are also key commercial and environmental drivers impacting turbine-engine materials.[5] To meet these demands, modern nickel-based alloys offer an efficient compromise between performance and economics.[6] The chemistries of several common and advanced nickel-based superalloys are listed in Table I.

As turbine-disc requirements have evolved, materials have been designed to optimize certain key features. The initial cast-and-wrought nickel-based superalloys were developed for increased temperature and strength capability. In the early 1970s, the emphasis turned toward powder-metallurgy (P/M) alloys for even higher temperature and strength applications. More recently, nickel-based superalloy developments have been driven toward improved damage tolerance through highly optimized fatigue-crack-growth properties. Additionally, issues such as component residual stresses have become critical to component design and lifing.

Optimized fatigue-crack-growth rates and reduced component residual stress levels have led to reductions in other properties, such as strength and temperature capabilities. The direction of materials for future applications is once again toward improved strength and temperature capability, while still maintaining or improving the damage tolerance and residual stress characteristics of the best materials currently being produced. This evolution in application requirements has caused materials and process engineers to tailor the processing route for turbine discs for the correct balance in properties.[7]

NICKEL-BASED SUPERALLOY MICROSTRUCTURAL FEATURES

The mechanical properties of nickel-based superalloys can be optimized by tailoring alloy chemistry and microstructural features through refined special practices and process control.[8,9] Nickel-

Table I. The Chemical Compositions of Several Superalloys (wt.%)

Alloy	Cr	Ni	Co	Mo	W	Nb	Ti	Al	Fe	C	B	Other
A286	15	26	—	1.25	—	—	2	0.2	55.2	0.04	0.005	0.3 V
AF115	10.7	56	15	2.8	5.9	1.7	3.9	3.8	—	0.05	0.02	0.75 Hf; 0.05 Zr
AF2-1DA	12	59	10	3	6	—	3	4.6	<0.5	0.35	0.015	1.5 Ta, 0.1 Zr
AF2-1DA6	12	59.5	10	2.75	6.5	—	2.8	4.6	<0.5	0.04	0.015	1.5 Ta, 0.1 Zr
Alloy 706	16	41.5	—	—	—	—	1.75	0.2	37.5	0.03	—	2.9 (Nb+Ta), 0.15 Cu
Alloy 718	19	52.5	—	3	—	5.1	0.9	0.5	18.5	0.08	—	0.15 Cu
APK12	18	55	15	3	1.25	—	5	2.5	—	0.03	0.035	0.035 Zr
Astroloy	15	56.5	15	5.25	—	—	3.5	4.4	<0.3	0.06	0.03	0.06 Zr
Discaloy	14	26	—	3	—	—	1.7	0.25	55	0.06	—	
IN100	10	60	15	3	—	—	4.7	5.5	<0.6	0.15	0.015	0.06 Zr, 1.0 V
KM-4	12	56	18	4	—	2	4	4	—	0.03	0.03	0.03 Zr
MERL-76	12.4	54.4	18.6	3.3	—	1.4	4.3	5.1	—	0.02	0.03	0.35 Hf; 0.06 Zr
N18	11.5	57	15.7	6.5	—	—	4.35	4.35	—	0.015	0.015	0.45 Hf; 0.03 Zr
PA101	12.5	59	9	2	4	—	4	3.5	—	0.15	0.015	4.0 Ta; 1.0 Hf; 0.1 Zr
René 41	19	55	11	10	—	—	3.1	1.5	<0.3	0.09	0.01	
René 88	16	56.4	13.0	4	4	0.7	3.7	2.1	—	0.03	0.015	0.03 Zr
René 95	14	61	8	3.5	3.5	3.5	2.5	3.5	<0.3	0.16	0.01	0.05 Zr
Udimet 500	19	52	19	4	—	—	3	3	<4.0	0.08	0.005	
Udimet 520	19	57	12	6	1	—	3	2	—	0.08	0.005	
Udimet 700	15	55	17	5	—	—	3.5	4	<1.0	0.07	0.02	0.02 Zr
Udimet 710	18	55	14.8	3	1.5	—	5	2.5	—	0.07	0.01	
Udimet 720	18	55	14.8	3	1.25	—	5	2.5	—	0.035	0.033	0.03 Zr
Udimet 720LI	16	57	15.0	3	1.25	—	5	2.5	—	0.025	0.018	0.03 Zr
V57	14.8	27	—	1.25	—	—	3	0.25	48.6	0.08	0.01	0.5 V
Waspaloy	19.5	57	13.5	4.3	—	—	3	1.4	<2.0	0.07	0.006	0.09 Zr

based superalloys are complex alloys with various microstructural features that contribute to the control of the mechanical properties. These features include grain size, γ′ size and distribution, carbide- and boride-phase content, and grain-boundary morphology.

Grain size is one of the most important features, as it greatly influences strength, creep, and fatigue crack initiation and growth rate.[10] Grain-size optimization and control is one of the primary goals during the forging of turbine-disc components. Considerable work has been done to develop predictive tools for recrystallization and grain growth of numerous nickel-based superalloys;[11–15] these efforts are continuing, and will be a vital part of alloy and process design.

The selection of the initial material manufacturing route is as important as the selection of the alloy when considering grain-size control. For example, cast-and-wrought material has typical grain-coarsening behavior, which is very rapid and nonuniform, as opposed to P/M materials, which typically coarsen in a more controlled and uniform manner. Figure 2 shows the grain coarsening behavior of cast-and-wrought and P/M U720LI. The average grain size as well as the as-large-as grain size coarsening rates are greatly different between these two pedigrees of U720LI.

The control of γ′ size and distribution is equally important in nickel-based superalloy materials, since precipitation of the γ′ phase provides the main mode of strengthening for these high-temperature alloys.[16,17] This phase is primarily controlled through heat treatment, making this processing step critical to all superalloy components.[18–27]

The heat treatment of nickel-based superalloys has and continues to be a topic of great interest.[28] Issues regarding cooling rates, γ′ nucleation rates, and growth rates highlight the complexity of these engineered materials. High cooling rates from the solution heat-treatment cycle promote fine γ′ formation and, consequently, high tensile and creep strengths. Overall alloy chemistry also plays an important role in γ′ formation size, morphology, and stability through specific phase chemistry and lattice mismatch issues. It is also clear that alloy

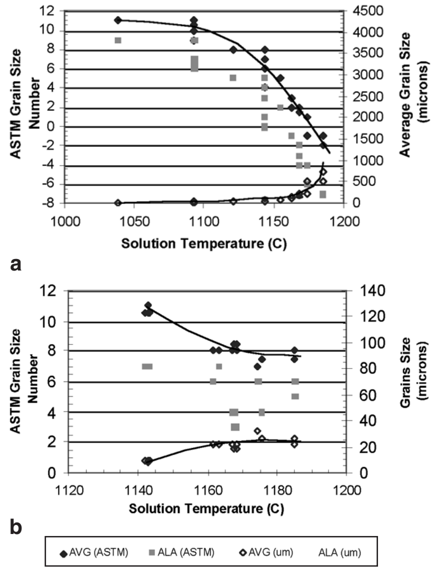


Figure 2. Plot of grain sizes of (a) cast-and-wrought U720LI samples and (b) P/M U720LI samples heat treated for one hour at various temperatures. AVG—average; ALA—as large as.

and process design can not be separated, but must work together for the best balance of mechanical properties for the desired applications.

Other microstructural features that impact turbine-disc performance, such as grain-boundary morphology and carbide/boride phase content and distribution, are of great interest and importance. Tailoring the morphologies of grain boundaries has a great potential for improved material performance. Efforts to develop wavy or serrated grain boundaries have shown improvements in creep and rupture capabilities.[29–38] These improvements have been attributed to reduced continuous grain-boundary segment lengths in any given direction. This, in turn, reduces wedge crack formation tendencies and minimizes or eliminates continuous-carbide film precipitation under service-stress conditions.

Carbides and borides are beneficial to wrought-processed nickel-based superalloy turbine discs. They improve grain-boundary performance during creep through grain-boundary sliding resistance. Carbides and borides phase content, type, morphology, and location can be effectively altered through thermo-mechanical processing. While some carbides and borides are beneficial, large quantities can be detrimental, such as in early-generation cast-and-wrought alloys, where stringers and clusters of carbides and carbonitrides are common sites for fatigue crack initiation.

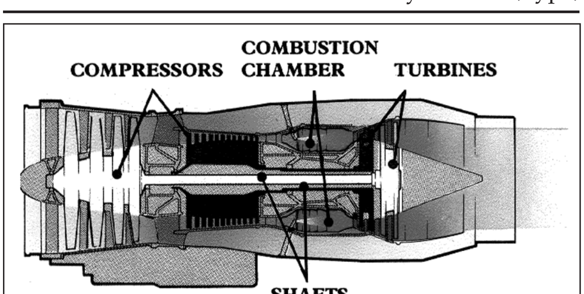


Figure 1. A schematic illustrating a cross section of a gas turbine engine.

SUPERALLOY DESIGN AND PROCESS ISSUES

There are a number of issues with regard to nickel-based alloy and process design. These include component residual stresses, alloy stability, and defects. All of these items are key for current alloy design and processing and are becoming increasingly important for future applications.

Residual stresses are locked-in thermal stresses, which primarily come from solution-heat-treatment cycles. Although it is important to cool components rapidly from a solution-heat-treatment cycle, the variation in cooling rate from surface to center results in large thermal stresses, often large enough to cause plastic strains and subsequent residual stresses.[39,40] Under extreme conditions, thermal stresses can even give rise to quench cracking.[41,42]

The magnitude of the residual stresses can be a large fraction of the material's yield strength in compressive and tensile directions. These locked-in stresses can greatly affect the performance of a component, both in maintaining tight machining tolerances and preserving final component strength capability. It is often thought that a component's strength capability can be measured by testing samples excised from the component. This is truly not the case, since the material's strength capability and the component's residual stress state need to be analyzed concurrently.

Alloy stability has been an issue for many years and will continue to be a concern as new alloys as well as applica-

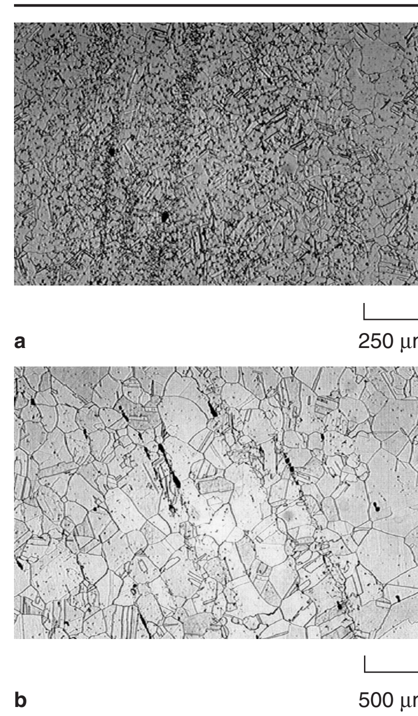
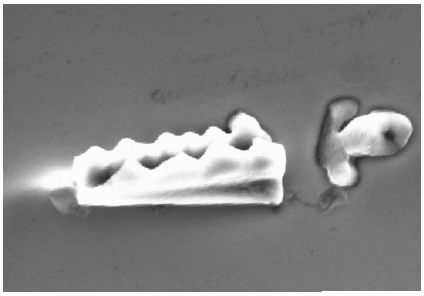
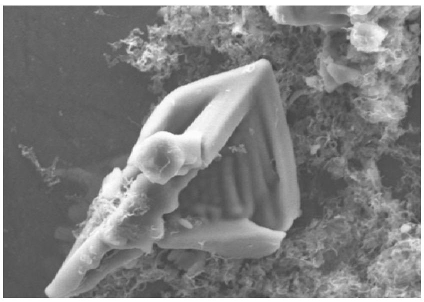


Figure 3. A cast-and-wrought U720LI sample exhibiting (a) grain size banding and (b) carbonitride stringers and clusters.



a 5 μm



b 10 μm

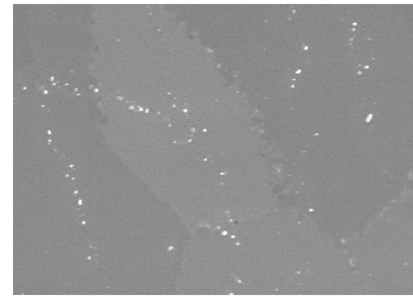
Figure 4. Scanning electron photomicrographs of (a) a partially extracted carbonitride particle and (b) an extracted carbonitride particle in a cast-and-wrought U720LI sample.

tions are developed. Tools such as PHACOMP[43] and, more recently, CALPHAD[44,45] have been utilized to predict alloy-phase stability. Sigma-phase formation has been a key focus of these tools. Consequently, alloy chemistries have been optimized or modified to avoid deleterious phase formation during the service life of components.

With the many economic pressures of today, it is not surprising that components produced from current alloys are being looked at for applications with increased life and higher temperatures. One of the workhorse superalloys, alloy 718, is being scrutinized for phase stability;[46,47] it is now being studied to determine the mechanism and formation rate of α-Cr. It is believed that this phase formation can greatly impact the material's mechanical properties. Studies of this type will be required of materials for use in future applications that have extreme service temperature and service life requirements.

All applications need to be designed in accordance to a material's capabilities and inherent defect content and potential. While cast-and-wrought nickel-based superalloys are common and widely used, they still have issues with regard to defect formation. These defects range from common solidification segregation resulting in grain size banding, to carbonitride stringers and clusters and very deleterious features, such as freckles or white spots.[48,49] Cast-and-wrought superalloys are prone to segregation problems. Figure 3a shows a banded cast-and-wrought U720LI microstructure. Gamma-prime lean bands result in grain coarsening during processing, while γ'-rich bands restrict grain growth and result in fine grain bands. Figure 3b shows typical carbonitride stringers in cast-and-wrought U720LI. This feature can be further seen in Figure 4a, where a carbonitride stringer particle is partially extracted out of an electropolished cast-and-wrought U720LI sample; Figure 4b shows a carbonitride particle after full extraction.

P/M processing is required of the most advanced, heavily alloyed nickel-based superalloys for the most difficult turbine-engine applications. P/M superalloy materials have been studied in great detail.[50–67] Although often thought of as not being as "clean" as cast-and-wrought materials, they do not possess the macroscopic solidification defects inherent to cast-and-wrought materials. Screening the powder material before canning and consolidation controls the defect size in P/M materials. Nickel-based superalloys produced by P/M exhibit networks of finely distributed carbides and oxides, which form on the prior atomized powder surfaces, resulting in prior particle boundaries (PPBs). Figure 5 shows a PPB network in P/M U720LI, which is not coincident with the alloy grain boundaries.



5 μm

Figure 5. Scanning electron photomicrograph of a PPB network in a P/M U720LI sample.

The West has adopted extrusion to consolidate and break-up PPBs and isothermal forging to further work the consolidated powder material. The Russian approach for P/M processing is to minimize oxygen contamination by use of plasma-rotating-electrode process (PREP) atomization, followed by screening and electrostatic cleaning and hot isostatic pressing (HIP) consolidation. Wrought processing, however, of P/M materials has also been shown even by the Russians to improve component properties over as-HIP materials.[66]

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UDIMET 720: THE EVOLUTION OF A NICKEL-BASED DISC ALLOY

Udimet 720, also known as U720, is a nickel-based superalloy originally designed for cast-and-wrought turbine blades.[68] (Udimet is a trademark of alloys developed and patented by Special Metals Corporation.) U720 has and continues to evolve as it is being applied to other applications, such as turbine-engine discs. The chemistry of U720 was modified in the mid-1980s by reducing the chromium content to avoid σ phase formation and reducing the carbon and boron contents to reduce the carbide, boride, and carbonitride stinger and cluster formation. The alloy was renamed U720LI, designating low inclusion content. This material has been utilized to a large extent for high-temperature, high-strength applications.

U720 and U720LI are of great interest for aircraft and land-based turbine disc use, and considerable work has been undertaken to understand the phases, phase stability, and mechanical properties of these materials. U720LI is being incorporated into the BMW-Rolls Royce BR700 aircraft engine; the Allison AE2100, AE3007, T406, and T800 aircraft engines;[69–71] the Rolls-Royce Trent aircraft engine;[72] and many other applications.

U720LI is produced in cast-and-wrought or P/M forms. For fine-grain, high-strength applications, the cast-and-wrought version of this alloy is acceptable. For applications where intermediate grain sizes are needed, such as for improved damage tolerance or other balances in properties, P/M U720LI is preferred, since the control of the grain size of this material is much more readily accomplished (Figure 2).

Efforts are in progress to develop processing routes for enhanced and optimized mechanical properties of U720LI. Based on comparisons of tensile strength properties versus temperature for U720 and U720LI in the literature[68,69,72–77] with results from a current study, U720LI is slightly stronger than U720. The results from the current study match well with the best U720LI properties. The same material exhibits a greatly enhanced creep capability over other U720LI materials.[68,76–78] The enhanced processed U720LI material outperforms U720 material in the high-stress/low-temperature regime and approaches the performance of coarse-grain U720 blade material in the high-temperature/low-stress regime. U720LI grain size and γ' size and distribution has been optimized in the current efforts, so that damage tolerance is improved over fine-grain, high-strength U720 or U720LI. The new process has also been optimized to reduce residual stress.

This new processing route for U720LI produces tensile strengths equivalent to current high-strength materials, improves creep resistance and damage tolerance, and reduces residual stresses. This will allow U720LI to grow into many future disc applications where these properties are required to be optimally balanced. U720LI is a clear example of how evolution through focused alloy and process improvements of an existing alloy can result in significant property enhancements.

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ABOUT THE AUTHORS

David Furrer earned his M.S. in metallurgical engineering at the University of Wisconsin–Madison in 1988. He is currently manager of advanced materials and process technology at Ladish Co., Inc.

Hans Fecht earned his Ph.D. in materials science at Universität Saarbrucken in 1984. He is currently professor, Abteilung Werkstoffe der Elektrotechnik–Materialwissenschaften, at the Universität Ulm, Germany.

For more information, contact D. Furrer, Ladish Co., Inc., 5481 S. Packard Avenue, P.O. Box 8902, Cudahy, Wisconsin 53110-8902; (414) 747-3063; fax (414) 747-3036; e-mail dfurrer@ladishco.com.