Dual-microstructure rotating turbine disks for aircraft engines have become a reality, and a cost-effective method to produce such disks has been developed and demonstrated.

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DUAL-MICROSTRUCTURE HEAT TREATMENT

Rotating disks for aircraft engines and land-based turbines must withstand higher operating temperatures and demonstrate longer service life than ever before, while also minimizing costs. One design and processing approach is to develop disk components with distinctly different microstructures optimized for required mechanical properties at various regions within the disks. A new method has been developed and demonstrated on a production scale to produce dual-microstructure disks in a very controllable, reproducible, and cost-effective manner.

This article describes disk requirements, discusses the dual-microstructure heat treatment, and reports results of extensive testing of the dual-microstructure turbine engine disks.

Turbine engine disk requirements

Turbine engines are manufactured from a series of rotating disks and cases. Blades attached to the disks compress incoming air and mix it with fuel. The compressed air-fuel mixture is then burned, and the high-temperature, high-velocity gases are expelled outward through another series of disks, which drive the compressor sections. The temperatures of the high-pressure compressor sections and high-pressure turbine sections have been continually increased over the years to allow higher thrust-to-weight ratios, fuel efficiencies, and reduced levels of NOx.

The rim of a turbine disk is hotter than the bore because it is near the very high-temperature gas path. High-temperature creep and fatigue crack-growth properties are needed at the demanding rim location, where sustained temperatures of some advanced engine disks are approaching 760°C (1400°F). However, these temperatures are pushing nickel-base superalloys to their limit.

The bore region operates at a cooler temperature, but is required to withstand extreme centrifugal stresses because the disk rotates at very high speed. Therefore, the bore region requires high tensile strength and low-cycle fatigue strength.

It is clear that to achieve such a component with a uniform, monolithic material, a compromise of properties is required to accommodate both the bore and the rim requirements.

To solve this problem, new nickel-base alloys are being developed to allow higher service temperatures. These include R88DT, N18, RR1000, ME3, and LSHR. Although they provide advantages over previous generations, the properties in any one region are limited in an effort to develop an optimal balance over the entire disk.

Manufacturing methods

In an effort to provide the best properties at each location on the disk, two manufacturing methods have been developed: dual-alloy disks and dual-microstructure disks.

• Dual-alloy disks: In this approach,
materials with optimal properties for each region are bonded together to form a single disk component. However, this method has many technical and economic hurdles. For example, the single heat treating methods utilized for dual-alloy disks are compromises for the two distinctly different alloys.

In addition, designing components with a rigid internal interface from materials with different elastic modulus values results in interface stress problems. Although this approach has promise, many such technical issues need to be resolved.

- **Dual microstructure disks:** Another approach that has garnered great attention is the development of a single-alloy disk that is thermo-mechanically processed to provide a dual microstructure. This eliminates the issues of internal interfaces, bond-line cleanliness, and compromised heat treatments. Many technologies have been devised to produce dual-microstructure disks.

  Pratt & Whitney has implemented one process to manufacture dual-microstructure disks for production disks within the F119 engine for the USAF F-22 Raptor. This approach relies on induction heating to selectively heat the outer rim to a high temperature to coarsen the grain structure. Other methods have been attempted, but industrial robustness and process costs have limited their application.

  However, a new method that relies on process modeling and specially de-
signed fixtures allows conventional batch heat-treat processing with existing furnace facilities. The process is called dual-microstructure heat treatment (DMHT).

**DMHT Process**

NASA Glenn Research Center developed the DMHT process, which has been demonstrated on a production scale at Ladish. Full-scale disks manufactured from the P/M nickel-base superalloy ME3 have been successfully treated with conventional heat treating equipment.

While previous dual-microstructure heat treatment processes required selective heating or selective cooling by complex facilities and methods, the new process produces a dual-microstructure from establishment of an engineered and pre-selected thermal transient within the disk component.

To enable the development of the thermal transient, special thermal masses and thermal insulators are added to the disk prior to loading into an isothermal heat treating furnace, as schematically shown in Fig. 1. The added thermal mass and insulators slow down the heating of the bore region, while the rim of the disk quickly heats to the furnace temperature. A natural thermal gradient is developed, in which a transition from a fine-grain structure to a coarse-grain structure is nearly stabilized after approximately one hour of solution heat treatment.

To study the robustness of this process, variations in furnace temperature, cycle time, and thermal fixture geometries were investigated. For each trial, a monitoring thermocouple placed within the thermal fixtures indicated the exact time to extract the disk from the solution heat treatment furnace. A thermocoupled disk has been processed to validate the model predictions, which have confirmed excellent repeatability.

Cooling from the DMHT process has also been investigated. Rapid removal of the thermal fixtures and oil quenching with a total transfer time of 25 seconds has been demonstrated. Other disk trial iterations involved removing the thermal fixtures, air cooling the DMHT processed disk, and subsequently re-solution heat treating at an isothermal, subsolvus temperature followed by oil quenching. The aging process for these disks was an 815°C (1500°F), 8-hour cycle.

**Metallographic analysis**

Metallographic analysis of the DMHT disks showed excellent results. Figure 2 shows an example DMHT disk macro-etched cross-section. The dual microstructure is clearly visible, and the transition was found to be at the exact location designed for each processing sequence.

In addition to the macrostructural analysis, the grain size and gamma-prime distribution from bore to rim were characterized on metallographic mounts cut from a central slice through the cross section of the disk. Metallography revealed the controlled variation in the demonstration disks. High magnification metallographic sections reveal a very fine grain structure, about ASTM 14 (3/6Dm) at the bore location. The grain size increases gradually in the web to about ASTM 12 (6/6Dm). The amount of primary gamma prime decreases, while the amount of cooling gamma prime increases in the web as compared to the bore.

A duplex grain structure is found near the transition zone, with further reduction in primary gamma prime and more cooling gamma prime. Finally, a uniformly coarse grain structure develops near the outer diameter of the disk, about ASTM 6 to 7 (45 to 32 μm). The gamma prime is present as cooling gamma prime particles about 0.1 to 0.3 μm in size, with little
Mechanical testing
A disk treated by DMHT plus oil quench cooling was sectioned to measure key mechanical properties over a range of temperatures. Tensile specimens were cut from the bore, transition, and rim of the disk. Creep and crack growth specimens were cut from the bore and rim, while fatigue specimens were cut from the bore of the disk. Crack growth was tested on a Kb bar specimen. Test temperatures were chosen to reflect specimen location: for example, rim specimens were generally tested at higher temperatures than bore specimens, although a certain degree of overlap was maintained for comparative purposes. A compilation of the tensile and creep data for the DMHT disk can be found in Table 1.

- Tensile strength: The tensile ductility of the DMHT disk is seen to be acceptable, with elongation values of 9% or greater, for all locations and temperatures evaluated. Figure 3 shows a comparison of the strength levels of the DMHT disk with the NASA Advanced Subsonic Transport (AST) ME2 data and NASA Ultra Efficient Engine Technology (UEET) ME3 data. In general, bore strength levels from the DMHT disk are comparable to the AST and UEET subsolvus data sets; however, the rim strength levels from the DMHT disk generally exceed that of the AST and UEET supersolvus data sets. In fact, the bore and rim strength levels are virtually identical for the DMHT disk.

- Creep rate: The times to 0.2% creep were measured at 700°C and 815°C (1300 and 1500°F) for bore and rim specimens from the DMHT disk. The data, shown in Table 1, indicate a significant advantage, with slower creep rates for the coarse-grain rim specimens at both temperatures, compared to the fine-grain bore specimens. Using a Larson-Miller plot, the creep rates of the DMHT data were compared with the AST and UEET data in Fig. 4. While the data for the DMHT rim specimens were equivalent or superior to those for the AST and UEET supersolvus data, the DMHT bore specimens were inferior to the AST subsolvus data set.

- Fatigue life: Minimum fatigue life of a disk is often observed at intermediate temperatures in the bore, between 350 and 550°C (660 and 1020°F). For this reason, low-cycle fatigue tests were run on DMHT bore specimens at 400°C (750°F). The results of these tests are presented in Fig. 5, along with data from the AST Program. The fine-grain microstructures, DMHT bore and AST subsolvus, have longer fatigue life than that shown by the coarse-grain AST supersolvus data.

- Crack growth: The last property to be evaluated for these demonstration disks was crack growth. Cyclic crack growth tests were run at 540°C (1000°F) and 0.3 Hz on DMHT bore specimens; while 90-second dwell crack growth tests were run at 700°C (1300°F) on DMHT rim specimens. This choice reflects design-limiting crack-growth criteria for modern disk applications.

The cyclic crack growth results for the DMHT bore specimens were similar to those for the AST and UEET subsolvus data. The 700°C (1300°F) dwell crack growth results for the DMHT rim are plotted in Fig. 6 with the AST and UEET data sets. The AST data set clearly shows that coarse-grain microstructures improve dwell crack growth resistance. Although the
coarse-grain rim specimen from the DMHT disk shows better dwell crack-growth resistance than the subsolvus AST material, it was clearly inferior when compared to the supersolvus AST material. This shortfall may be attributed to differences in heat treatment, specifically cooling rates and aging sequence, between the supersolvus AST disk and the DMHT disk.

These results show that the DMHT process has the potential to produce complex components with unique properties within the rim and bore regions. Further heat treatment process development is required to fully optimize the regional properties. Therefore, pre- or post-DMHT sub-solvus heat treating may be beneficial.

**Future efforts**

Efforts are in progress to further optimize the thermal cycle for dual-microstructure disks manufactured from P/M superalloys ME3 and LSHR. Automation methods to process many disks in a batch mode with conventional cooling methods are being pursued.

Further assessments of post-DMHT cooling are also required. In addition, selective cooling rates for optimum mechanical properties, and issues relating to cooling the rim and bore from different temperatures, are being addressed. The utilization of the Ladish SuperCooler process may be critical in optimizing mechanical properties and residual stresses.

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