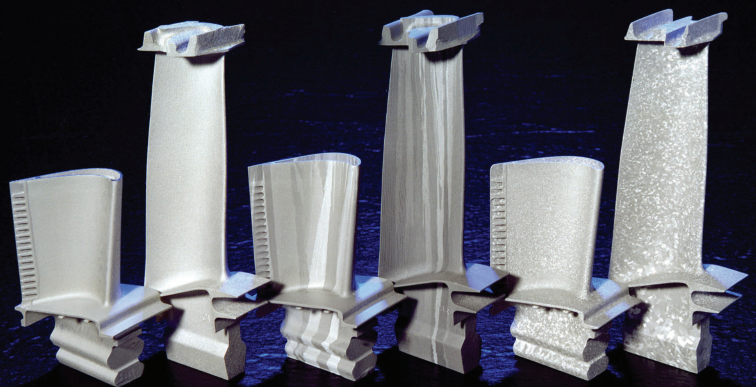
PRATT & WHITNEY

Single Crystal Turbine Blade



ASME HISTORIC ENGINEERING LANDMARK

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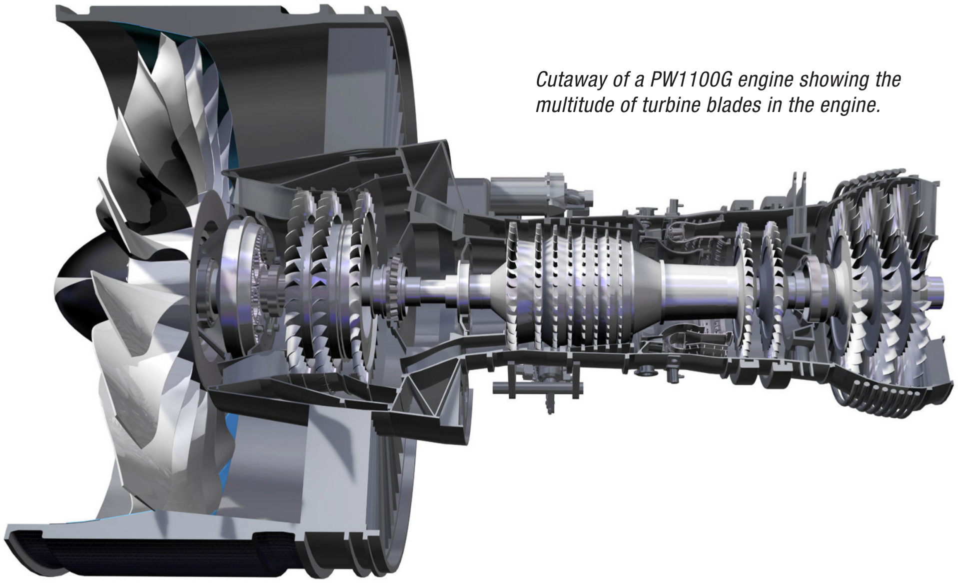
The development of single crystal turbine blades by Pratt & Whitney engineers is one of the game-changing technology breakthroughs that help produce the incredible performance of today's gas turbine engines.

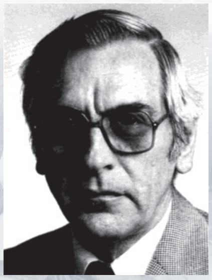


Cutaway of a PW1100G engine showing the multitude of turbine blades in the engine.

Basic thermodynamics says that the higher the temperature at which a jet engine can operate, the more efficient the engine is. There are limitations. Engines produce a lot of heat and stress, and turbine components bear the brunt of it. The gas stream leaving the combustion chamber where fuel and air are mixed and ignited can be 3000 degrees Fahrenheit. The problem that arises is that the metal that turbine blades are made from, nickel-based superalloys, can begin to melt between 2300 degrees Fahrenheit and 2500 degrees Fahrenheit. So to allow the blades to operate above their melting point, they are made with special materials using a special process to produce an intricate pattern of internal cooling passages and then coated with ceramics for thermal protection.

The blades also have to be immensely strong because they endure tremendous stress, spinning at thousands of rpms. The centrifugal forces across the span of a blade can reach 20,000 times the force of gravity. Think of it this way — each blade individually is working as hard and producing as much power as a high-performance race car engine.

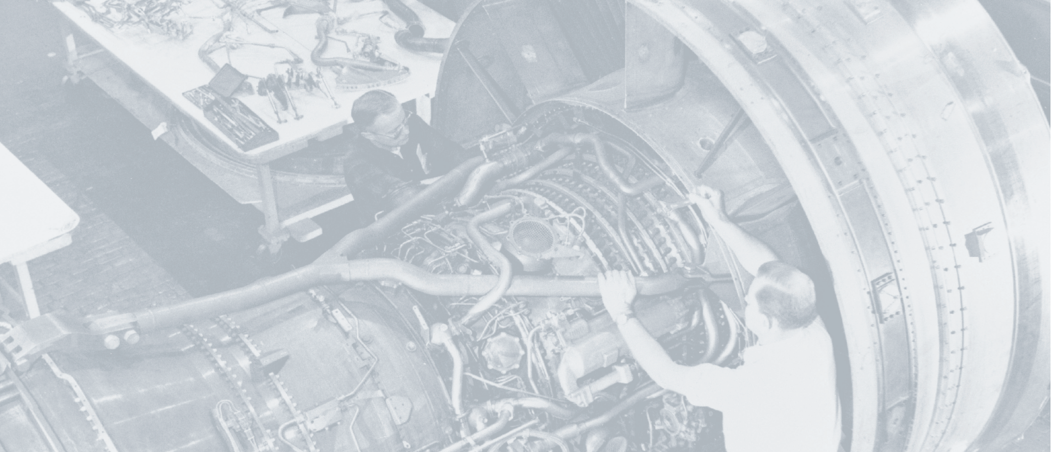
Beginning in the 1960s, Pratt & Whitney engineers at the Advanced Materials Research and Development Laboratory (AMRDL) started probing ways to improve turbine performance further. Key leaders in this effort were Frank VerSnyder and Maurice "Bud" Shank. Shank, a faculty member at the Massachusetts Institute of Technology, joined Pratt & Whitney to form AMRDL. He in turn recruited VerSnyder who eventually became assistant director of materials research at the United Technologies Research Center in East Hartford, Connecticut, and was recognized as one of the world's leading experts in high-temperature metallurgy.



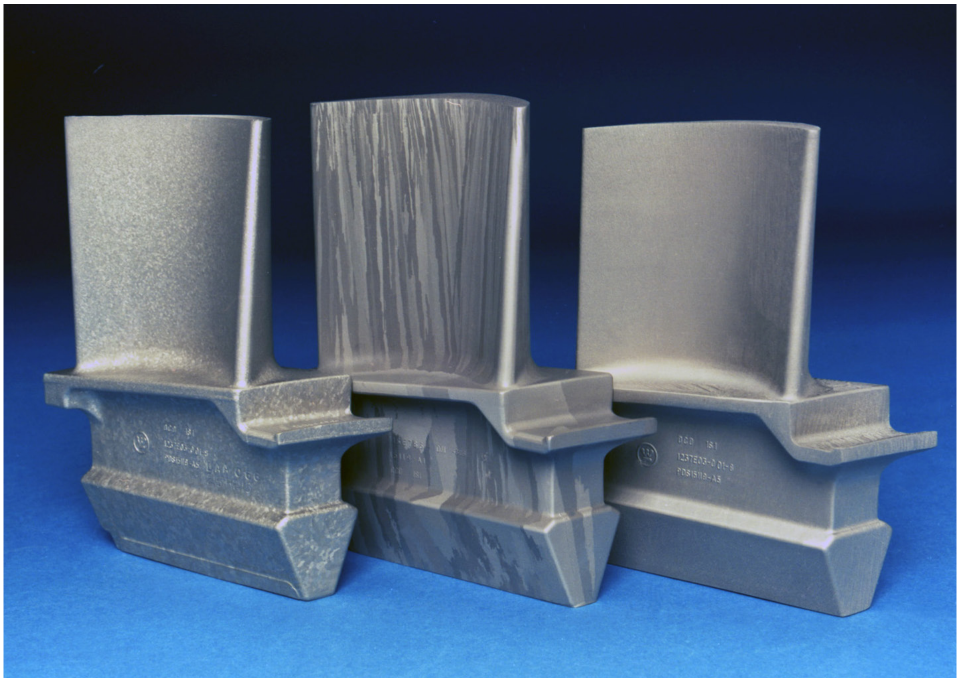
Frank VerSnyder

Maurice "Bud" Shank

The teams they led investigated the actual metallic structure of the blades. If you could see inside conventionally cast metals you would see a multitude of very tiny crystals also known as grains that looks like a very intricate mosaic. The atoms in each grain are oriented the same but are oriented differently from their neighbors, creating what are called grain boundaries. All kinds of bad things can occur is this tiny world — unwanted chemical activity, slippage under high stress and the formation of voids. The biggest problem is "creep," where the blade starts to deform as the grain boundaries weaken. One engineering paper sums up creep as "an insidious life limiter." Oxidation, corrosion and microscopic cracks also can occur at grain boundaries. All of this shortens the life of the turbine. It also means that to avoid these problems the turbine temperature has to be lowered, hurting performance efficiency.

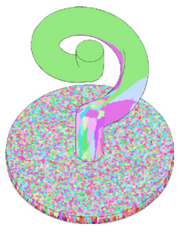


Photographs are courtesy of Arconic.



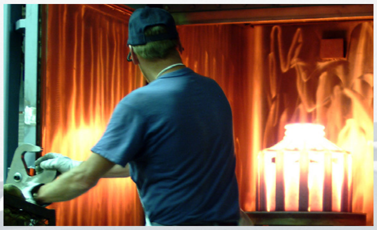
These turbine blades have had their surfaces etched with acid to reveal their inner structure. The one at the far right is a single crystal, the one in the middle is directionally solidified, and the one at the left is made up of small crystal grains, with numerous boundaries.

The first step the AMRDL scientists and engineers took was to see if they could eliminate the crystal boundaries in the direction prone to deformation. Using a special vacuum casting furnace with tightly controlled temperature zones, they poured molten superalloy into a ceramic mold and used a controlled cooling process to directionally align the grains along the span of the turbine blade, making it much stronger. They had invented "directional solidification." The resulting blade structure was comprised of parallel columns of crystals with no transverse boundaries on the blade. Aligning these columns with the stress axis of the blade resulted in significant increase in creep and thermal fatigue properties while reducing the number of boundaries assisted in enhanced oxidation and hot corrosion resistance. This technology was first used in 1972 in the J58 engine for the SR-71 Blackbird, the super spy plane that operated at the edge of space at fantastic speeds.



If directional solidification was good, wouldn't a process to eliminate all grain boundaries be even better? In 1970 the team found that by introducing and solidifying the molten superalloy directionally through a smooth bent structure, you created a filter that admitted only one crystal into the mold and started the buildup of a single crystal blade where all the atoms are aligned in a repeating arrangement with no boundaries to weaken the structure. The structure eventually took the shape of a helix. This crystal "selector" was an odd-looking thing and inevitably was dubbed "the pigtail." It took time and effort to refine the manufacturing process so that it was repeatable and could produce the necessary number of blades cost-effectively. A typical commercial engine uses 100-200 single crystal blades.

A mathematical modeling image (above graphic) illustrates how a helical formation selects out a single crystal from a solidifying metal alloy. Each color represents a different crystal grain. (Image courtesy of Charles-André Gandin, CNRS.)



A worker prepares to remove a glowing-hot mold from a furnace after casting.

One key step was learning how to precisely control heat conduction in one dimension as the mold is withdrawn into a cooler chamber from its heated chamber. Any disruption can cause localized formation of secondary crystals. Also, engineers had to develop new superalloys that eliminated the elements needed to strengthen grain boundaries and substituted other metallic elements that increased strength and heat resistance.

A ceramic mold for multiple directionally solidified turbine blades is placed in a vacuum furnace at Howmet's foundry in Terai, Japan.

By the early 1980s, single crystal turbine components began to have practical applications. In 1980, the JT9D-7R4 engine used for the Boeing 747, McDonnell Douglas DC-10, and the Airbus A300 was the first commercial application. Single crystal components were key to the success of the TF30 engine used on the F-111 and F-14 jet fighters and the F100 engine used on the F-15 and F-16 fighters. In 1975 Pratt & Whitney's work in single crystal technology received the ASM International Materials Achievement Award and in 1986 the prestigious National Medal of Technology and Innovation, which was awarded by President Ronald Reagan.

Since then single crystal technology has moved through the entire engine industry. Single-crystal turbine airfoils have as much as nine times the life in terms of creep deformation and thermal fatigue resistance compared to multi-grain components. They help engines operate more efficiently and cleanly. They make possible the 25,000 hour time between major overhauls of today's engines. They are indeed an aviation landmark.

ADDITIONAL READING:

Donachie, Matthew J. & Stephen J. Superalloys-A Technical Guide, ASM International, 2002 2nd Edition, ISBN: 0-87170-749-7

Langston, L. S. 2013. The adaptable gas turbine. American Scientist 101:264–267.

Simcoe, Charles R. 2016. Metallurgy Lane: Pioneers in Metals Research-Part VI. Advanced Materials and Processes March 2016:30–31.

The History and Heritage Program of ASME

Since the invention of the wheel, mechanical innovation has critically influenced the development of civilization and industry as well as public welfare, safety and comfort. Through its History and Heritage program, the American Society of Mechanical Engineers (ASME) encourages public understanding of mechanical engineering, fosters the preservation of this heritage and helps engineers become more involved in all aspects of history.

In 1971 ASME formed a History and Heritage Committee composed of mechanical engineers and historians of technology. This Committee is charged with examining, recording and acknowledging mechanical engineering achievements of particular significance.
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The Landmarks Program illuminates our technological heritage and encourages the preservation of historically important works. It provides an annotated roster for engineers, students, educators, historians and travelers. It also provides reminders of where we have been and where we are going along the divergent paths of discovery.

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