Modern aeropropulsion is possible only because of the materials that have enabled continuous improvement in high-temperature operation, higher power, and reduced weight over the past 50 years. This is the second of a four-part series about development of these materials.

Three major systems comprise the modern airplane: the aircraft structure that encompasses the fuselage, wings, and landing gear; the avionics that enable flight through crowded skies in nearly all weather conditions; and the propulsion system that powers the aircraft (Fig. 1). Improvements in materials have been critical to advances in all three systems; indeed, the U.S. National Academy of Engineering identified Advanced Materials as one of the top ten accomplishments of the 20th century.

The materials challenges presented by gas turbine engines for jet aircraft are particularly daunting given the high stresses, high temperatures, and ultra-high reliability demanded of these engines and their components. This series of articles highlights the story of the evolution of the materials and processes that have been crucial to making modern jet engines a reality.

This article describes vacuum arc remelting, vacuum induction melting, and the development of superalloys and titanium alloys.

**Vacuum arc remelting**

Vacuum arc remelting (VAR) was first developed as a process for the melting of metals in 1839. However, it was not widely practiced for the commercial production of structural materials until after World War II, more than a hundred years later, when vacuum technology became commercially available.

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However, refractory-lined VIM furnaces are not suitable for titanium, because molten titanium has high reactivity with most ceramics, and forms brittle inclusions. In addition, titanium’s high melting point and reactivity made its containment in metallic crucibles impractical.

The problems associated with melting and alloy synthesis of titanium were solved by development of non-consumable and later consumable electrode arc melting in a water-cooled copper crucible. The molten titanium is contained in a thin layer of titanium (known as a skull) that solidifies on the cooled copper walls.

VAR became widely practiced and generally resulted in acceptable product. However, occasionally Zone D defects (defined in Part I as exceptionally deleterious defects that randomly develop at extremely low frequency, such as one or fewer occurrences per million opportunities) appeared in the form of tungsten or other particles spalled from the non-consumable electrode, and these could cause premature component failure. This problem was abated through radiographic inspection, which could detect the presence of the high-density tungsten particles in the low-density titanium component. The Zone D defects were all but eliminated by the subsequent introduction of consumable electrode vacuum arc melting, in which the electrode was also the product being melted.

Today’s titanium alloys for critical applications are either triple vacuum arc melted with the product of each cycle melted into a water-cooled (non-reactive) mold, or melted in a “cold hearth” furnace (electron beam or plasma arc) followed by a VAR melt.

The advantage of electron-beam or plasma arc melting is that it does not require the forming of a consolidated body (electrode) for remelting, and therefore scrap can be recycled in its unconsolidated form. In addition, cold hearth melt furnaces may be designed such that longer molten metal residence time is possible, increasing the probability that high-melting-point harmful species, such as titanium nitride, will be dissolved.

During VAR, some volatile species such as chlorides are removed during the melt pool’s brief exposure to the vacuum. However, VAR is not as effective as VIM in reducing the amounts of minor and trace elements, because no reactions during VAR are as effective as the slag reduction of contaminants achieved during the much longer, less dynamic, and more flexible VIM process.

Early superalloys

The term superalloy refers to a class of nickel-base and cobalt-base alloys specifically designed for service in the hot sections of gas turbine engines. High-temperature superalloys alloys are called “super” because they possess outstanding strength (tensile, creep, and fatigue strength) and excellent ductility and toughness at high temperatures (0.75 of solidus temperature) that no other metallic system has been able to match. Thus, the mechanical properties of superalloys have truly enabled efficient gas turbine design. Achieving a suitable property balance has been challenging and has required significant processing advances, as well as the more widely appreciated alloy development.

During the 1950s, materials available for gas turbine engines were much improved in temperature capability through chemistry changes (alloy development) and melting improvements. The initial alloys were primarily existing, prosaic, conventional solid-solution strengthened alloys. In fact,
they were derivatives of oxidation-resistant rotor stainless steels adapted for aggressive conditions such as high-temperature oxidation and/or corrosive environments.

The addition of titanium and aluminum (two reactive elements) to nickel-base alloys opened the age of superalloys: an intermetallic phase (Ni₃Al), known as gamma prime (γ) was precipitated, with the titanium substituting for some aluminum in the gamma prime phase. Gamma prime is a highly effective strengthening mechanism that is extremely stable at high temperatures. At the time of its discovery, gamma prime in its coherent lattice-straining form could not be resolved by then-current metallography equipment, but its existence was uncannily inferred by materials scientists. This truly ranks as one of the great discoveries of the 20th century.

The most commonly known rotating superalloy components are turbine disks and turbine blades, shown in Fig. 2 and 3. A typical jet engine contains superalloys in static structures as well, such as pressure cases and frames. A turbine frame is shown in Fig. 4.

**Titanium alloys**

Titanium, despite its higher cost and physical property limitations, became the overwhelming preferred material for several key gas turbine component innovations. The density of titanium is about 50% that of steel or superalloys, offering opportunity for significant weight saving in the temperature range extending to approximately 500°C (930°F).

Titanium is produced by chlorination of the minerals rutile or ilmenite into a titanium-rich liquid form, which is reduced to a spongy bulk product that is close to the needed purity. This titanium sponge is subsequently crushed and vacuum-distilled into relatively pure particles that are generally less than one inch long in any direction. Titanium sponge is a porous product resembling crushed stone in appearance, but it is more malleable than stone. The sponge is mixed with alloying elements, and with selected scrap in the case of cold hearth melting, consolidated, and melted (Fig. 5).

An early and very significant design innovation made possible by titanium was the ducted fan engine. The key metric is the bypass ratio, the ratio of air that bypasses the engine core to that passing through it. The bypass of air is subsequently mixed with the jet engine exhaust at discharge. This permits a thrust increase with minimal weight increase.

The fan engine significantly improved fuel efficiency, and has therefore made jet-propelled travel cost effective, while at the same time increasing mission range and reducing noise. In the early 1960s a bypass ratio of 3.5 to 1 appeared to be the limit, with most engines at that time well below the 3.5 ratio. However, spurred by improvements in fan blades, bypass ratios more than two times this limit are now achievable by high bypass-ratio, single-fan engines. It should be noted that the development in the 1990s of fan blades made from advanced composites offered a technology very competitive to titanium.

**Titanium challenges**

The application of titanium to engine components was not without challenges. It is significant to note that despite the many problems, the systems benefits offered by titanium forced resolution of these concerns rather than the abandonment of titanium. Among the challenges:

- **Hydrogen embrittlement:** Titanium is susceptible to hydrogen embrittlement. Under tensile stresses and low temperature, hydrogen migrates readily through titanium metal to form titanium hydrides that lead to subsequent brittle fracture at less than design-load minimum. To solve this problem, chemical and thermal processes were designed to prevent introduction of hydrogen into titanium components. Vacuum degassing and vacuum stress relief solved this shortcoming.

- **Tungsten contamination:** Another problem was
anode ‘drop in’ and retention as elemental tungsten during non-consumable arc melting. Eliminating the cause of this defect was the primary reason that consumable electrode melting was implemented.

- Hot-salt stress corrosion: Titanium alloys with high alpha-phase (close-packed hexagonal microstructure) content were found to be susceptible to hot-salt stress corrosion under certain severe service conditions. The more susceptible alloys were therefore eliminated from service at elevated temperatures.

- Alpha case: The formation of a brittle oxygen-rich surface layer, known as ‘alpha case,’ was found to be caused by the heating of titanium components in air or in a less-than-perfect vacuum. Oxygen is an alpha stabilizer, and it also embrittles alpha titanium, leading to early crack initiation and premature failure. This defect was overcome by heat treating components in vacuum, and/or chemical milling after heat treating to remove the contaminated layer. Similar problems with welded structures were overcome by electron beam or other vacuum chamber welding processes. In other cases, parts were welded within a protective cloud of inert gas, followed by chemical milling to remove the brittle layer.

- Dwell time fatigue: Creep-resistant, forged titanium alloys with large regions of aligned, crystallographically oriented alpha phase (i.e., colonies) were discovered to be susceptible to Dwell Time Fatigue, also known as Cold Dwell Fatigue. This is a creep-fatigue interaction phenomenon that substantially reduces fatigue life compared to continuous-cycle fatigue. It occurs at sustained (dwell) loads at relatively low temperatures, i.e., less than 200°C (390°F). These alpha colonies form during a relatively slow cool through the beta transus following a beta heat treatment, and may not be eliminated by subsequent deformation processing in the alpha/beta region. Modification of the thermo-mechanical cycle for converting ingot into wrought billet avoids the susceptible microstructure, and has effectively eliminated the dwell fatigue problem.

- Inclusions: Random development of highly stabilized, hard, brittle particles such as titanium nitrides (Type I defect), and tungsten carbides (high-density inclusions, or HDI) can reduce the mechanical properties of titanium. These particles serve as crack-initiation sites and result in reduced fatigue life. Occasionally a Type I or HDI defect survives the melting process, but they are generally found during subsequent ultrasonic inspection, since reduction operations cause the defect to crack or develop a void within the matrix.

Type I defects fundamentally arise from the reactivity of molten titanium. Tungsten carbide HDIs are typically introduced from the revert stream as broken pieces of a cutting tool mixed in with machining chips. The use of cold hearth melting has essentially eliminated HDIs since HDIs fall to the bottom of the molten hearth and are incorporated into the solid skull. Type I defects are removed via the extended residence time in the molten titanium pool.

Regions of solidification segregation (Type II defect) can be detrimental in terms of reducing fatigue life, although not to the same magnitude as inclusions. These defects can be avoided or eliminated by improved process control and melting methods.

- Fires: Self-sustaining titanium fires can ignite in an engine under conditions of elevated temperature and pressure, and high mass flow. Typically these fires are ignited by a high-contact-stress abrasion against a titanium structure. Successful mitigation strategies have involved design practice changes, such as coating of titanium structures to minimize the effect of abrasion, and development of alloys that have improved resistance to combustion.

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The authors wish to thank James C. Williams and Harry A. Lipsitt for careful reading of the manuscript and constructive comments.