Introduction

THERE IS NO STRICT DEFINITION of a superalloy, although a commonly accepted one is that a superalloy is an alloy based on group VIII elements (nickel, cobalt, or iron with a high percentage of nickel added) to which a multiplicity of alloying elements are added. The defining feature of a superalloy is that it demonstrates a combination of relatively high mechanical strength and surface stability at high temperature (Ref 1).

The primary application that has driven superalloy development is for use as air foils in the hot section of gas turbine engines (GTEs), but they have been used successfully in other applications, such as rocket components, nuclear reactors, industrial furnaces, heat exchangers, petrochemical equipment, petroleum production equipment, automotive turbochargers, and biomedical devices.

Superalloys are among the most compositionally complex metallic alloys ever developed for commercial use. Their compositional complexity allows the development of a wide range of alloys that can be optimized through processing for specific applications. The need for materials with higher-temperature capability has driven superalloy development to the present level of sophistication. The high level of investment and the complexity of composition and processing make the cost of superalloys typically in the range of 30 to 200 times that of plain stainless steel (Ref 2).

Although there are a number of other material groups that can be used at high temperatures, such as ceramics and refractory metal alloys, superalloys are unsurpassed in terms of the combination of high-temperature mechanical properties and environmental resistance, as shown in Fig. 1.1, and are the primary choice for structural applications at high temperatures. Although ceramics have very good environmental resistance, their low fracture toughness makes them unsuitable for most structural applications. Refractory metal alloys retain their mechanical properties at higher temperature because of their high melting points, but they have poor oxidation
The combination of environmental resistance and superior mechanical properties at high temperatures sets superalloys apart from other alloy systems (Ref 1).

Simultaneously achieving optimal properties in any material is rarely possible, so a superalloy composition is often optimized for particular mechanical properties at the expense of oxidation/corrosion resistance or vice versa, or the properties represent a compromise, with manufacturability (castability, forgeability, weldability) and cost taken into account.

This review provides an overview of superalloys, strengthening mechanisms, and phases and also discusses the roles of alloying elements. Throughout the text, reference is made to numerous superalloys whose compositions are defined in Appendix A. Note that this is not a definitive list of superalloy compositions but merely a selection of some of the most notable alloys. Properties for each alloying element are included in Appendix B. The mechanical properties of selected superalloys are tabulated in Appendix C.
1.1 Historical Development

Superalloy development has been driven primarily by the need for materials that can withstand the increasing operating temperatures and stresses of components in GTEs. There is some debate as to who is the creator of the GTE, with some crediting Dr. Frank Stolze (1872), who filed a patent that described a device resembling the GTE, and others crediting Charles Curtis, who produced some working models in the early 1900s. Both Stolze’s paper design and Curtis’s working models had a common flaw, which was that the compressor required more power than the turbine could produce, therefore making them mechanical curiosities rather than useful devices.

The first self-sustaining GTE, unveiled in Paris in 1903, consisted of a three-cylinder reciprocating compressor and an impulse turbine. With a three percent thermal efficiency, it gave a humble start to the technology that today drives ships and airplanes and provides reliable electric generation. The Norwegian engineer Aegidus Elling later produced a GTE based on a centrifugal compressor and radial turbine that could produce 11 hp at a turbine inlet temperature of approximately 400 °C (750 °F) (Ref 3). This comparatively low temperature permitted the use of austenitic stainless steels as structural materials, which had been discovered in the 1910s and quickly became the first choice for high-temperature applications (Ref 1).

The development of GTE technology then started in earnest, with the General Electric company, in collaboration with the U.S. Army, starting a gas turbine division under the direction of Dr. Stanford A. Moss from Cornell University, which resulted in the General Electric turbosupercharger engine for aircraft use during World War I. This not only resulted in development of aerodynamic design but also of high-temperature materials. In approximately 1918, British patents were awarded for Nichrome, a Ni-20Cr alloy, which was a starting point for future superalloys (Nimonic, Inconels) (Ref 1, 4). In 1929, Bedford, Pilling, and Merica patented the addition of small amounts of titanium and aluminum to Nichrome (Nimonic 80) for increased strength. Not until after the invention of the electron microscope (1931) could Taylor and Floyd conduct their research and report in 1951 that it was the precipitation of the $\gamma'$ (Ni$_3$Al) phase that caused the higher strength that was the subject of the Bedford, Pilling, and Merica patent. By 1935, Elling had improved his GTE design to the point where it produced 75 hp yet had a turbine inlet temperature of 550 °C (1000 °F), which was still within the temperature capability of austenitic stainless steels. The need for superalloys was not realized until the development of the aircraft GTE.

The aircraft GTE was developed independently by Hans von Ohain and Max Hahn, working for an engineering firm called Ernest Heinkel in Germany, and at a similar time by Sir Frank Whittle, working in collaboration
with the Royal Aircraft Establishment in England. The Heinkel engine He-178 was patented in 1935, five years after Whittle patented his engine, and in 1939 was the first GTE to successfully power an aircraft. Subsequently, Whittle had his first successful flight in 1941. This marked an important year for superalloy development because the turbine inlet temperature had risen to 780 °C (1450 °F), which precluded the use of conventional austenitic stainless steels. This led to the first use of superalloys in GTEs, represented by the wrought Rex-78, which was essentially a heavily modified or “super”-alloyed stainless steel (Ref 3).

The development of cobalt-base superalloys occurred at the same time as the introduction of the austenitic stainless steel-based superalloys. In the early 1900s, patents were issued for Co-Cr and Co-Cr-W systems developed for environmentally aggressive applications, such as cutlery, machine tools, and wear-resistant surfaces (Ref 5). By the time the United States had developed its first aircraft GTE in 1943, cobalt-base superalloys had been introduced, and Haynes Stellite 21 (a cast alloy intended primarily for dental implants) was chosen as the very first turbine blade material.

Most of the early nickel-iron- and cobalt-base alloys were strengthened by carbide dispersions, although Nimonic 80 did exhibit some precipitation hardening due to the formation of a γ′-Ni3Al phase. In the late 1940s, molybdenum was introduced into alloy M-252, producing a significant amount of solid-solution strengthening and leading to a more widespread use of refractory metals in nickel-iron- and nickel-base superalloys (Ref 1). The next major step in superalloy development occurred around the 1950s, when Eiselstein introduced alloy 718, a superalloy strengthened by the γ″-Ni3Nb precipitate.

The superalloy development from the 1930s to 1950s can be considered as being based on microstructure optimization. The next step in the history of superalloy development was characterized by process optimization. In 1952, Falih N. Darmara introduced commercial vacuum melting technology, with the first vacuum-melted alloys beginning to appear in approximately 1955. Both vacuum induction melting (VIM) and vacuum arc remelting allowed the charge to remain molten for longer periods of time, providing greater opportunity for complete degasification and removal of volatile impurities as well as for sampling and adjusting the composition of the melt. Vacuum induction melting also allowed more effective use of trace amounts of beneficial elements, such as boron, manganese, and silicon, as deoxidants, leading to improved high-temperature properties, especially ductility (Ref 6).

Although vacuum casting increased alloy performance by improved compositional control, the more significant effect of VIM was to allow much higher levels of aluminum and titanium to be added to the alloy, leading to the widespread development of γ′ precipitation-hardened nickel-base superalloys. Without vacuum melting and casting, these alloying ele-
ments would oxidize rapidly, negating their value as strengthening agents and rendering the alloys unfit for most structural applications.

Other superalloy derivatives, such as oxide-dispersion-strengthened (ODS) alloys and mechanically alloyed alloys, were developed at Dupont in 1965 and INCO in 1966, respectively. Later, starting in 1969, Pratt and Whitney Aircraft pioneered an entirely new field with the development of directionally solidified alloys for airfoils (Ref 7).

While the vacuum casting processes had opened the door to higher levels of alloying, the precipitation of detrimental phases and the subsequent loss of properties in superalloys during service revealed the need for compositional limits based on phase stability that were largely independent of the manufacturing process. The formation of detrimental phases was found to be associated with high chromium levels, which prompted a reduction of chromium levels in superalloys from approximately 20 to 10 weight percent. The reduction in chromium made the alloys vulnerable to hot corrosion, which was painfully evident in helicopter engines ingesting sea spray during the Vietnam War. Although chromium levels could not be increased without loss of mechanical properties, the environmental resistance of the low-chromium alloys was clearly unacceptable.

The solution was to use coatings for increased environmental resistance. Diffusion coatings were the first to be developed in which large amounts of principally aluminum were diffused into the surface of the substrate superalloy. These coatings proved to be highly successful because their increased oxidation and corrosion resistance permitted turbine inlet temperatures up to 1200 °C (2200 °F) (Ref 8). The first commercial application appeared during the late 1950s on cobalt-base first-stage turbine vanes. In the early to mid-1960s, this coating technology was applied to nickel-base superalloy turbine blades (Ref 9, 10). The topic of protective coatings was given much attention at the first conference dedicated to superalloys, which took place in 1968 at the Seven Springs Mountain Resort in Champion, Pennsylvania.

The other major class of turbine coatings, MCrAlY (where “M” is cobalt, nickel, iron, or nickel/cobalt), began its development in 1965, with the first application appearing in 1969 (Ref 11). The first patent for an MCrAlY coating on a nickel or cobalt substrate was awarded in 1970 to Talboom and Grafwallner (Ref 12) of United Aircraft Corporation, in which an FeCrAlY-type coating was proposed. It was later discovered that the poor stability of iron aluminate compounds, compared to nickel aluminate, caused rapid aluminum depletion in the coating by diffusion of aluminum to the coating/substrate interface (Ref 9). This determined the later development of MCrAlY coatings to be based on cobalt and nickel, such as CoCrAlY (Ref 13), NiCrAlY (Ref 14), and NiCoCrAlY (Ref 15).

By the 1970s, it was becoming evident that while superalloys with protective coatings had sufficient strength and creep resistance and adequate environmental resistance, the general failure mode had shifted to thermo-
mechanical fatigue (TMF). This prompted a new generation of alloys that were optimized for improved TMF resistance through processing using techniques of directional solidification and powder metallurgy. The last major development in superalloy technology came about in 1979, when PWA-1480 became the first commercial single-crystal (SX) superalloy (Ref 7), which permitted higher creep life and temperature capability than had ever been achieved before. Since then, progress has continued toward the development of alloys containing rhenium and ruthenium and optimized for SX processing.

The path of future superalloy development is unclear. Single-crystal superalloys are reaching their temperature limits of 1200 °C (2200 °F), with incipient melting occurring in the vicinity of 1300 °C (2370 °F). Another class of superalloys, ODS superalloys, also reach their highest useful temperatures at 1200 °C (2200 °F) (Ref 4). With further increases in the turbine inlet temperature, researchers are now striving to find the next generation of materials, in combination with thermal barrier coatings, that will perform at even higher temperatures. More recently, the emphasis in new superalloy development is on cost reduction (replacement of ruthenium, for example) and improvements to SX casting yields in manufacturing (Ref 16).

1.2 Applications of Superalloys in the GTE

Because the driving force for superalloy development has been the demands of GTE applications, a review of superalloys commonly used in the engine is presented. It is important to note that not all superalloys have the same characteristics; each alloy is chosen, depending on the function of the component, for an optimal combination of manufacturability, cost, and mechanical, thermal, and environmental properties.

Superalloy applications in GTEs can generally be divided into two groups:

- **Stationary parts**: Includes combustor cans, nozzles, guide vanes, seals, and casings
- **Rotating parts**: Includes discs, shafts, blades, and spacers

The combustor endures the highest temperatures in the engine but carries limited structural loads, which makes creep and oxidation resistance among the main concerns when selecting the material. An additional consideration in combustor design is the complicated shape, which requires a number of sheet metal forming operations and joining methods. Superalloys such as Nimonic 75, Hastelloy X, Inconel 600, and Haynes 188 are commonly selected for this application because of their excellent formability and weldability.
The next major engine components are the turbine vanes, which see slightly lower temperatures than the combustor, but oxidation resistance is still a significant consideration. The difference in pressure on the airfoil surfaces also causes stresses that make creep resistance a key consideration in materials selection. One of the most common phenomena observed is the “bowing” of the airfoil due to creep deformation. Typical alloys selected for the vane assembly are Waspaloy, X-40, alloy 713, MAR-M 302, B-1900, and columnar-grained MAR-M 200.

Turbine blades are exposed to the hot gas stream and are subject to hot corrosion and oxidation in the same way as combustor and vane surfaces. Additionally, the turbine blades must withstand significant structural loads, caused by centrifugal and thermal stresses. Furthermore, the tips of the rotating blades must maintain very tight clearances with respect to the stationary components to improve engine efficiency, which means the alloy must be highly resistant to creep deformation. Another important issue is hot corrosion from the effect of salt deposits when sulfur, as a fuel impurity, reacts with airborne sea salts in a marine atmosphere to condense as sodium sulfate (Ref 17). Among the most notable blade alloys in the order of historical development are Udimet 500, Inconel 100, Udiment 700, Inconel 738, columnar-grained MAR-M 200, MAR-M 200 + Hf, PWA 1484, and CMSX 2.

Turbine disks are designed for high static strength, fatigue resistance, and toughness and do not experience temperatures as high as the turbine blades, which has led to widespread use of alloys such as Incoloy 901, Waspaloy, Astroloy, A-286, and Inconel 100. The desire for tight clearances throughout the engine gas path to decrease pressure losses has led to the development of low-thermal-expansion superalloys, such as Incoloy alloys 903, 907, 909, and (more recently) Inconel 783, for components requiring critical clearance, such as casings (Ref 1). The extreme temperatures in the engine impose stringent requirements even on the auxiliary components, with alloys such as MP35N, MP159, Inconel X750, and Inconel 751 being developed specifically for applications where stress relaxation is to be avoided (for example, bolts, springs, and other fasteners) (Ref 18).

REFERENCES