6

Production and casting of aerospace metals

6.1 Introduction

There are many stages in the manufacture of aircraft structures and engine components using metals, and it begins with the production and casting of the metal alloy. The mechanical properties, corrosion resistance and many other properties that influence the selection and performance of metals in aircraft are determined by their method of production and casting. The production process involves the melting of the base metal, addition of selected alloying elements in carefully controlled concentrations to the molten metal, and then casting of the molten metal into a solid product for subsequent forming and machining into the final aircraft component. The structure and properties of the metal alloys are highly sensitive to the processes used in their production and casting.

In this chapter, we study the processes used to produce and cast metal alloys for aircraft structural components. The making of metal alloys by the addition of alloying elements is described, including the selection and solubility of the elements into the base metal. The key aspects of metal casting are examined, including the process of solidification, the structure and properties of cast metal, the formation of defects and damage which can affect structural performance, and the process methods used to ensure high quality casting. The main methods used to cast metal alloys for aircraft structures and jet engine components are described, including permanent mould casting, pressure die casting, sand casting, investment casting, directional solidification casting, and single crystal casting.

6.2 Production of metal alloys

6.2.1 Addition of alloying elements to metal

Metals are not used in aerospace applications in their pure (unalloyed) condition. Pure metals are too soft to use in aircraft structures and engines, and must be alloyed with other elements to produce high-strength materials. For instance, the addition of a few percent of copper to aluminium increases the strength by 500–600%: about 80 MPa for pure Al to 450–500 MPa for the Al–Cu alloy. As another example, adding just 0.8% carbon to iron makes high-strength steel more than 1000% stronger than the pure metal.

There are many important reasons for alloying. The most common reason is to increase the mechanical properties of the base metal, such as higher strength, hardness, impact toughness, creep resistance and fatigue life. Alloying can also affect the other properties of metals: magnetic properties, electrical conductivity and corrosion resistance. In a few cases, alloying has the benefit of lowering the density of the metal, such as the addition of lithium to reduce the weight of aluminium alloys. In the majority of cases, however, alloying has little or no major effect on density unless a high concentration is added to the base metal. Another reason for alloying is to increase the maximum working temperature of metals or improve their toughness at very low temperatures. Certain metals are alloyed to improve their corrosion resistance and durability in harsh environments. Alloying may also reduce the material cost when a cheap alloying element is added to an expensive base metal, although this should be considered a side benefit rather than the main reason for alloying.

The process of adding alloy elements to a base metal is relatively simple, although aerospace alloys are subject to stringent quality control that requires their production under carefully regulated conditions. The base metal is melted inside a large crucible within a temperature-controlled furnace. The metal is usually in a pure form (>99% purity), although it often contains trace amounts of impurity elements that were not fully removed during the smelting and refining of the ore. All the base metals used in aircraft structures and engines, aluminium, magnesium, titanium, iron and nickel, contain impurities. For example, aluminium alloys used in aircraft structures contain low concentrations of silicon and iron impurities from the bauxite ore. In general, the effect of impurities is deleterious whereas the effect of alloying elements on properties is beneficial. Provided the concentration of impurity elements is kept low then they do not pose a problem and, in some materials, may be beneficial to the processing or mechanical properties. For example, small amounts of silicon increase the fluidity of molten aluminium, which makes it easier to cast without the formation of pores and cavities. As another example, low concentrations of iron and atomic oxygen impurities in titanium increases the yield stress by solid solution strengthening.

The base metal is heated inside the furnace to a temperature sufficient to melt and dissolve the alloying elements into the melt. The furnace environment is controlled during the melting of reactive base metals, such as titanium, nickel or magnesium, to stop oxidation and contamination from the air. The melting of reactive metals is performed under vacuum or inert gas (e.g. argon). Vacuum induction melting (VIM) is one of the most common methods, whereby melting of the base metal and alloying elements is performed under high vacuum to minimise oxidation and remove dissolved gases (such as hydrogen and nitrogen) from the melt. Alloying elements are added to the molten base metal in measured amounts to produce the metal alloy melt. The elements are usually added as powder or small pellets, which are dissolved into the liquid metal and distributed through the melt by stirring and mixing. Once the alloying elements have dissolved in the molten metal it is ready for casting.

6.2.2 Solubility of alloying elements

Alloying is based on the principle that the alloying elements are soluble in the base metal. That is, the alloying element can dissolve as individual atoms when added to the molten base metal, and may remain dissolved when the material solidifies and cools to room temperature. There are two types of solubility: unlimited solubility and limited solubility.

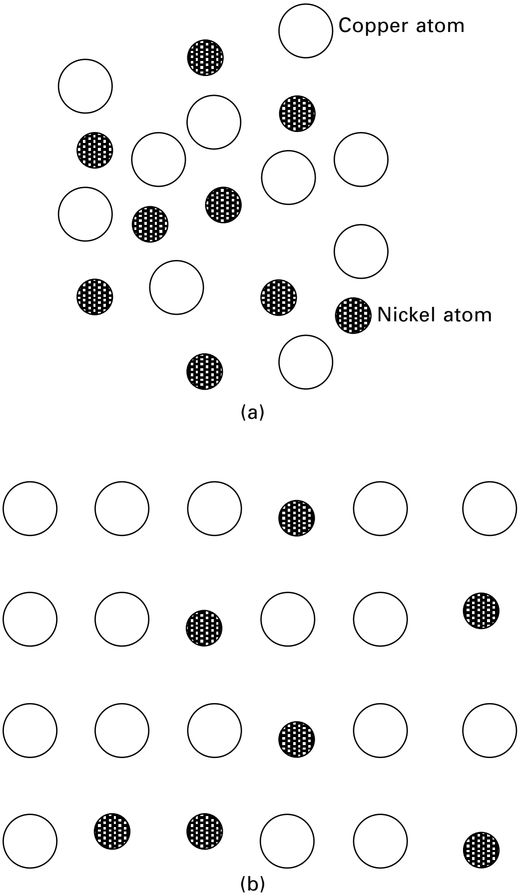
Unlimited solubility means that the alloying element completely dissolves in the base metal, regardless of its concentration. For example, nickel has unlimited solubility in copper in concentrations less than 30% by weight. After solidification, the copper and nickel atoms do not separate but instead are dispersed throughout the material (Fig. 6.1). The structure, properties and composition are uniform throughout the metal alloy, and there is no interface between the copper and nickel atoms. When this occurs the alloy is called a single-phase material.

Unlimited solubility occurs when several conditions, known as the Hume–Rothery rules, are met:

- Size factor: The atomic sizes of the base metal and alloying element must be similar, with no more than a 15% difference to minimise the lattice strain.
- Crystal structure: The base metal and alloy element must have the same crystal structure.
- Electronegativity: The atoms of the base metal and alloying element must have approximately the same electronegativity.

The Hume–Rothery conditions must be met for two elements to have unlimited solid solubility. Even when these conditions are met, however, there can be instances when unlimited solubility still does not occur.

Limited solubility means that an alloying element can dissolve into the base metal up to a concentration limit, but beyond this limit it forms another phase. The phase which is formed has a different composition, properties and (in some cases) crystal structure to the base metal. Most of the alloying elements used in aerospace base metals have low solubility. For example, when copper is present in aluminium it is soluble at room temperature up to about 0.2% by weight. At higher concentrations the excess of copper reacts with the aluminium to form another phase ($CuAl_2$). As another common example, when carbon is added to iron in the production of steel it has a solubility limit of under 0.005% by weight at 20 °C. In higher concentrations,



6.1 Unlimited solubility of nickel in copper: (a) molten alloy; (b) solid alloy.

the excess of carbon atoms form carbide particles (e.g. Fe_3C) which are physically, mechanically and chemically different to the iron.

The limited solubility of alloying elements is an important means of increasing the strength of aerospace metals by precipitation hardening. The concentration of alloying elements used in the main types of base metals for aircraft are often well above their solubility limit to promote strengthening by precipitation and other hardening mechanisms. However, there is a practical limit to the amount of nonsoluble alloying elements that can be added to a base metal. When there is too much of the alloying element then the metal can become brittle and not useful for structural applications.

6.2.3 Selection of alloying elements

The alloy produced is determined by the types and concentrations of alloying elements used in the base metal. For example, the aluminium alloy known as 2124 Al, commonly used in aircraft structures, contains 3.8–4.0% (by weight) copper and 1.2–1.8% magnesium together with smaller amounts of other alloying elements (e.g. zinc) and impurities (e.g. iron, silicon). The amount of alloy elements added to the liquid metal is often specified over a narrow range because it is often impractical to add precise amounts. For example, the magnesium content in 2124 Al can be anywhere between 1.2 and 1.8% by weight, but when the content is outside these limits then the alloy is no longer classified as 2124 Al. After the alloying elements have fully dissolved into the melt, the metal is then solidified for processing into an aircraft component.

The types and amounts of alloying elements determine the metallurgical and mechanical properties of metals. Different alloying elements alter the properties in different ways. For example, when copper is added to aluminium it has a powerful strengthening effect but when used in titanium it has virtually no influence on the strength properties. As another example, chromium in steel promotes high corrosion resistance but has no impact on the corrosion properties of most other metals.

Certain alloying elements improve the strength properties by solid solution hardening or precipitation hardening, other elements increase the strength by refining the grain size, whereas different elements again may enhance the corrosion or oxidation resistance. For this reason, a number of alloying elements are used in the same metal rather than a single element. For instance, titanium alloys used in aircraft structures often contain two dominant alloying elements (aluminium and vanadium) with small concentrations of other elements (e.g. tin, zirconium, molybdenum). Another example is nickel superalloys that contain large amounts of many different alloying elements to increase the maximum working temperature, including iron, chromium, molybdenum, tungsten, cobalt, aluminium and niobium. Some alloying elements have several functions, such as chromium in stainless steel that increases both strength and corrosion resistance.

The concentration of alloying elements is also critical to controlling the mechanical and durability properties. The properties of metals do not necessarily increase steadily with greater additions of alloying elements; instead there is an optimum concentration. For example, the optimum copper content in aluminium for maximum strengthening is 3–5%; below this range the metal is too soft and above this range too brittle. The types, approximate concentrations and main functions of the principal alloying elements used in aerospace structural metals are given in Table 6.1.

Table 6.1 Alloying of the main types of base aerospace metals (SSS = solid solution strengthening; PH = precipitation hardening)

Base metal	Alloy element	Alloy content (wt%)	Main functions of alloying element
Aluminium	Copper	1–5	Increased strength by SSS and PH ($CuAl_2$)
	Zinc	5–8	Increased strength by SSS and PH (AlZn)
	Magnesium	0.4–1.8	Increased strength by SSS and PH (Al_2CuMg)
	Manganese	0.2–1.0	Increased strength by SSS and PH ($Al_{20}Cu_2Mn_3$)
	Lithium	2–3	Reduced density and increased strength by SSS and PH
Magnesium	Zinc	4–6	Increased strength by SSS and PH ($MgZn_2$)
	Aluminium	5–6	Increased strength by SSS and PH ($Mg_{17}Al_{12}$)
	Rare Earth elements	1–2	Increased strength by SSS and PH (e.g. $Mg_{12}NbY$, MgCe)
Titanium	Aluminium	5–6	Stabilise α-phase, increase strength by SSS and PH
	Vanadium	4–10	Stabilise β-phase, increase strength
	Tin	2–11	Increase strength by SSS
	Niobium	0.7–1.0	Increase strength by grain size refinement
Steel	Carbon	<0.8	Increased strength by SSS and carbide hardening (Fe_3C)
	Manganese	<1	Increased strength by SSS
	Nickel	2–18	Increased strength by SSS and PH
	Molybdenum	0.1–0.5	Increased strength by SSS
	Chromium (in stainless steel	12–18	Increased corrosion resistance and strength
Nickel	Iron	2–20%	Increased strength by SSS
	Carbon	<0.2%	Increased creep resistance and strength by carbide hardening
	Chromium	10–20%	Increased corrosion resistance and strength by PH
	Molybdenum	2–9%	Increased creep resistance and strength by SSS
	Cobalt	1.5–15%	Increased strength by SSS
	Aluminium	0.2–5%	Increased creep resistance and strength by PH
	Tungsten	0.5–12.5%	Increased creep resistance and strength by SSS
	Niobium	1.5–5%	Increased creep resistance and strength by PH

6.3 Casting of metal alloys

6.3.1 Shape and ingot castings

Casting is the operation of pouring molten metal into a mould and allowing it to solidify. The pouring temperature is usually 50–180 °C above the melting point of the metal alloy. There are two broad classes of casting operations known as shape casting and ingot casting. Shape casting involves pouring the liquid metal into a mould having a shape close to the geometry of the final component. The shape casting is removed from the mould after solidification, and then heat treated and machined into the finished component. Ingot casting, on the other hand, involves pouring the metal into a mould having a simple shape, such as a bar or rod. After cooling, the ingot is strengthened and shaped by working processes such as forging, extrusion or rolling. Both shape and ingot castings are used in the production of aerospace components. However, primary aircraft structures are most often fabricated from ingot castings.

6.3.2 Solidification of castings

Solidification of the metal within shape or ingot casting moulds has a strong influence on the microstructure and mechanical properties. The solidification process is complex and does not simply involve the metal changing immediately from liquid to solid when cooled to the freezing temperature. When molten metal is cooled below the equilibrium freezing temperature there is a driving force for solidification and it might be expected that the liquid would spontaneously solidify. However, this does not always occur – pure metals can be cooled well below their equilibrium freezing temperature without solidifying. This phenomenon is known as undercooling or supercooling. For example, liquid aluminium can be undercooled to 130 °C below the equilibrium freezing temperature (660 °C) and held there indefinitely without solidifying. Similarly, pure nickel can be supercooled as much as 480 °C below the freezing temperature (1453 °C) before becoming solid. The reason for this behaviour is that the transformation from liquid to solid begins with the formation of tiny solid particles or nuclei within the melt. The nuclei develop spontaneously in the liquid as nano-sized particles composed of several dozen atoms arranged in a crystalline structure. The nuclei are freely suspended in the melt and are surrounded by liquid metal. The creation of solid nuclei in this way is called homogenous nucleation. The nuclei often dissolve back into liquid before they grow to a critical size that is thermodynamically stable, and it is this instability that allows the large supercooling of pure metals. It is only when nuclei grow beyond a critical size, which requires cooling of the liquid well below the equilibrium freezing temperature, that the solidification process stabilises and the metal completely solidifies.

In practice, large undercooling does not occur with metal alloys because solidification occurs by a process called heterogeneous nucleation. Most alloys freeze within about 1 °C of their equilibrium melting temperature because the nucleation of ultra-fine solid nuclei occurs at free surfaces, such as the mould walls or solid impurity particles in the melt. The heterogeneous nucleation of solid nuclei at pre-existing surfaces gives them greater stability than the nuclei which develop by homogenous nucleation. Once the nuclei have formed by heterogeneous nucleation they grow by atoms within the liquid attaching to the solid surface. At the equilibrium freezing temperature, a metal contains an extremely large number of nuclei. Each nucleus forms the embryo to a single grain, and the grains grow until no liquid remains and the metal has completely transformed into a polycrystalline solid. The sequence of events in the solidification of a metal under the conditions of heterogeneous nucleation is presented in Fig. 6.2.

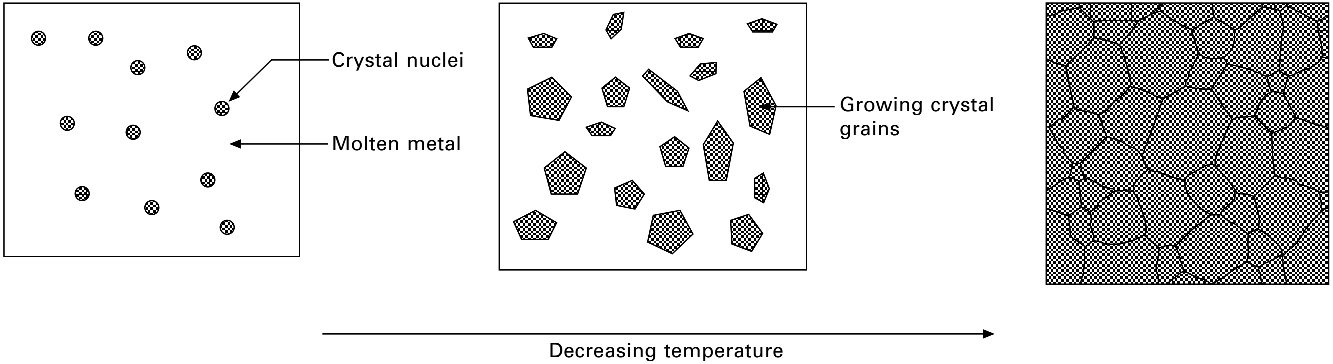
6.3.3 Structure of castings

Chill, columnar and central zones

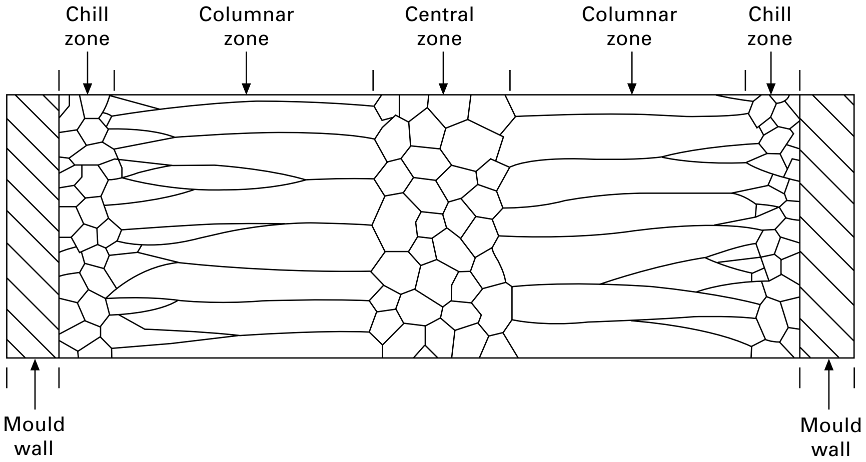
The solidification of shape and ingot castings often occurs in three separate phases, with each phase developing a characteristic arrangement of grain sizes and shapes. The grain structures through the section of an ingot from the mould wall to the centre are shown in Fig. 6.3. From the surface to core these regions are called the chill zone, columnar zone and central zone, and each has a distinctive grain structure. The solidification process that leads to these different grain structures is shown schematically in Fig. 6.4.

The chill zone is a thin band of randomly orientated grains at the surface of the casting. This is the first phase to develop during solidification because the mould surface rapidly cools the metal below the melting temperature. Many solid nuclei particles are created by heterogeneous nucleation at the mould wall and grow into the liquid to form the chill zone. Each nucleation event produces an individual crystal, or grain, in the chill zone, which then grows. The grains grow until they impinge on another grain, when the growth process stops.

When the pouring temperature of the molten metal into the mould is too low, the entire casting rapidly cools below the melting temperature. The nuclei particles that develop at the mould walls break away and are swept throughout the melt under the turbulence created by pouring. When this occurs the chill zone, which consists of equiaxed grains, extends through the entire casting and no other zones develop. However, most casting is performed with a high pouring temperature that keeps the metal at the centre



6.2 Solidification sequence for a metal.

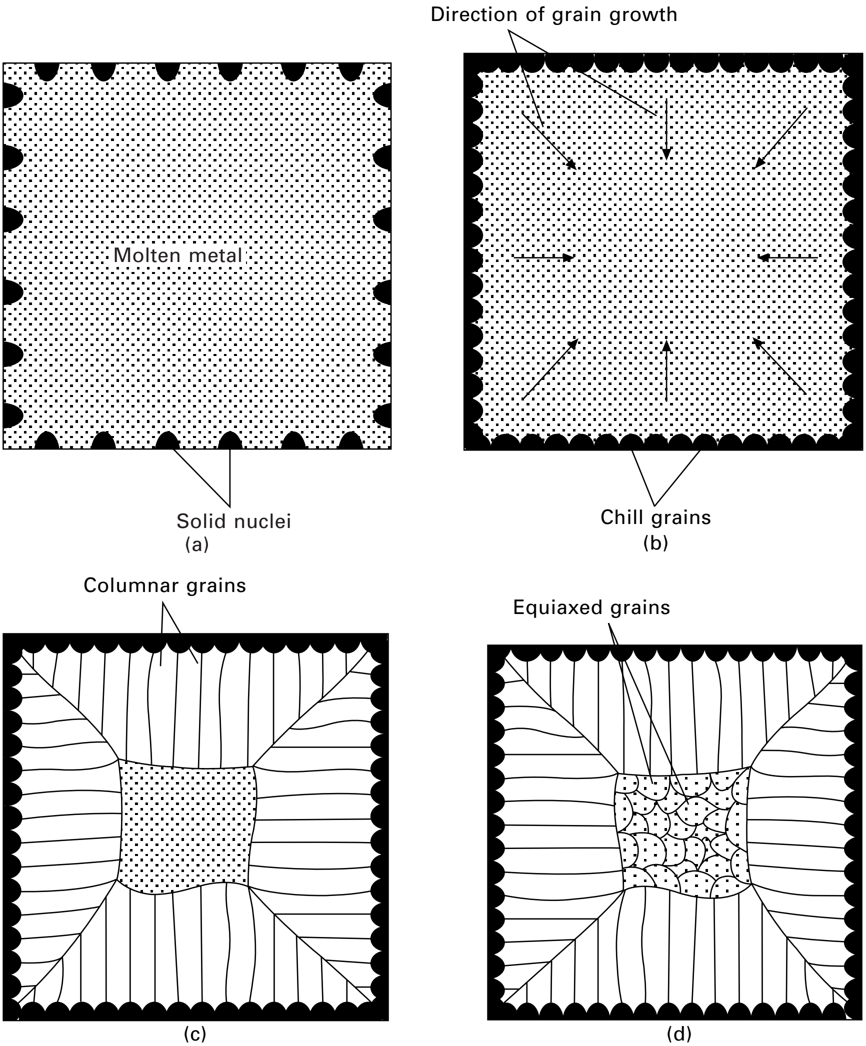


6.3 Section through a casting showing the formation of the grain structures during solidification (reproduced with permission from R. E. Reed-Hill, *Physical metallurgy principles* (2nd edition), Van Nostrand Company, New York, 1973).

above the melting temperature for a long time. Under these conditions, the columnar zone develops from the chill zone.

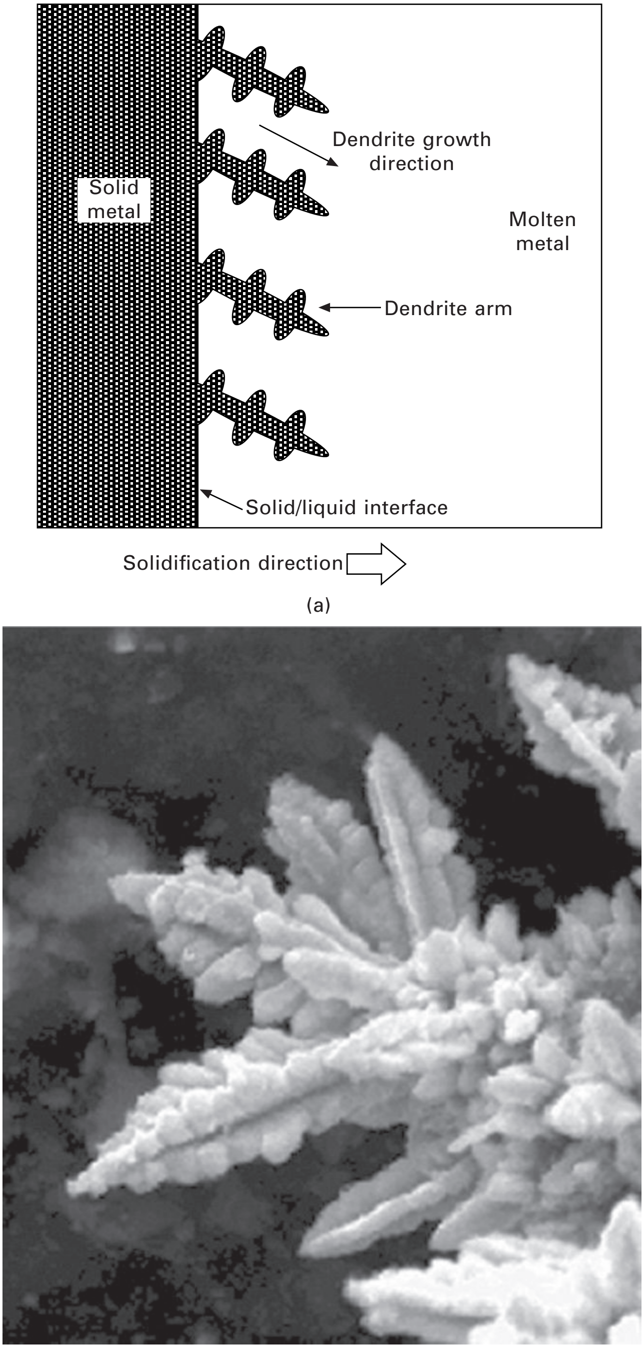
The columnar zone forms by the solidification of liquid metal into elongated grains. The columnar grains grow perpendicular to the mould wall by a solidification process involving dendrites. When the temperature falls in the liquid just ahead of the solid/liquid interface then it becomes unstable and crystalline stalks known as dendrites grow out from the interface. Secondary and tertiary dendrite arms grow out from the primary stalk, and the branched dendrite structure often appears like a miniature pine tree. (Dendrite comes from the Greek word dendron that means tree). Dendrites have a primary arm that extends from the solid–liquid interface, secondary arms that branch from it, and tertiary arms that branch from the secondary arms. During solidification a number of dendrites of almost equal spacing are formed and they grow parallel to each other as depicted in Fig. 6.5. The growth direction of dendrites depends on the crystal structure of the metal; fastest growth occurs along the most energetically favourable direction. Dendrites develop into columnar grains which grow in the direction opposite the heat flow, or from the coldest towards the hottest regions of the casting. Each crystal that is formed consists of a single dendrite. During solidification the turbulent motion of molten metal ahead of the solid–liquid interface may break off dendrites and carry them into the melt. These dendrites act as nuclei for more grains and multiply the number of grains that nucleate in the liquid.

The metal sometimes continues to solidify in a columnar manner until all the liquid has solidified. More often, however, a central zone (also called



6.4 Solidification process comprising: (a) formation of solid nuclei at the mould walls by heterogeneous nucleation; (b) growth of the chill zone from the mould walls into the melt; (c) growth of columnar grains; and (d) final solidification of casting by formation of equiaxed grains in the central zone.

the equiaxed zone) develops at the core of the casting. The equiaxed zone contains relatively round grains with a random orientation, and they often stop the growth of columnar grains. The amount of the final cast structure that is columnar or equiaxed depends on the cooling rate and alloy composition. A sharp thermal gradient across the solid–liquid interface owing to rapid



(a)

(b)

6.5 Dendritic growth into the liquid from the solid/liquid interface: (a) schematic, (b) photograph.

cooling encourages columnar solidification whereas a low thermal gradient promotes equiaxed solidification.

Grain refinement of castings

The mechanical properties of metals are dependent on the grain structure. As described in chapter 4, the yield strength of metals increases when the grain structure becomes finer. Other properties such as ductility, fracture toughness and fatigue resistance are also improved by reducing the grain size. Therefore, it is often desirable to minimise the grain size in cast structural alloys. (The exception is the casting of metals requiring creep strength at high temperature, such as nickel superalloys used in gas turbine blades and discs, when a coarse grain structure is beneficial).

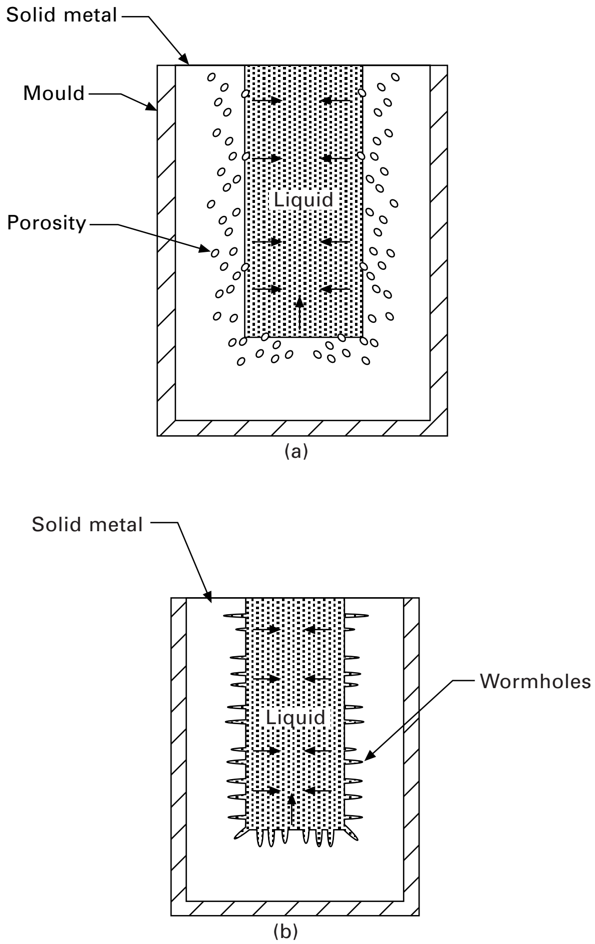
Grain size is controlled by the pouring temperature and solidification rate; lower pouring temperatures and faster solidification rates promote a finer grain structure. Mould walls are often chilled to increase the solidification rate and thereby refine the grain structure. Grain size is also controlled by the use of inoculates or grain refiners, which are chemicals added to the melt to promote many sites for heterogeneous nucleation during solidification. Inoculates act as the nuclei to which the atoms of the molten metal attach to transform from the liquid to solid states. For example, small amounts of titanium (0.03% by weight) and boron (0.01%) are added to liquid aluminium alloys to promote grain refinement. The elements react to create tiny inoculating particles of aluminium titanium (Al_3Ti) and titanium diboride (TiB_2) which cause a large reduction in grain size. Grain refinement is also an important strengthening process for magnesium alloys used in aerospace components. The Mg–Al and Mg–Al–Zn alloys are grain refined with carbon-containing compounds which form inoculating particles of aluminium carbide (Al_4C_3 or $AlN.Al_4C_3$).

6.3.4 Casting defects

Stringent regulations apply to the quality of metal castings used as the stock material for primary aircraft structures. Castings must not contain defects that compromise structural integrity and could cause unexpected failure of components. Casting defects that can cause structural failures include porosity, shrinkage and intermetallic inclusion particles. The nonuniform distribution of alloying elements in the casting, which is called segregation, is another problem because it leads to nonuniformity in the mechanical properties. In other words, discrete regions of soft and hard metal can exist within the same component owing to alloy segregation.

Porosity and shrinkage

Porosity occurs in the form of irregularly shaped cavities known as blowholes or long tubular cavities called wormholes (Fig. 6.6). Molten metals often contain dissolved gases such as hydrogen and nitrogen which develop into gas bubbles during cooling of the liquid and then become trapped by the solid growing around them. Blowhole porosity consists of small and irregularly shaped cavities filled with trapped gas. Blowholes can also form by the shrinkage of the metal during solidification. The amount of shrinkage experienced by aerospace alloys is given in Table 6.2. Shrinkage is a major problem with aluminium castings because the material contracts by anywhere from 3.5 to 8.5% during solidification, resulting in a significant number of



6.6 Two forms of gas porosity: (a) blowholes and (b) wormholes formed during solidification of metal castings.

Table 6.2 Average shrinkage values during solidification of aerospace metals

Material	Shrinkage (%)
Aluminium	7.0
Magnesium	4.0
Titanium	1.8
Low-carbon steel	2.7
High-carbon steel	4.0

blowholes and cavities. To avoid shrinkage, a reservoir of molten metal (called a feeder or riser) must be placed on the casting to feed liquid metal into the mould cavity.

Wormhole porosity occurs when gas bubbles grow in length at the same rate as the liquid–solid interface moves. The gas bubbles form worm-shaped holes that grow in the heat flow direction from the casting. Both blowholes and wormholes are detrimental to the structural integrity of the casting, but can be removed under the extreme pressure of hot working (described in chapter 7) which squashes the holes and welds their sides together. When the welds are successful, the holes are eliminated and any gas inside the cavities is absorbed into the solid casting.

Inclusion particles

Large inclusion particles are another defect often found in castings. These particles may form during the casting of metals that are strengthened by precipitation hardening, which includes most of the structural aerospace alloys. During the casting and solidification process, alloying and impurity elements react with the base metal to form inclusion particles that are extremely brittle. When the particles are above a critical size (typically 1–2 mm) they easily fracture under load, which forms the site for crack growth through the cast metal. Cracks may also occur at the interface between the inclusion particle and metal. Another problem is that the inclusion and metal have different coefficients of thermal expansion, which results in thermally induced stresses in the metal surrounding the inclusion during solidification. As a result, the inclusion acts as a stress concentration point in the cast metal which may lead to cracking at low stress. It is essential that inclusion particles are removed by solution heat treatment before the metal is used in an aircraft, otherwise cracking and failure can occur.

Segregation of alloying elements

Segregation of the alloying elements is another problem with castings. There are two types of segregation, macrosegregation and microsegregation, which occur at different levels in the casting. Macrosegregation is where the average alloy composition varies over a large distance through the casting. Macrosegregation often occurs between the surface and core of the casting, with the alloy composition of the surface (which freezes first) being different from the centre owing to diffusion of alloy elements ahead of the solid/liquid interface. Alloying elements can either diffuse from the liquid into the solid, which raises the alloy content near the surface, or the elements can migrate from the solid into the liquid which enriches the central region of the casting. The mechanical properties vary from the surface to centre of the cast metal owing to the change in alloy content. The effect of macrosegregation on the properties can be minimised by hot working the cast metal; this involves plastically deforming the casting at high temperature and redistributing the alloying elements. The hot working of cast metal is described in chapter 7.

Microsegregation is the local variation in alloy composition on a scale smaller than the grain size. Microsegregation occurs over short distances, often between the dendrite arms which are typically spaced several micrometres apart. The dendrite core, which is the first solid to freeze, is richer in the alloying elements with higher melting temperatures.

Segregation can be removed by a heat treatment process known as homogenising anneal, which involves heating the solid metal to just below the melting temperature for an extended period of time to allow the alloying elements to disperse throughout the casting. Homogenisation treatments are generally effective in producing a levelling of micro-scale concentration differences in alloying elements, although some residual minor differences may remain.

Section 6.8 presents a case study of casting defects causing engine disc failure on United Airlines flight 232.

6.4 Casting processes

There are many commercial processes to produce castings for processing into aircraft components. Casting processes are usually classified into two broad groups distinguished by the mould type: reuseable casting moulds and single-use casting moulds. This section briefly describes the processes commonly used for casting metals for aircraft structures and engines. The processes are permanent mould casting, pressure-die casting and single-crystal casting, which are reusable moulding methods; and sand casting and investment casting, which are single-use moulding methods. These processes account for the majority of castings for aircraft structural components.

6.4.1 Permanent mould casting

Permanent mould casting is a process for producing a large number of castings using a single reusable mould. The casting process simply involves pouring molten metal into a mould where it cools and solidifies. The mould is then opened, the casting removed, and the mould is reused. The mould is made from a high-temperature metallic material, such as cast iron or hot work die steel, which can withstand the repeated heating and cooling involved with large volume production.

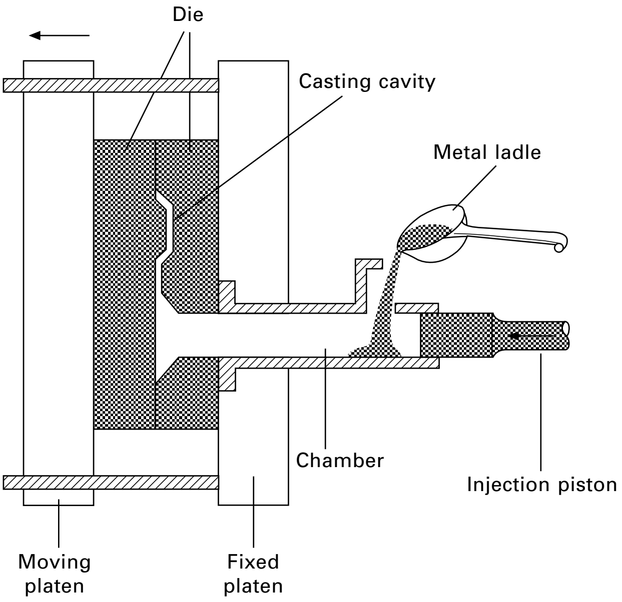
Permanent mould casting produces metal with better dimensional tolerance, superior surface finish, and higher and more uniform mechanical properties when compared with metal solidified using sand casting (which is described in section 6.4.3), which is another popular casting process. Permanent mould castings have relatively high strength, toughness and ductility owing to the mould walls rapidly removing heat from the liquid metal. This generates a fast solidification rate which produces a fine grain structure in the cast metal. Disadvantages of permanent mould casting is the high cost of the reusable mould, and that the casting process is usually viable only when high-volume production can offset the cost or it is critical that high-quality castings are produced. The most common application of permanent mould casting in the aerospace industry is the casting of aluminium, titanium and steel ingots, which are then processed by working operations (e.g. forging, rolling) into aerospace structural components.

6.4.2 Pressure die casting

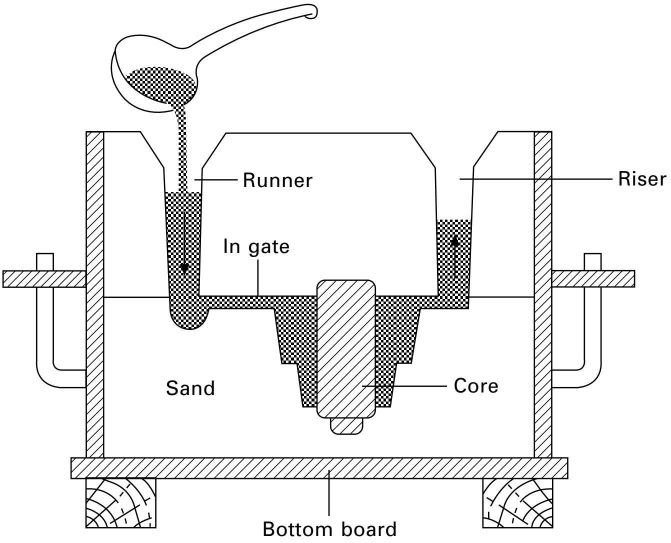
Pressure die casting involves squeezing molten metal into a mould cavity under high pressure and then holding the metal under pressure during solidification, as shown in Fig. 6.7. Pressure is applied by the action of a hydraulic piston ram that injects molten metal through a steel die and into the mould. The metal casting is removed from the mould following solidification, and the process repeated using the same permanent mould. The process is suitable for very high rate production because of the fast solidification rate of the casting. Many aluminium and magnesium alloys are cast using this method.

6.4.3 Sand casting

Sand casting involves the pouring of molten metal into a cavity-shaped sand mould where it solidifies (Fig. 6.8). The mould is made of sand particles held together with an inorganic binding agent. After the metal has cooled to room temperature, the sand mould is broken open to remove the casting. The main advantage of sand casting is the low cost of the mould, which is a large expense with permanent mould casting methods. The process is



6.7 Pressure die casting (image from The Open University).



6.8 Sand mould casting (image from The Open University).

suitable for low-volume production of castings with intricate shapes, although it does not permit close tolerances and the mechanical properties of the casting are relatively low owing to the coarse grain structure as a result of slow cooling rate.

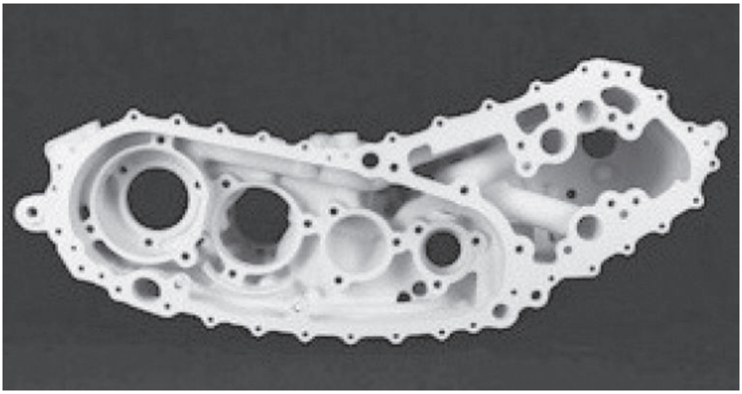
Sand casting is the process of choice for the aerospace industry for the economical production of small lot sizes. The industry uses sand casting for producing magnesium alloy and certain types of aluminium alloy components with complex shapes. Figure 6.9 shows the housing of an aircraft engine made using sand cast magnesium alloy. The housing is a thin wall component containing small diameter cooling holes, which demonstrates the capability of sand casting to produce complex shapes.

6.4.4 Investment casting

Investment casting is generally used for making complex-shaped components that require tighter tolerances, thinner walls and better surface finish than can be obtained with sand casting. The distinguishing feature of investment casting is the way the mould is made. A pattern of the part is made with wax, which is then dipped into fine ceramic slurry that contains colloidal silica and alumina. The mould is dried and heated inside an oven to melt out the wax leaving behind a ceramic shell mould for casting. The investment casting method, also called the lost wax process, is used for precision casting of aerospace components such as gas turbine blades. The investment casting of aluminium alloys results in lower strength than sand castings, but offers tighter tolerances, better surface finish and the capability to produce thin-walled sections.

6.4.5 Directional solidification and single-crystal casting

Many mechanical properties are improved by reducing the grain size. A metal with a fine grain structure has higher strength, ductility, toughness and

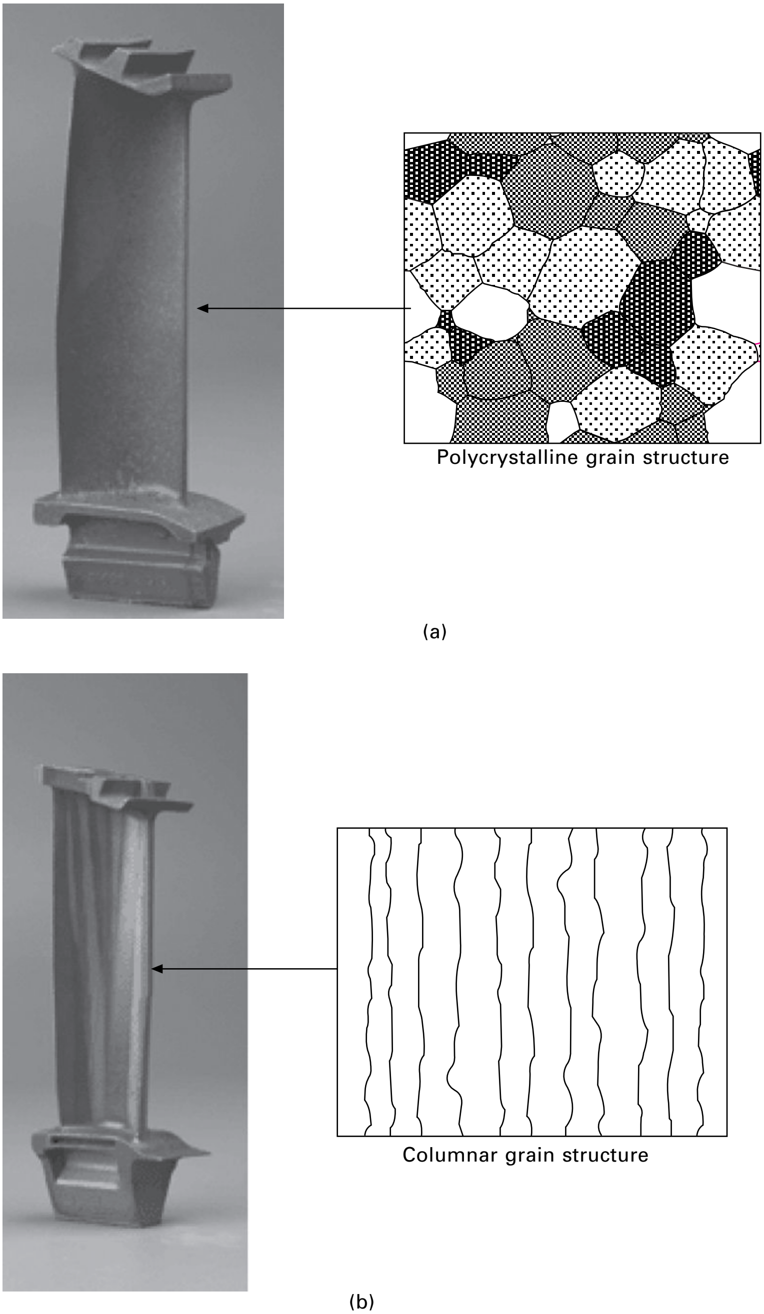


6.9 Sand cast magnesium gearbox housing (from www.tagnite.com/applications/).

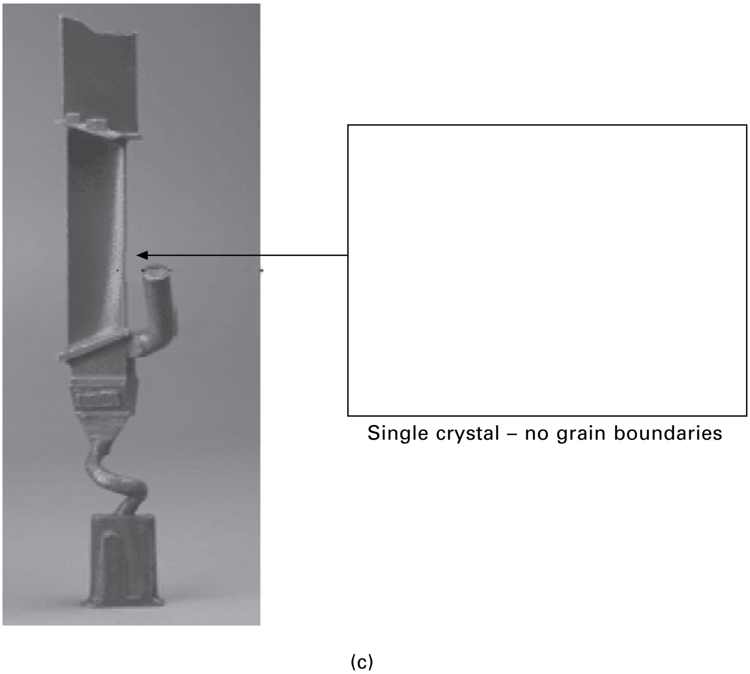
fatigue resistance than the same metal containing coarse grains (as explained in chapter 4). An important mechanical property which opposes this trend is creep, which is the plastic deformation of a material when sustaining an applied elastic load for a long period of time. The resistance of metals against creep deformation increases with their grain size. This occurs because an important process driving creep is sliding of the grain boundaries at high temperature. Increasing the grain size reduces the number of grain boundaries per unit volume of material, and this reduces grain boundary sliding and thereby improves creep resistance. (A complete description of the creep properties of aerospace alloys is given in chapter 22). Therefore, materials that require high creep strength, such as the nickel superalloys used in the hottest sections of jet engines, must have a coarse grain structure. Specialist casting methods are used to produce very large grains during the solidification of superalloys and other metals for high-temperature applications. Two methods used to improve the creep properties of high-temperature metal alloys are directional solidification and single-crystal casting (Fig. 6.10).

Directional solidification involves slowly withdrawing the cast metal from the furnace to produce a coarse, columnar grain structure. Molten metal is rapidly cooled directly onto a chill plate immediately upon leaving the furnace. The chill plate generates a steep temperature gradient along the casting, with the temperature dropping several hundred degrees within a short distance from the exit of the furnace. The chill plate moves away from the furnace at a speed of only a few inches per hour. The sharp temperature gradient and slow solidification rate generate the conditions that allow the solid/liquid interface to advance slowly in the heat flow direction, thus forcing the grains to grow as very long columns. Directionally solidified metal consists of long, thin grains in the solidification direction with very few or no transverse grain boundaries. When the cast metal is externally loaded in the grain direction it is the transverse grain boundaries which cause creep deformation, and minimising their presence by directional solidification improves the creep resistance.

An advance on the directional solidification process is single-crystal casting, which is used to produce metals with exceptional creep resistance. The development of single-crystal casting has led to a 100 °C improvement in temperature capability over conventionally cast alloys with a polycrystalline grain structure. More than 1.5 million high-pressure gas turbine blades made by single-crystal casting are currently in service on civil and military aircraft. Single-crystal casting is increasingly being used for producing nozzle guide vanes. Single-crystal metals are produced by allowing just one grain to grow into the main body of the casting. The mould end has a constriction in the shape of a corkscrew through which only one crystal can pass. A single crystal grows through the constriction and into the main section of the casting without the formation of grain boundaries. The solidified casting consists of



6.10 Turbine blade made with nickel-based superalloy using: (a) investment casting resulting in a polycrystalline grain structure, (b) directional solidification resulting in a columnar grain structure and (c) single crystal solidification resulting in no grain boundaries.



6.10 Continued

a single-crystal metal that has exceptional resistance to creep softening and thermal shock owing to the absence of grain boundaries.

6.5 Summary

The mechanical properties of cast metals are not uniform because of the development of chill, columnar and equiaxed zones during solidification inside a mould. Primary aircraft structures must have uniform properties and, therefore, metal alloys must be homogenised by heat treatment and working operations after casting.

The method used for casting is dependent on several factors, with the most important being the mechanical properties and volume of production. Permanent-mould casting methods generally produce higher strength castings than nonpermanent moulds because of their finer grain structure. Permanent mould methods are suited for a large number of castings whereas nonpermanent moulds are more economical for a small volume production.

A fine grain structure is often desirable in aircraft structural alloys because it results in high strength, ductility, toughness and fatigue resistance. The grain size of cast metals is reduced by rapid cooling and the use of inoculators.

A coarse grain structure is needed in jet engine components to provide high creep resistance. Directional solidification and single-crystal casting methods are often used for producing superalloys for engine components with exceptional creep strength.

Defects that reduce the structural integrity of cast metals must be eliminated. Porosity and macrosegregation are removed by hot working; large intermetallic precipitates are eliminated by solution heat treatment; and microsegregation is overcome by homogenising anneal treatment.

6.6 Terminology

Blowhole: Irregular shaped cavity in cast metal formed by trapped gas.

Chill zone: Region within cast metals (usually closest to the mould wall) where the cooling rate is the fastest.

Columnar zone: Region within cast metals (usually between the chill and equiaxed zones) where the grain structure is elongated in the solidification direction.

Dendrites: Fine branches of solid material that project into the melt zone during solidification.

Equiaxed zone: Region within cast metals (usually the core of the casting) where the grains are approximately the same size in every direction.

Equilibrium freezing temperature: Temperature when solidification of molten material occurs under standard thermodynamic conditions.

Heterogeneous nucleation: Formation of nuclei of solid particles within molten metal that occurs at a pre-existing nucleation site (e.g. mould wall, inoculate particle).

Homogenising anneal: Heating process used to eliminate clustering of alloying elements caused by microsegration and to disperse the elements through the metal. The process is performed on the solid alloy at high temperature, but does not involve melting.

Homogenous nucleation: Formation of nuclei of solid particles within molten metal that occurs without a pre-existing nucleation site.

Hume–Rothery rules: Conditions that determine whether an alloy or impurity element occupies an interstitial or substitutional lattice site. The rules are based on differences in the atomic size, crystal structure and electron valence state of the solute and solvent. Substitutional lattice sites are usually occupied when the atomic size of the solute is within 15% of the solvent and the electron valence number of the solute and solvent is within two. When these conditions are not met the solute is usually interstitial.

Ingot casting: Casting process that uses a mould with a simple shape (usually flat bar) to produce an ingot of the cast metal.

Inoculates (also called grain refiners): Elements or compounds added to molten metal which serve as the nucleation sites of grain growth during solidification. Inoculates are used to refine the grain structure of cast metal.

Limited solubility: Solute can dissolve in solid solvent to a limiting concentration, and at higher amounts the excess of solute forms a second phase within the solvent.

Macrosegregation: Nonuniform distribution of alloying elements in metals above the microstructural level.

Microsegregation: Nonuniform distribution of alloying elements in metals at the microstructural level.

Shape casting: Casting process that uses a mould shaped close to the geometry of the final metal component.

Solution heat treatment: Heating process used to dissolve second-phase particles and disperse the alloying elements evenly throughout the cast metal. Process performed on the solid alloy at high temperature, but does not involve melting.

Undercooling (also called supercooling): Process by which metals remain liquid when cooled below the equilibrium freezing temperature.

Unlimited solubility: Solute can dissolve into the solid solvent to any concentration without the formation of a second phase.

Wormhole: Elongated cavity in cast metal formed by trapped gas.

6.7 Further reading and research

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Cantor, B., and O'Reilly, K., *Solidification and casting*, Institute of Physics, 2003.

Campbell, F. C., *Manufacturing technology for aerospace structural materials*, Elsevier, Amsterdam, 2006.

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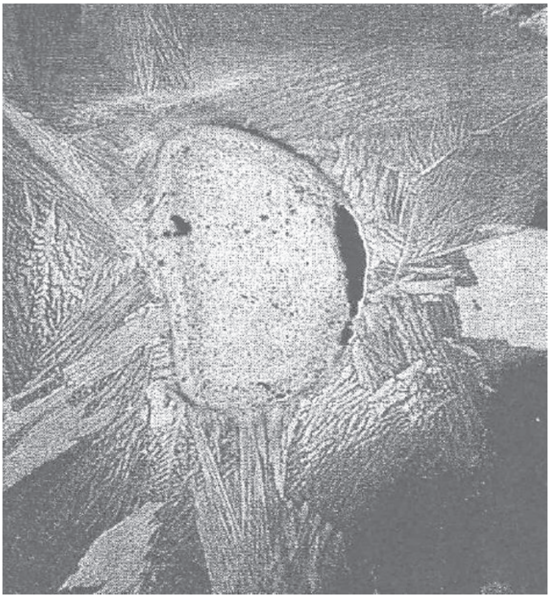
6.8 Case study: casting defects causing engine disc failure in United Airlines flight 232

The United Airlines flight 232 accident tragically highlights what happens when defects are present in safety-critical titanium components. Flight 232 was a scheduled flight of a Douglas DC-10 from Denver to Philadelphia on July 19, 1989. The aircraft suffered an uncontained failure of the number two engine (mounted in the tail) while cruising at 38 000 feet. The titanium (Ti–6Al–4V) fan disc, which is the size of a large truck tyre and weighs 150 kg, broke suddenly while spinning at several thousand revolutions per minute. Engine fragments pierced the tail section in many places, including both horizontal stabilizers. Pieces of shrapnel punctured the right horizontal stabilizer and then severed all three hydraulic lines, allowing fluid to quickly drain away causing a loss in the flight control system. The pilots lost hydraulic control of the ailerons, rudder, flaps and other control surfaces. The flight crew performed an amazing feat by flying the aircraft by adjusting power to the two wing-mounted engines and managed an emergency landing at Sioux City Airport, Iowa. The lack of flight control caused the aircraft to crash and break-up on landing, killing 110 of the 285 passengers and 1 of the 11 crew members (Fig. 6.11).

The Federal Aviation Administration launched an immediate investigation into the cause of the engine fan disc failure. The investigation discovered that the disc failed because of an intermetallic particle, called a hard alpha inclusion, in the titanium alloy (Fig. 6.12). An excess of nitrogen, present in the titanium ingot during processing, created the hard alpha inclusion. The inclusion cracked and then fell out during final machining, leaving a small cavity (about the size of a sand grain). A fatigue crack grew from the cavity during normal operation of the engine until eventually, after around 18 years of operation, it was large enough for the titanium disc to catastrophically fail. Titanium is a safe, reliable material for fan discs, and it only failed because the cavity was not found during manufacture and the fatigue crack not detected during routine engine checks. This accident shows the need for stringent quality control procedures when manufacturing aircraft components and the requirement for careful, thorough examination over the aircraft life.

6.11 Wreckage from flight 232.



6.12 Hard alpha inclusion in titanium alloy (from F. C. Campbell, *Manufacturing technology for aerospace structural materials*, Elsevier, 2006).