Chapter 2
Processing of Aerospace Metals and Alloys: Part 2—Secondary Processing

S. Narahari Prasad, P. Rambabu and N. Eswara Prasad

Abstract The basics of different techniques of secondary processing of metals and alloys are presented and discussed. This chapter will also provide details of the processing of superalloys (nickel- and cobalt-based) and steels.

Keywords Secondary processing · Metal forming · Steels · Titanium alloys · Nickel superalloys

2.1 Introduction

Metallic materials are initially consolidated by a primary melting process into ingot, billet or bloom, that are subsequently shaped into various forms for commercial applications. The resultant mechanical properties are determined by the combination of alloy design and thermo-mechanical processing that involves hot deformation and heat treatment to obtain the right microstructure [1–10].

Secondary processing such as forging, hot rolling, closed-die forging, precision forging, radial forging, ring rolling, extrusion, cold rolling, and cold drawing of wires and tubes is the backbone of modern manufacturing industries, as well as being a major industry itself. In most of the secondary processing operations the shapes of the products depend on the nature of plastic deformation that the metal undergoes [1, 9]. Hence it is essential to study the influence of various plastic flow/deformation mechanisms on the processing as well as the properties of the as processed material. Also one needs to study the effects of processing conditions and the intensity (extent of) of processing on the properties.

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The plastic flow properties are influenced by factors such as selection of tool geometry, equipment, tool and die material; and processing conditions such as workpiece, die temperatures and lubrication. Because of the complexity of deformation processes, analytic, physical or numerical models are relied on to aid in designing such processes to ensure the reproducibility of physical and mechanical properties. It is important to note that metal forming processes provide materials for further processing in order to obtain final products, either fully finished or semi-finished.

Most of the metal working process requires a combination of properties for successful forming. The three most important factors are reduction (strain), rate of reduction (strain rate), and temperature of the workpiece at any time. For heat-resistant alloys the parameters are designed to obtain better stress rupture, creep, and low-cycle fatigue life. Hence the aims are uniform grain refinement, controlled grain flow and structurally sound components.

In order to get the best properties from an alloy, the starting material has to be of the highest quality. This means the use of advanced melting techniques to obtain low gas and inclusion contents and reduced ingot segregation. This is followed by ingot breakdown, homogenization and final finishing procedures that ensure a sound and microstructurally uniform product.

One of the most important aspects of secondary processing is the workability of a metal or material, which includes forgeability, rollability, extrudability and formability. Workability of any material depends not only on the microstructure of the material, but also on the external processing parameters such as applied temperature, strain rate and strain, and more importantly the stress state in the deformation zone. In this context, the use of a processing map, which is an explicit representation of the microstructural response to the imposed process parameters, is almost essential.

A processing map involves superimposing a power dissipation map on an instability map developed from dynamic materials modelling. Such a map for metallic materials shows several safe domains for processing in terms of temperature and strain rate, and may also contain regions of flow instability and cracking that should be avoided.

2.2 Fundamentals of Metal Forming

Casting, machining, joining and deformation are the four most fundamental metal working or processing technologies. Casting makes good use of the fluidity of a metal in the liquid state to take the mould shape as it solidifies. Machining of blanks (half-products) provides the final desired shape with good accuracy and precision, but much material is removed, resulting in low yield. Joining processes can be used to fabricate complex shapes starting from simple shapes, and these processes have a wide range of applications.

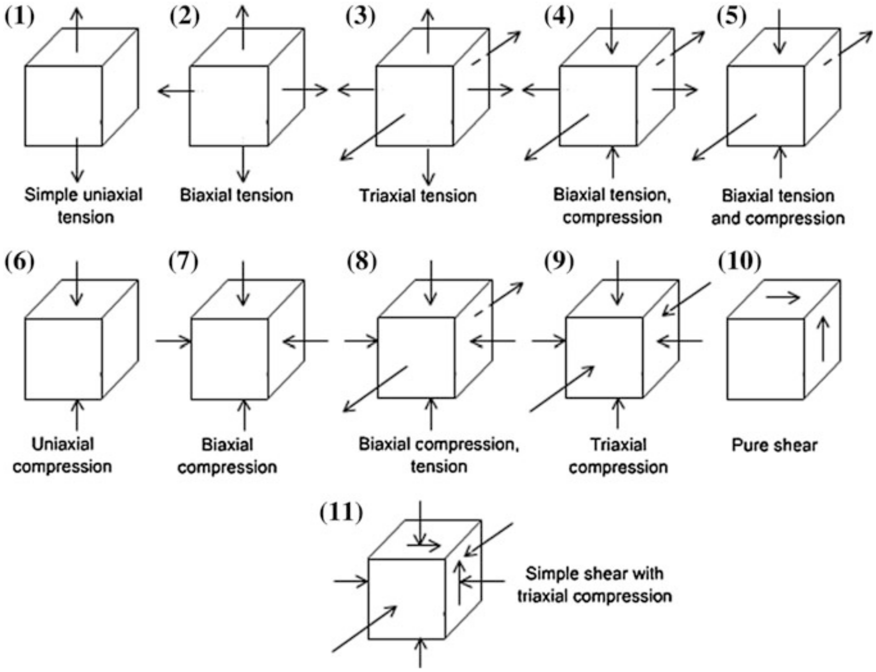


Fig. 2.1 Stress states during metal deformation and forming

As a metal is deformed into a useful shape, it experiences stresses such as tension, compression, shear, or various combinations of these. Figure 2.1 illustrates these stress states.

In order to deform the metal, one has to employ stresses that produce permanent plasticity, which occurs when one exceeds the elastic deformation conditions. Further, to deform the metal by cold working (that is when the working temperatures are less than 0.4–0.45 times the homologous temperature—the melting temperature expressed in Kelvin scale, designated as T_M), one has to use pressures that are much higher than those for hot working (working temperatures > 0.45 T_M). Often a combination of hot and cold working is used. When metals are cold-formed there is no grain recrystallization and no dynamic recovery from the induced deformation. As deformation proceeds, the resistance increases owing to strain hardening. In general, this refers to resistance build-up in the grains by the generation of dislocations and crystal lattice distortions.

One more metal deformation process which is carried out at temperatures intermediate to hot and cold forming is called warm forming. Advantages and disadvantages of cold, warm and hot forming processes are shown in Table 2.1.

Table 2.1 Advantages and disadvantages of cold, warm and hot forming

Forming process	Advantages	Disadvantages
Cold working	Good surface finish and dimensional control Better strength, fatigue (steels), and wear properties owing to strain hardening Directional properties may be imparted	Higher forces with heavier and more powerful equipment are required: hence higher cost Intermediate annealing may be one of the additional requirements Unacceptable levels of residual stresses may be produced
Warm working	*Compared to cold rolling* Lesser loads on tooling and equipment Greater metal ductility *Compared to hot forming* Better surface finish, closer dimensional accuracy Lesser scaling and decarburization Reduced tool and die wear	Virtually no significant disadvantages
Hot working	No strain hardening Less force required for deformation, and hence, larger components may be manufactured Lower capacity equipment sufficient (reduces equipment costs) No residual stresses in the material Reduces segregation and thus the structure becomes more homogenous	Needs external heating Poor surface finish Surfaces will often get oxidized Less accuracy and dimensional control of components Reduced life of tooling and equipment

2.3 Bulk Deformation Processes

Considerable effort is required for the design and optimization of bulk metal working processes. For example, defects introduced at one stage are carried forward and amplified downstream. Therefore the optimization of processing parameters during thermo-mechanical processing is very important to produce defect-free products. Some of the important processes are discussed in the following subsections.

2.3.1 Forging

Forging is a process in which material is shaped by the application of localized compressive forces exerted manually or with power hammers, presses or special forging machines. The process may be carried out on materials in either the hot or cold state. When forging is done cold, the processes are given special names. Therefore the term ‘forging’ usually implies hot forging carried out at temperatures above the recrystallization temperature of the material.

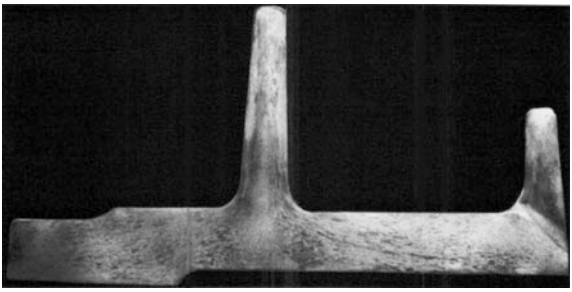


Fig. 2.2 Directions of grain flow in a closed-die forging

Forging is an effective method of producing many useful shapes. The forged parts have good strength and toughness, and they can be used reliably for highly stressed and critical applications. This improvement in properties occurs because forging (i) breaks up the metal ingot dendritic structure and associated segregation, heals porosity, and aids homogenization; (ii) produces a fibrous grain structure that enhances mechanical properties parallel to the grain flow. The three most important categories of forging that are widely used are as follows: (i) open-die forging, (ii) closed-die forging (see Fig. 2.2 for the nature of grain flow in a closed-die forged metal piece) and (iii) press forging. Yet another important category is net shape or precision forging, and this route in general has the following benefits:

1. Greater strength to weight ratio.
2. Elimination of welding: Switching to closed-die forging from multipart welding leads to cost reduction, in addition to property improvement.
3. Reduced inspection and testing: As there are no welds, inspection is easier.
4. Replacing assemblies, fabrications: cost saving is usually achieved when forgings replace complex fabrications and assemblies.
5. There is no doubt that precision forging is more economical than fabricating metal components by extensive machining, particularly when the parts requirement is large. There are also limitations on the maximum size that can be handled through machining.
6. Quicker production, shorter delivery: less machining; faster turnaround.
7. Design optimization: Further cost reduction may be achieved by optimizing pre-forging shape/size, blocker forging design, reducing draft angle, tolerances, testing material, etc.

No other metal working process (casting, welding, machining, etc.) permits this degree of grain size and shape control and consequent property enhancement.

2.3.2 Rolling

The second most important secondary processing method is ‘rolling’. It consists of passing metal between two rollers which exert compressive stresses and reduce the metal thickness. Rolling is important because it is very versatile, capable of producing many shapes, and also it is economical. Rolled products include sheets, structural shapes and rails, as well as intermediate shapes for wire drawing or forging, circular shapes, ‘I’ beams and railway tracks. The latter two types of product are manufactured using grooved rolls.

2.3.3 Extrusion

This is a process used to create objects of a fixed cross-sectional profile. In this process a material is pushed or pulled through a die of the desired cross-section in a continuous or non-continuous manner. The two most important extrusion processes are as follows: (i) hot extrusion and (ii) cold extrusion. There are several advantages of an extrusion process. Two main advantages of extrusion over other manufacturing processes are the ability to create very complex cross-sections, and to work materials having limited ductility, since only compressive and shear stresses are involved. Extrusion also forms parts with an excellent surface finish.

The other important, but less versatile secondary processing methods are pilgering and drawing.

2.4 Secondary Processing for Specific Aerospace Materials

Aerospace specifications call for stringent quality requirements with respect to careful selection of raw materials, primary melting techniques, material processing steps, chemistry limits, low inclusion contents and microstructures.

2.4.1 Titanium Alloys

Secondary processing of titanium alloys is discussed extensively in Chap. 6 of Volume 1 of these Source Books and in Ref. [11].

2.4.2 Superalloys

Secondary processing of nickel-base superalloys is discussed to some extent in Chap. 9 of Volume 1 of these Source Books and in Refs. [12, 13]. Some additional information will be given here.

Superalloys are high-performance materials designed to provide high mechanical strength and resistance to surface degradation at high temperatures. They combine high tensile, creep rupture and fatigue strengths; good ductility and toughness; and excellent resistance to oxidation and hot corrosion. Additionally, superalloys are designed to retain these properties during long-term exposure at elevated temperatures.

Increased knowledge of the alloy system(s) has resulted in thermo-mechanical treatments that improve the properties of forgings, notably the creep resistance and high- and low-cycle fatigue crack resistance.

The material characteristics that largely influence workability are flow stress and ductility. As these alloys are designed to resist high temperatures, they are difficult to work because of their very high flow stress and limited ductility. The workability largely depends on cleanliness.

The hot working temperature is chosen such that the majority of precipitates are in solution. The high concentrations of dissolved alloying elements give rise to higher flow stresses, higher recrystallization temperatures and lower solidus temperatures. These factors limit the useful hot working temperature range. Furthermore, the alloy ductilities are influenced by the deformation temperature, strain rate, prior history of the material, composition, degree of segregation, cleanliness, and the stress state imposed by the deformation process.

Hot Working Cycles: Superalloys have low thermal conductivity and hence need to be heated to the hot working temperature at a slow rate. The forging temperature depends on the composition of the alloy and to some extent on the heat treatment and end use. High forging temperatures cause grain growth in most heat-resistant alloys; thus the forging temperature ranges are relatively narrow and temperatures must be precisely controlled. Lower hot working temperatures have positive effects on the workpiece, but will increase the forging load and erode the dies.

It is not essential to maintain a particular atmosphere for heat-resistant alloys. However, high-sulphur fuel should be avoided as it may contaminate the material. In such cases it may be better to use electrically heated furnaces, which also allow closer temperature control. For liquefied petroleum gas (LPG)-heated furnaces the atmosphere may be maintained from neutral to oxidizing. Alternatively, providing a protective atmosphere will result in cleaner surfaces.

Temperature measuring instruments should record the heating cycle so that temperature variations during loading and discharge are recorded. These measurements will also help in estimating the right time required for reheating. Forging stock needs to be continuously monitored for temperature during hot working, and when the lower limit of hot working temperature is reached, the stock has to be recharged into the furnace. The temperature of the stock has to be raised to the hot working temperature and the stock soaked for an appropriate period. Long soaking periods are not required for reheating the stock as the material has high internal heat content.

Forging dies may be heated with gas- or kerosene-fired torches so that heat loss due to the dies is reduced.

Iron-Base Superalloys: These alloys are superaustenitic stainless steels alloyed with reactive elements such as titanium, aluminium, boron and niobium, and they respond to solution treatment and ageing. The forging practices of these alloys are in many ways similar to those for austenitic stainless steels.

These alloys are alloyed with aluminium and titanium that may form nitride and carbonitride segregations, which develop into stringers and affect the forgeability. The inclusion content also affects the hot working of the alloy, and so the melt route and processing should account for this.

Nickel-Base Alloys: All nickel-base alloys are less forgeable than the iron-base alloys, requiring more force to produce a given shape. The forging processes are highly refined to control temperatures, strain rate, strain and alloy condition. These controls are necessary to achieve uniform critical properties such as grain size and other characteristics after heat treatment. In addition, the alloys are sensitive to minor variations in composition, which can cause large variations in forgeability, grain size and final properties.

Cobalt-Base Alloys: Hot workability of cobalt-base alloys is difficult, since they contain carbon and form hard carbides. They require comparatively higher pressures than iron-base alloys. The cobalt-base alloys need to be reheated repeatedly in order to recrystallize the workpiece and lower the forging pressure.

Forging parameters such as temperature and amount of reduction have considerable effect on the grain size. Coarse grains are associated with low ductility, notch brittleness and low fatigue strength. Hence close control of the forging parameters and final heat treatment is necessary.

Cobalt-base alloys are characterized by low thermal conductivity, and they need to be heated slowly to the soaking temperature to attain temperature uniformity. The amount of forging and reduction will depend on the forging operation and component design. These alloys are prone to grain coarsening when the material is heated above 1175 °C, so the initial reduction is small to consolidate the surface, and the reductions are gradually increased with decreasing cross-section. The reheating time also becomes shorter.

Forging reductions should be such that they induce sufficient strain in the material to cause recrystallization during the reheating period. The final reduction should be close to 20 % so that after subsequent solution treatment the microstructure consists of fine grains.

2.4.3 Special Steels

High-Strength Low-Alloy Steels: These are readily forged into a wide variety of shapes using hot-, warm- or cold-forging processes. Despite the large number of available compositions, all of the materials in this category exhibit essentially similar forging characteristics. Carbon content of the steel has the most influence on the upper limit of forging temperatures, which decrease with increasing carbon content.

The hot forging of carbon and alloy steels into intricate shapes is rarely limited by forgeability aspects. Section thickness, shape complexity and forging size are limited primarily by the cooling that occurs when the heated workpiece comes into contact with the cold dies. For this reason, equipment that has relatively short die contact times, such as hammers, is often preferred for forging intricate shapes in steel.

Maraging Steels: These require higher forces for forging since they are highly alloyed. However, they can be forged easily into any shape.

Stainless Steels: The stainless steels, especially the martensitic and precipitation hardening (PH) grades are used as structural materials where a combination of high strength as well as corrosion resistance is required. The PH stainless steels in particular have good strength, toughness, corrosion resistance, fabricability and weldability, and comprise an important class of engineering materials for aerospace applications. They can be used in corrosive environments and at temperatures up to 350 °C.

In the case of austenitic and martensitic stainless steels the high temperature phase delta ferrite will form if the hot working temperature is not restricted. Thus all reheating and cooling operations should be optimized to ensure freedom from phases that could interfere with the product quality and mechanical properties.

Stainless steels require higher forging pressures and are considerably more difficult to forge than low-alloy steels, because of their higher elevated temperature strength and also the limitations on the maximum temperatures at which stainless steels can be forged. Forging load requirements vary very much with different types of stainless steels; the most difficult alloys to forge are those with the greatest strength at elevated temperatures.

2.5 Recent Advances in Secondary Processing

2.5.1 Rapid Prototyping Using LENS

Laser engineered net shaping (LENS) is a novel rapid prototyping process [14, 15]. It comprises a diverse set of techniques which involve continuous flowing of

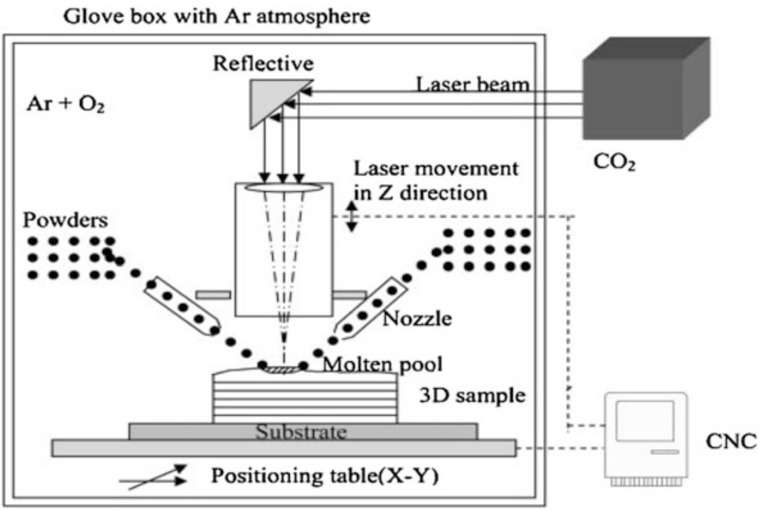


Fig. 2.3 Schematic of LENS process

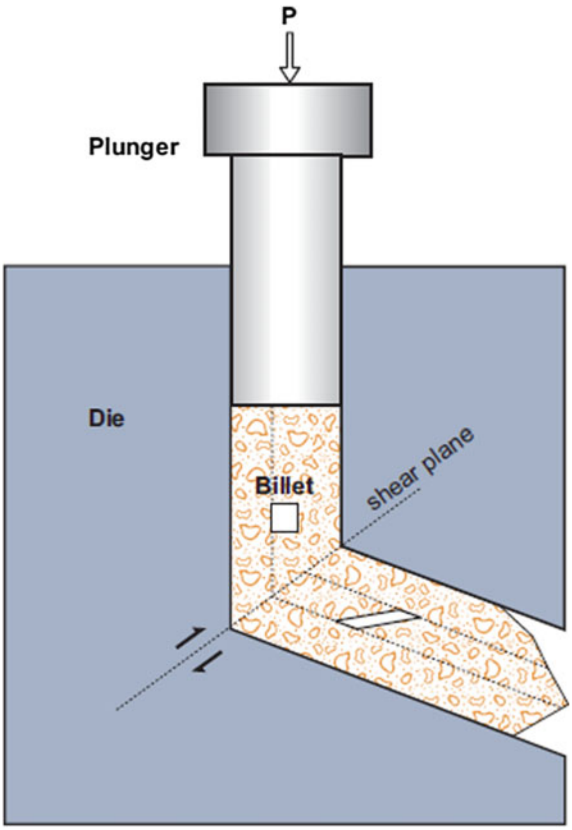
metallic powders into a melt pool that is generated on a substrate material by a focused high power laser beam as shown in Fig. 2.3.

A proper synchronization of the actions of the deposition head (consisting of powder flow mechanism and laser column), the software and the computer numerical control (CNC) platform, enables 3-D functional parts to be realized by depositing line by line, and layer by layer. An inert gas shroud is used to shield the melt pool from atmospheric oxygen for better control of properties. Parts have been fabricated by LENS processing from numerous materials including stainless steels (316, 316L, 17-4 PH), nickel-base alloys (INCO designations 718, 625, 600 and 690), tool steel (H13) and the titanium alloy Ti-6Al-4V. The resultant mechanical properties confirm the LENS process as a viable method for fabricating structural components [16].

2.5.2 Equal-Channel Angular Extrusion (ECAE)

ECAE enables deforming a billet of bulk material by shear without changing its overall dimensions. The die is formed from two channels with equal cross-section. These intersect to form a sharp corner, e.g. 90° or 120°. As the billet is pressed through the die it deforms by shear at the die corner. Since the billet dimensions are unchanged by the processing, the deformation can be repeated several times to obtain ultrahigh strain levels. A schematic is shown in Fig. 2.4.

Fig. 2.4 Schematic of the ECAE process



ECAE processing can be varied by changing the die angle, and also by rotating the billet between successive passes. Billet rotation between passes requires round or square cross-sections.

Materials processed by ECAE include aluminium, magnesium and titanium alloys, copper and tungsten. The grain sizes obtained from ECAE are mostly larger than 100–150 nm, irrespective of the metal or alloy. Thus ECAE materials are not truly nanocrystalline (nc), but rather ultrafine-crystalline (ufc)—also called ultrafine-grained (ufg). The more recent research on ECAE is largely concerned with modelling and determining the processing parameters that affect and control the material homogeneity.

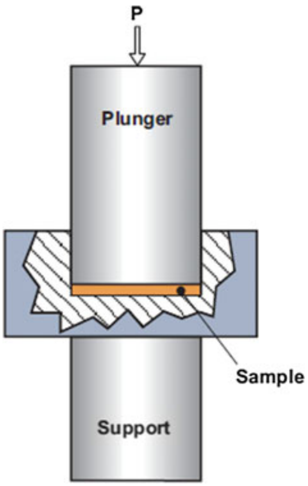


Fig. 2.5 Schematic of the HPT process

2.5.3 *High-Pressure Torsion (HPT)*

A disc-shaped sample with thickness 0.2–0.5 mm is placed between support and plunger anvils and compressed under a pressure of several GPa. The plunger anvil is rotated, and friction causes shear straining of the sample (see Fig. 2.5).

Owing to the high pressure, high strains can be imposed without fracture of the sample. HPT is convenient for investigating the influence of different parameters on the evolution of nanotechnology microstructures and their bulk properties, since it is relatively straightforward to adjust and control the cumulative strain, applied pressure and deformation speed. However, HPT is not a contender for manufacturing nanotechnology bulk metals.

2.5.4 *Cryomilling*

Cryomilling involves ball-milling attrition (repeated mechanically-induced fragmentation and coalescence) of elemental or alloy powders in liquid nitrogen, whereby mixtures of elemental powders undergo mechanical alloying. The starting powders are often spherical, or at least fairly regular in size. During attrition the powder particles are first flattened and then undergo concomitant fragmentation or coalescence.

The overall effect of attrition is eventually to produce powder particles with nanoscale grain sizes, which can be as small as 15–30 nm. However, the powders have to be consolidated to bulk metal, for example by vacuum degassing, hot (HIP) or cold (CIP) isostatic pressing and extrusion. Any heat treatments (e.g. HIP) during consolidation inevitably cause grain growth, such that the microstructures are ufc or even microcrystalline (mc), i.e. grain sizes in the submicrometre (100–1000 nm) to micrometre range (>1000 nm).

Cryomilling has been particularly successful—as a grain size reduction technique—for aluminium alloys. This is because the milling process results in nano-dispersions of oxides and nitrides that help to inhibit grain growth during consolidation. However, these particles are detrimental to the ductility. There are also problems in controlling material purity and obtaining full density in the consolidated product. And, of course, the entire production process, *which includes manufacturing the elemental or alloy powders to close specifications*, is much more costly than obtaining bulk materials by conventional ingot metallurgy.

2.5.5 Vacuum Plasma Spray (VPS) Forming

The VPS process first requires the synthesis of a pre-alloyed powder by inert gas atomization. The powder particle size and shape need to be closely controlled, in order to achieve optimum flow during subsequent vacuum (low pressure) plasma spraying. After spraying to the required thickness, the spray deposit is removed from the substrate. VPS deposits are characterized by a multiscale microstructure. The overall microstructure consists of splats, intersplat boundaries and porosity. As with cryomilling, the VPS process requires manufacturing metal powders to close specifications before obtaining the final product. This is a major cost disadvantage, even though consolidation is relatively straightforward.

2.5.6 Electrodeposition

This method has been used to make thin bulk samples for *model material* research, especially nickel and binary nickel alloys. Conventional electrodeposition under continuous direct current conditions can produce fine-grained nickel down to the nc range, but apparently only for sample thicknesses $\sim$20–30 μm. Thicker samples are obtainable from a patented process of pulsed direct current electrodeposition. Grain sizes can be closely controlled in the nc, ufc and mc ranges for sheets with thicknesses of 100–150 μm. It is possible to obtain thicknesses in the millimetre range, but through-thickness grain uniformity and processing-induced residual stresses become potential or actual problems.

2.6 Summary

The basics of different types of secondary processing techniques and the choice of techniques for particular types of products are discussed. The technology of manufacturing most of the advanced alloys is available in India, but there is a size (capacity) gap between the available processing facilities and the needs of the aerospace industry. Secondary processing facilities like rolling mills capable of producing larger sheets and plates, and forging presses with higher capacity are required for indigenous processing, so that imports can be reduced or avoided.

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