Chapter Three

MANUFACTURING TECHNIQUES

This chapter discusses the primary manufacturing techniques that are currently used to make aircraft structural components. This discussion is intended as background for the cost results outlined in the next chapter, which vary by manufacturing technique. First we discuss the composite manufacturing techniques currently in use. These techniques are hand layup, automated fiber placement (tape layup or tow/slit tape placement), and RTM. We then discuss some promising new techniques that may mature and become important in the future as well as some minor techniques in use today. Subsequently we discuss metal manufacturing techniques, including both conventional and promising newer techniques.

COMPOSITE MANUFACTURING TECHNIQUES

We begin with some general observations about which composite manufacturing techniques are best for what kind of part. Almost any part can be fabricated by hand layup, although the process may be time-consuming and expensive for large or complex parts.[1] Flat parts with simple contours are suitable for either hand layup or automated tape layup, while more complicated contours are more suitable for automated tow/slit tape placement. Most internal primary structural parts are suitable for either hand layup or RTM. Parts that

[1]For example, costly special platforms and tooling might be necessary. Stories are told of workers being suspended by harnesses in midair and being moved about to hand-lay material on large wing skin parts. This was done so that the workers would not damage other areas of the skin by walking on them.

require extreme dimensional accuracy, small tolerances, and unitization are especially suitable for RTM.

Hand Layup

Hand layup is the oldest and most frequently used composite fabrication process. In it, fabrication workers place successive layers (plies) of prepreg broadgoods, such as tape or fabric, on tools to form the part. Figure 3.1 illustrates this process. First, the plies are cut out of rolls of prepreg either by hand or, more commonly, with automated cutting equipment using reciprocating knives or lasers.[2] At the same time, the tool on which the part will be laid up must be inspected; tools must be cleaned with chemical solvents after each autoclave cycle. Fabrication workers are guided in ply placement either by Mylar templates or by automated optical projection systems such as the optical laser ply alignment (OLPA) system. It is critical that plies be laid in the correct order and in the correct direction, as it is this directional alignment that gives composite parts strength and stiffness in the right directions. Parts can have as many as 80 plies that must be laid down and stacked in the proper sequence, with the fibers of each ply of tape or fabric oriented in the proper direction.

After several plies have been laid on the tool, the plies are debulked. In this process, pressure is applied to the laminate pile to remove voids and to ensure that the stacked plies are sufficiently compacted. The process of laying up and debulking plies uses more than 40 percent of part fabrication labor (Boeing, 1999).

After all the plies have been laid up, the part is bagged and sealed before being cured in an autoclave. The bagging process involves placing materials such as peel ply, release fabric, bleeder ply, breather ply, a caul plate, and a plastic, heat-resistant bag over the tool and part. The matrix bleeder materials are important because some excess resin must be bled out of the laminate during the cure. If this does not occur, the excess resin degrades final part properties and adds weight. Proper bagging and sealing are also critical. If vac-

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[2]This technology is similar to that used in the garment industry to cut fabric.

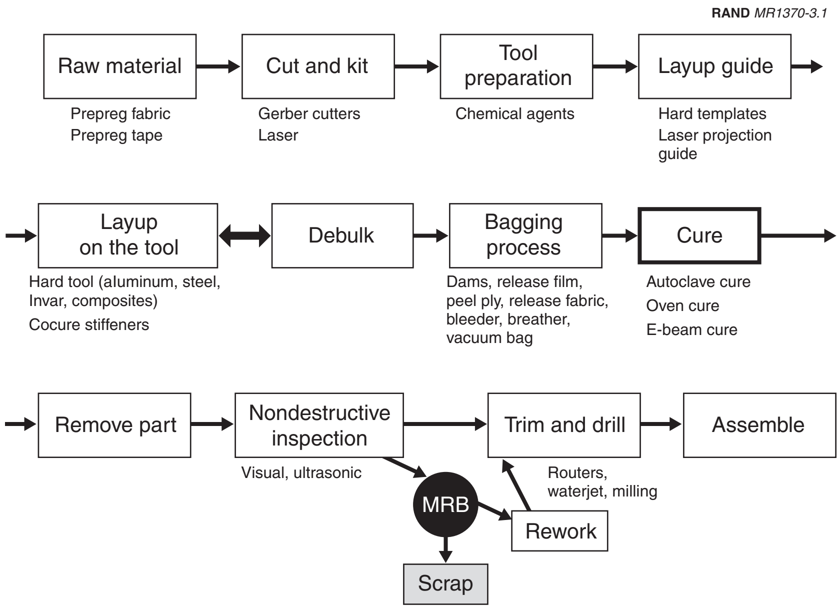

Figure 3.1—Hand Layup Process Steps

uum seal is lost during the cure cycle, it is likely that the part either will not meet dimensional tolerances or will have unacceptable voids or delaminations.

The part is then cured under heat and pressure in an autoclave. A typical carbon-epoxy cure takes 5 to 10 hours, with temperatures reaching 350°F and pressures reaching 100 psi. Carbon-BMI autoclave cures require about 11 hours at comparable temperatures and pressures. Carbon-BMI parts also require a postcure cycle of roughly 18 hours at around 450°F in an oven or autoclave. (Some companies also put some toughened carbon-epoxy parts through a postcure cycle.) Thermoplastics have autoclave processing times of around 4 hours and require temperatures between 500°F and 700°F. After cure, the part is nondestructively inspected. If it passes NDI, the part is then trimmed. The bagging, curing, NDI, and trimming steps use another 40 percent of part fabrication labor (Boeing, 1999). After the part is trimmed, holes are drilled if fasteners are used in subassembly or final assembly. This completes the fabrication step for the part.

If the part fails NDI, it is sent to a material review board (MRB). The MRB decides on the disposition of the part, which can be "use as is," "rework and repair," or "scrap" depending on the type, location, and severity of the defect.

Automation in Hand Layup

The hand layup process has become more automated over the past ten years. Plies are now almost always cut by machine rather than by hand, which, in addition to being a faster process, is also more accurate, leading to less scrap and less required inspection. Moreover, the sets of plies that will make up a part are increasingly being labeled and arranged into kits using automated pick-and-place techniques. This process is also faster and more accurate than manual procedures.

A more important automation development that has only recently gained widespread use is the OLPA system. In this system, workers are shown where to place each ply by means of an optical boundary projected onto the tool or laminate surface. This system has three main advantages. First, it lowers the labor time required to lay up parts, since workers no longer have to select and position Mylar templates (see Chapter Four for estimates). Second, it improves part quality by increasing the accuracy of part layup—especially directional fiber alignment, which is critical. Finally, it eliminates the need to design, fabricate, maintain, and replace Mylar templates.

Of course, engineering costs are associated with all of these automated techniques. Computerized instructions must be developed for the cutting, kitting, and laser projection machines, with one set of instructions for each part. However, the digital output of the CAD/CAM systems that are used to design parts can be processed by translation programs to generate such instructions. This greatly lowers the costs of developing the instructions (which is equivalent to programming the cutting, kitting, and projection machines).

Automated Fiber Placement

Automated fiber placement is the process by which plies of composite material are placed on a tool surface in their proper position by a machine rather than by hand. Today, industry primarily uses two types of fiber placement techniques. The first is done with a tape layup machine. This machine is fed by a roll of prepreg tape that is usually six inches wide. A dispensing roller head is moved, based on computerized numerical control (CNC) instructions, to the proper place and orientation over the tool. It then rolls a piece of tape across the tool surface in the appropriate length and direction and automatically cuts the tape when it is done laying that piece. Subsequently it moves to a different position and repeats the process until the part has been laid up. This technique is considered first-generation fiber placement technology and is most suitable for minimally contoured large skins.

The other fiber placement technique is called tow/slit tape placement. This is similar to tape layup except that the machine is fed by 8 to 32 individual narrow strips of tape between 0.125 and 0.25 inch wide. The feed can be tow (individual narrow tapes) or slit tape (a wide tape cut lengthwise into narrow strips). The dispensing roller head then lays these narrow strips of tape down simultaneously with the capability to stop and start individual strips in any pattern. With this capability, part thickness and thus strength can be varied nearly continuously along the part to best meet expected loads at minimum weight. In addition, the ability to vary the effective width of the ply being laid down just by varying the number of contiguous strips being dispensed at any time allows the roller head to follow complex part contours, thus permitting geometrically complex parts to be laid up (see Figure 3.2). This technique can therefore lay up complex contoured parts such as inlet ducts and fuselage skins.

Some hand layup work is still involved in automated fiber placement techniques. In such cases, the machines are occasionally stopped for manual placement of cutouts, inserts, or stiffeners onto the fiber layers, after which automated placement continues.

Automated fiber placement techniques offer several advantages over hand layup. First, the time and labor hours required to lay up a part decrease (estimates of such savings are in Chapter Four). This is partly because, as shown in Figure 3.3, several steps in the hand layup process are reduced or eliminated. Cutting and kitting are eliminated because the fiber placement process effectively does this

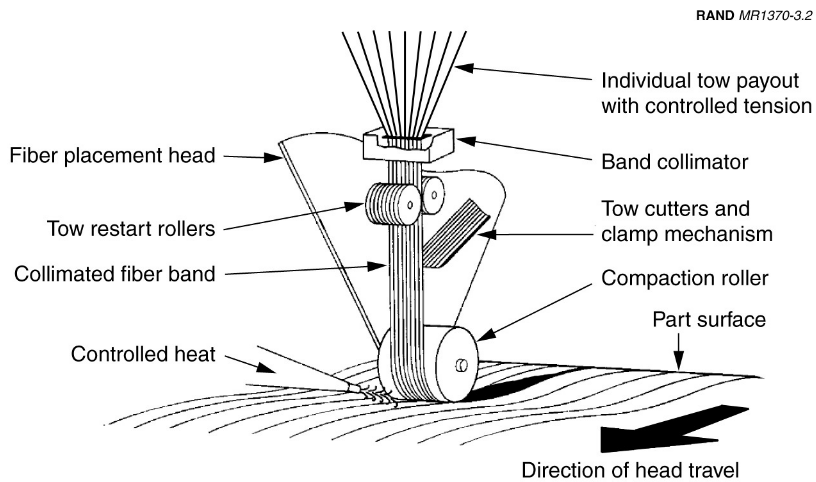

Figure 3.2—Fiber Placement Machine Fiber Placement Head

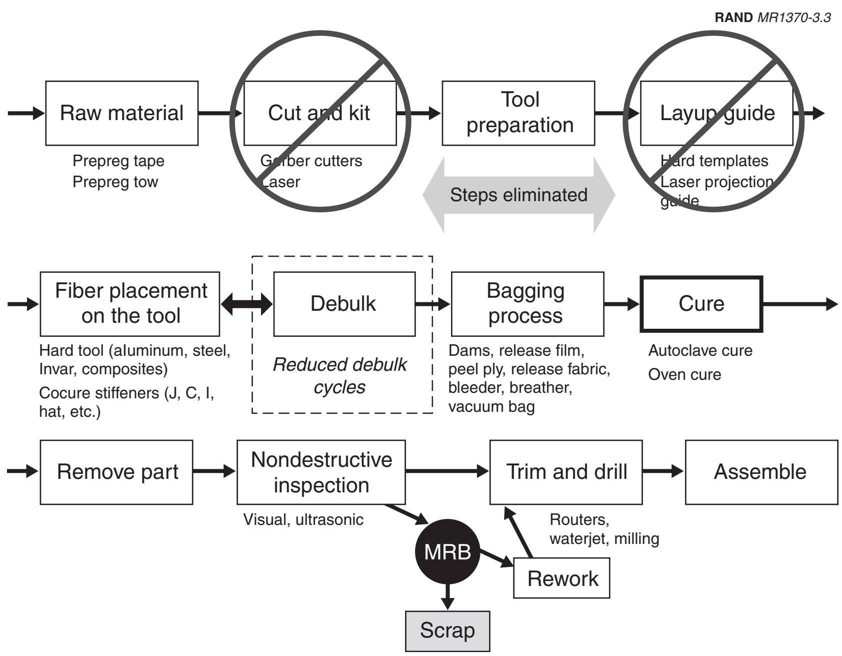

Figure 3.3—Automated Fiber Placement Steps Compared to Hand Layup

as it proceeds, dispensing and cutting the tape. Layup time is reduced in that the machine can lay tape faster than people can. Debulking is reduced by virtue of the fact that the fiber placement dispensing head compacts and heats the tape, and lays it down with pressure. Thus, manual debulking has to occur less frequently.

The second advantage, as noted above, is that tow/contoured tape placement allows fine part-thickness control to optimally balance weight and strength, since the tape pattern can be tailored to strength requirements. Third, the machine can orient the plies more accurately than people can, so part quality improves. Fourth, losses due to cutting the raw material out of wide rolls are eliminated, so the material buy-to-fly (BTF) ratio is improved. Finally, equipment needed to guide hand placement of the plies, such as Mylar templates or OLPA systems, is not required. One cost offset is that CNC instructions for fiber placement must be created for the machines. With CAD/CAM improvements, however, this penalty is not overwhelming. Another cost offset is the cost of the fiber placement machine itself. A tow/contoured tape machine can be in the $6 million to $7 million range (installed). The savings it allows in other ways, however, generally make this a good investment for substantial production runs.

Resin Transfer Molding

In RTM, catalyzed resin matrix material is injected into a closed tool or mold containing a fiber part preform, and heat and pressure are then applied to the tool/fiber/matrix package to cure the part. Figure 3.4 is a schematic of the process.

The preform can be created in two ways. One is by weaving or braiding dry carbon fiber into a three-dimensional form. The second is by laying up layers of carbon tape or fabric by hand with 5 to 6 percent resin applied. The preform is then placed into the RTM mold.

The RTM mold is a set of matched metal dies. Once the preform is in the mold, additional resin is injected under heat and pressure to bring the resin content to about 40 percent of the final part weight. Extremely low viscosity resin must be used to permeate the preforms quickly and evenly. The mold is then placed into a heated press in

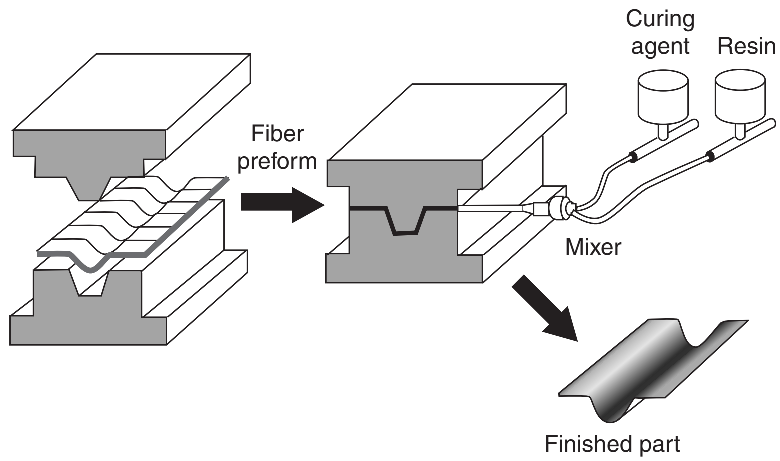

Figure 3.4—RTM Process

which the two halves of the mold are compressed and the part is cured under the heat and pressure applied by the press. After the part is removed from the mold, the process is much the same as with hand layup or automated fiber placement. Figure 3.5 illustrates the steps of the overall RTM fabrication process.

The primary advantage of RTM is that it can produce geometrically complex parts with precise dimensional tolerance, which also implies little variation from part to part. This complexity capability means that compared with metal assemblies, substantial part unitization can occur, yielding the associated weight and assembly time savings described in Chapter Two. One disadvantage is that the initial tooling cost is high owing to the need to make matched tools that will not warp under the pressure and heat required for cure. To meet this requirement, production tools are made of highly durable (and hence expensive) material, usually Invar. Therefore, RTM is most attractive for longer production runs.

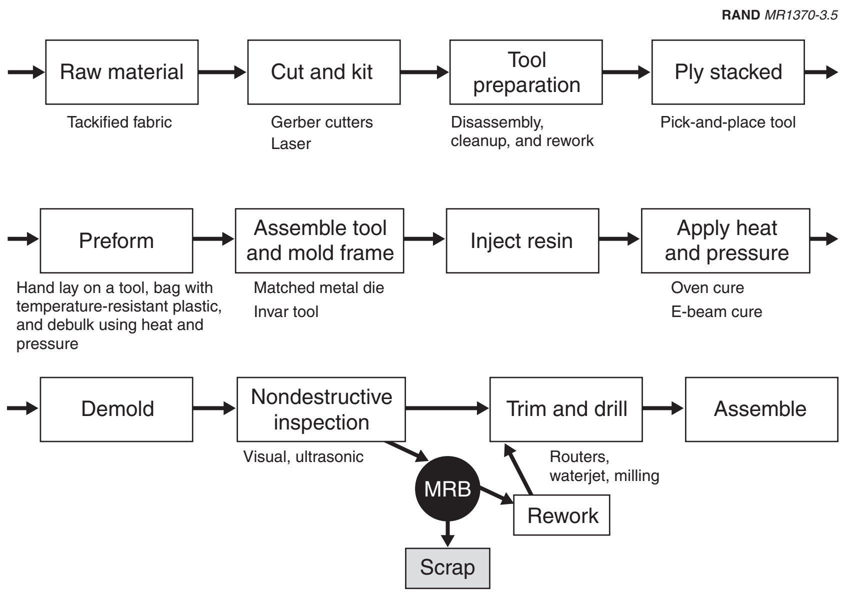

Figure 3.5—RTM Fabrication Process Steps

Other Current Composite Manufacturing Techniques

This section briefly discusses two manufacturing techniques used in composite manufacture today that are not widely applied to airframe parts: filament winding and pultrusion.

Filament Winding. Filament winding is the automated process of pulling dry fiber bundles, or narrow tapes or tows, through a resin bath and then immediately winding them onto a rotating mandrel (tool). This method was one of the first composite fabrication techniques. A prepreg tow can also be used in the filament-winding process, which eliminates the need for the resin bath (also called a wetting station). The applications of this process are limited to cylindrical parts such as rocket motor cases, pressure vessels, and tubes.

Pultrusion. In the pultrusion process, a continuous bundle of dry fiber is pulled through a heated resin-wetting station and then into heated dies. The cross-sectional shape of the pulled fiber is formed by these dies, and the resin is cured in them. Parts are then made by slicing the long cured piece that emerges. The pulling through the dies, which is done by automated equipment, occurs continuously. This process is limited to straight parts with a constant cross section, such as structural members (e.g., I beams, T beams, or frame sections) and ladder rails.

Possible Future Manufacturing Techniques

This section briefly discusses a variety of composite manufacturing techniques currently being developed. None of these are widely used in manned airframe applications today, but all have the potential to improve manufacturing efficiency. Only the outcome of the development process will tell us whether they will reach their potential for airframe applications.

Vacuum-Assisted Resin Transfer Molding (VARTM). VARTM is very similar to the RTM process except that the resin is drawn into the preform and mold with vacuum pressure rather than being pumped in. Generally, fiber preform is put on a one-sided mold and is covered with a rigid or flexible top and vacuum sealed. The resin is then introduced. This technology eliminates the need for expensive matched metal tooling and allows for the fabrication of large, unitized composite assemblies. It is often used with resins that cure at relatively low temperature.

Resin Film Infusion (RFI). In RFI, a dry preform is placed in a mold on top of a solid resin plaque or film. Heat and pressure are then applied so that the resin infuses throughout the preform, and the cure occurs under this heat and pressure as well.

A variation of this process is called stitched resin film infusion, (S/RFI). In this process, the preform consists not only of layers of horizontally woven patterns but also of vertical stitching through the weave layers and sometimes dry preform stiffeners attached with stitches as well. Parts made with this technique should have improved survivability from ballistic impact and increased tolerance to low-velocity skin impacts. Additional development and testing are required before the process will be accepted for military aircraft parts.[3]

Out-of-Autoclave Curing. Since autoclaves are expensive to maintain and operate as well as a process bottleneck, industry is exploring other means of curing composite parts. A variety of radiation curing methods, such as electron beam (E-beam), microwave, X-ray, and ultraviolet (UV), are being evaluated. Currently, E-beam appears to be the most promising technique. This is a rapid curing process that uses electron beam radiation rather than heat to cure the part. The E-beam process may also have an application in assembling composites without fasteners by cocuring of parts. E-beam equipment is generally not expensive, but facilities and equipment to house and control the radiation are a major investment. Again, more development work is needed before this technique will be accepted for aircraft parts.

METAL MANUFACTURING TECHNIQUES

This section begins with a review of metal manufacturing processes that have long been in use. We then describe in more detail two relatively new processes for which we have specific cost estimates in the next chapter: HSM and HIP investment casting of titanium. We then briefly discuss one promising new technique that is still in development for airframe uses: laser forming of titanium.

Conventional Processes

In the airframe industry, most metals are processed using conventional techniques such as CNC machining, forging, casting, and superplastic forming and diffusion bonding. The most widely used fabrication method is machining a plate or sheet of metal. In this process, a CNC milling machine is used to remove excess material from a raw metal billet, thus forming a part.

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[3]In a pilot project in which a stitched composite wing was made, a computer-controlled, multineedle-stitching gantry sewed together up to 20 stacks of precut, knitted carbon tow plies at a combined rate of 3200 stitches per minute. Braided and stitched stiffeners were folded into T shapes and sewn on. They perform the same function as spanwise stringers in a conventional aircraft (Proctor, 1998).

In the forging process, fully consolidated billet material is heated and plastically deformed by compressing the metal between an upper and lower die to shape the part. Typical parts made by forging are airframe structural components such as frames, bulkheads, ribs, and spars. After the forging process, parts usually require some machining.

In the conventional casting process, molten metal is introduced into a mold cavity, and after cooling and solidification, the metal takes the shape of the mold cavity. Today casting has limited applications because it has highly conservative design allowables.[4] This is because of the potential for microporosity in a cast part, which can seriously weaken the part. Thus, parts made from castings are required to be heavier than parts made with other processes. To date, there is not enough confidence that testing will detect such porosity; hence the conservative allowables. Like forgings, castings result in near-net shapes, which then still require some machining to finish.

Superplastic forming and diffusion bonding (SPF/DB) require similar processing environments and are often done together. Superplastic forming consists of placing flat sheet stock over a die of the desired part shape. The titanium stock is heated to 1625°F to 1650°F, and a burst of inert gas forces the flowing material into the die. The metal stock assumes the required part shape and is held under temperature and pressure for a short time before cooling. In diffusion bonding, the surfaces to be bonded are held together under near-melting temperatures and high pressure. Bonds are formed as a result of the diffusion of atoms across the mating surfaces, and these bonds have a strength approaching that of the parent metal.

SPF/DB processes are primarily used to make titanium parts (aluminum can be SPF but not DB). SPF/DB can produce unitized complex shapes (saving weight and assembly time) with close tolerances.

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[4]This is accomplished by applying a casting knockdown factor to the strength the designer would otherwise be allowed to assume for the part.

High-Speed Machining of Aluminum

HSM is, as its name implies, a fast metal machining procedure. Conventional machining of aluminum is done with cutter rotations of roughly 3000 revolutions per minute (RPM); high-speed machines have rotations of 10,000 to 40,000 RPM with considerably higher metal removal rates than conventional machining. One advantage of this technique is simply faster part fabrication and hence a reduction of machine operator hours per pound of part. A more fundamental advantage is that with multiaxis cutters running at high speeds, HSM can produce more complex unitized parts than can conventional machining. Unitized parts, as noted previously, save weight and assembly time.

HSM is also characterized by a significant reduction in machining forces and heat absorption by the part. It dramatically shifts the heat energy distribution from the cutter/workpiece to the chips. Because of the reduced heat buildup and force required of the cutter, the webs and flanges of the part can be thinner, thus saving weight.

High-Performance Machining of Titanium

High-performance machining (HPM) of titanium is essentially the same concept as HSM of aluminum but with significantly reduced feed rates and cutter speeds. The normal CNC machining rate for titanium is roughly 250 RPM. It is hoped that as a result of the improvements associated with HPM, rates of some 700 RPM can be achieved. This is still an immature technology with substantial development work required before it will be ready for factory use.

Hot Isostatic Press Investment Casting of Titanium

Another process experiencing more widespread use in making airframe parts is HIP investment casting of titanium. The first step in this investment casting process is preparing a wax model of the part. This can be done by stereolithography[5] or by using a hard mold. A

[5]Stereolithography is a process that produces a three-dimensional object from a 3D CAD file by using a computer-controlled laser to cure a photosensitive resin layer by layer.

ceramic mold is then prepared by dipping the wax model in a ceramic slurry. The mold is then dried, baked, and fired, during which the wax is melted out of the mold. (The term “lost wax” is sometimes used to describe this process.) Molten metal is subsequently poured into the ceramic mold. The part in the mold is then subjected to very high temperature (1700°F to 1750°F) and high pressure (around 15,000 psi) in a cycle lasting as long as eight hours. This is the “hipping” process, which is meant to force micropores out of the part, thereby increasing strength (and preventing the porosity problem we discussed in regard to conventional casting). Some machining or chemical milling is still required. HIP investment casting costs more per pound than the traditional investment casting process (see the estimates in Chapter Four). However, significant weight savings should occur in each part as allowables are adjusted to reflect the higher confidence in part integrity (i.e., reduced porosity). Finally, as with conventional castings, HIP-cast parts can be highly unitized, with the associated savings.

Laser Forming of Titanium

Laser forming of titanium is a technology now in development; it has not yet been used in airframe part production. In this process, a computer-controlled laser system fuses titanium powder into part preforms in an inert atmosphere.[6] The preform is then heat treated and machined into final net shape. This new technology has the potential for excellent mechanical properties and a very low BTF ratio.

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[6]This information is based on AeroMet Corporation’s presentation at the Defense Manufacturing Conference, December 1999, in Miami Beach, FL.