# THE PRC'S ACQUISITION OF MACHINE TOOLS, COMPOSITE MATERIALS, AND COMPUTERS FOR AIRCRAFT AND MISSILE MANUFACTURING

Since the Second World War, the aircraft industry has been among those sectors of the manufacturing industry in the forefront of users of advanced machine tools. Machine tool application in the aircraft industry has been dual-use. The same types of tools and manufacturing processes have been used for both military and civilian aircraft, especially large transport aircraft.

Many of the same machine tools and manufacturing processes are also used in manufacturing strategic and tactical missiles.

The requirements of the aircraft industry, although far outweighed by those of other industries in terms of production volume, have played an important role in helping to motivate the development of machine tools of high precision and versatility. For example, in the United States, some of the earliest research on numerical control of machine tools was sponsored by the U.S. Air Force. The work was done at MIT, with application to aircraft manufacturing as the objective.[179]

**The PRC, too, has recognized the importance of machine tools in both its military and civilian aircraft production programs,** as well as in industry generally. Particularly since the 1960s, it has embarked on a variety of programs both to acquire machine tools from foreign sources, and to develop an indigenous machine tool industry.

The United States has exported substantial numbers of advanced machine tools to the PRC for aircraft co-production programs, including the Boeing 737 and the McDonnell Douglas MD-80, under end-use agreements and controls. (Prior to the

1960s, before the ideological break with the Soviet Union, the PRC relied to a considerable extent on technology transfer in the aircraft and missile field from the Soviet Union. More recently, since the collapse of the Soviet Union, transfer of aircraft technology from Russia, driven by economics if not ideology, has been increasing.)

## Manufacturing Processes for Aircraft Structures

Aircraft structures are constituted mainly of metal parts and subassemblies, employing aluminum alloys, titanium alloys and, to a much lesser extent, steel alloys.

Over the past 30 years, there has been increasing use made of fiber composites of high strength-to-weight ratio, especially in military aircraft; but metal parts remain the predominant structural material for most aircraft, military or civilian.[180]

Metal parts are typically fabricated from sheet, bars (billets), molded pieces (castings), or shaped pieces (forgings). Almost all metal parts require, at some stage of manufacturing, processing to their final dimensions and finish by cutting, metal removal, shaping, or forming. This requires the use of machine tools.

Most of these machine tools are general purpose, and can be used to process a wide variety of parts, as well as to join component parts into subassemblies and assemblies by use of riveting, welding, and bonding. The various types of automatic machinery used in these joining processes may be general purpose, or may be specifically designed or modified for the particular assembly being fabricated.

Machine tools used in aircraft manufacturing today are generally **numerically controlled (NC)**. The more advanced and modern manufacturing facilities are **computer-numerically controlled (CNC)**. Many of today's high-tech machines also have automatic tool changing capability. In factory layouts, these machines are part of *machining centers* where they are integrated with automated systems for materials and workpiece handling (for example, transportable pallets that carry the workpieces).[181]

Another level of automation and process integration that has been achieved in large-scale production only recently (for example, in the Boeing 777) is the integration of computer aided design (CAD) with computer aided manufacturing (CAM).[182] With CAD/CAM, the output of the computer design process is translated directly into numerical computer code that can be sent directly to computer-controlled machines and machining centers.

The next step in manufacturing process integration is **computer integrated manufacturing (CIM)**.[183] In this step, integrated computer controls manage the entire product flow from design to sales to delivery, including not only CAD/CAM but also:

- **Materials ordering**
- **Warehousing**
- **Inventory control**
- **Factory scheduling**

Finally, the integration is being extended to networks of geographically scattered suppliers, creating global infrastructures supporting international manufacturing enterprises.[184]

## High-Tech Metal Cutting

To a considerable degree, the extent of advanced capability of computer-numerically controlled machine tools is indicated by the number of axes that can be controlled. (This is often how the sophistication of these machines is described in export control documents.)

The "number of axes" means the number of motions of either the tool or the workpiece that can be simultaniously controlled.[185] Thus, a drilling machine in which the tool can travel vertically, and the workpiece is held to a bed that can travel both horizontally and laterally, is a three-axis machine. Three-axis machines are widely used, and widely available worldwide.

A milling machine is one of the most versatile machine tools. And when a milling machine's cutter is fixed, and the workpiece is mounted on a pallet that can not only move vertically, horizontally, and laterally, but also rotate about two perpendicular axes, it becomes a five-axis milling machine. There are other combinations of tool and pallet motions that may be advantageously embodied in five-axis milling machines, depending on the particular applications of those machines.

There is no fundamental difficulty in conceiving or understanding the design and operation of these sorts of five-axis machines. It is believed that some five-axis machines may have been manufactured in the PRC.[186] However, the design and production of five-axis milling machines capable of maintaining the highest levels of accuracy and control of workpiece tolerances — during high-speed machining, over the entire range of three-dimensional motions and rotations that the machine may trace out in machining a complex part — calls for a high degree of capability in machine tool and supporting technologies (for example, materials and quality control).

**It is not believed that the PRC has yet attained that level of capability.** But such sophisticated five-axis machines have been exported from the United States to the PRC under license, with end-use controls, for use in co-production of commercial aircraft. In addition, the PRC may have been able to import them from one of the several non-U.S. countries that manufacture them.

The value of high precision multiple-axis machines in manufacturing is that they broaden the range of design solutions available for structural elements and for structural assemblies. In most cases, an aircraft structural designer (or computer design program) without such advanced machine capabilities would have to design less optimal parts and structures. This would mean disadvantages in terms of the extra weight of the parts and structures, and a higher unit cost relative to what could be achieved with more advanced machine tools.

However, in some instances, increased effort by highly skilled craftsmen can offset the disadvantages of using less advanced or lower-precision machine tools. In advanced industrial economies such as the United States, the high cost of such skilled labor almost always strongly favors investments in more advanced machinery. In the PRC, the cost tradeoffs in favor of advanced machinery over additional skilled labor are less.

**Nevertheless, for the PRC, the advantages of having advanced machinery for manufacturing both modern civilian transport and military aircraft** remain sufficient to motivate continuing efforts on their part to acquire them. In co-production arrangements with the major aircraft producers, it is usually necessary for the PRC to be provided with the same types of machines with which the parts being co-produced were originally designed.

The progress in refinement of machine tools has been substantial in recent years. For the most part, this progress is the result of advances in control systems, and in the machines' associated software. The mechanical components of machine tools have remained mostly unchanged over the past decade, although there have been a few improvements, such as higher spindle speeds. The more modest advances in the mechanical precision and versatility of machine tool control have complemented the rapid advances in computer-aided design and manufacturing. In part, the improved mechanical components themselves are the result of these vastly improved CAD/CAM capabilities; the improved machine tool components also make it possible to use CAD/CAM capabilities more effectively.

The following table indicates the improvements in the accuracy and repeatability of five-axis machines over the past decade.

**Recent High-Tech Improvements in the Accuracy and Repeatability for 5 Axis Machines**

| | **1988** | **1998** |
|---|---|---|
| **Linear Accuracy** | 0.0005 – 0.0010 inches | 0.0001 – 0.0002 inches |
| **Repeatability** | 50 millionths of an inch | 5 to 10 millionths of an inch |
| **Rotary Accuracy** | 0.01 to 0.001 degrees | Better than 0.001 degrees |

Thus, 10-year-old machines are well below current best levels of accuracy.

**The current thresholds for subjecting metal cutting machines to export controls** are, for example, positioning accuracy of 4 to 6 microns (around 0.00012 inches) and rotary accuracy, when specified, of 0.003 degrees. Milling machines with five or more axes are subject to export controls regardless of accuracy.

In the advanced industrialized nations, machine tool accuracy has increased across the entire spectrum of computer-numerically controlled machine tools. For example, the latest grinding machine tools for use in high-volume production can produce concentric circles accurate to within five ten-thousandths of an inch. These same machines can guarantee flatness to within 50 millionths of an inch. They can bore holes with dimensions accurate to within four ten-thousandths of an inch, and then repeat the process endlessly with a variation of no more than 0.0002 inches. Today's specialty machines have even better accuracy and repeatability figures.

## Metal Forming for Aircraft Manufacture

Sheet metal forming operations are important in aircraft manufacture. For example, the process known as **"stretch forming"** — in which a metal sheet is held at its edges, and stretched over a form or die that can be moved — is used to manufacture large sections of skin (up to 40 feet long) for the Boeing 757 and 767.[187]

Visitors to PRC aircraft manufacturing plants several years ago noted that there seemed to be only a limited capability for stretch forming, especially for larger, heavier workpieces.[188]

There are many variations of metal forming operations. In **"stretch-draw forming,"** a metal sheet is gripped in tension, and then pressed by upper and lower mating dies using hydraulic force.[189] Other types include:

- **Press brake bending**
- **Spinning**
- **Deep drawing**
- **Rubber forming,** in which the metal sheet is forced into a rubber medium on one side by a die on the opposite side[190]
- **Hydraulic stretch forming presses,** used to form extruded parts to shape
- **Hot forming**, of special importance in manufacturing titanium aerospace parts

**One modern type of forming operation is known as superplastic forming,**[191] because it takes place at a temperature above which some metals become plastic. The titanium alloy Ti-6AL-4V, which is widely used in aircraft parts, can be formed this way using a variety of forming techniques.

A more complex application of superplastic forming is done in combination with **diffusion bonding**.[192] In this process, two sheets are diffusion bonded at designated areas under high temperature. The unbonded areas of one of the sheets then undergoes superplastic forming into a die, forced by argon gas pressure. These techniques have been extended not only to titanium alloys, but to some aluminum alloys as well.

Superplasticity and diffusion bonding technologies for alloys of titanium, aluminum, and certain other metals are subject to export controls.

## Non-Mechanical Manufacturing Processes

There are a number of manufacturing process to remove, shape, and finish structural and component parts that do not rely on cutting with solid tools. Instead, these processes use chemical, electrical, thermal, and other methods to cut, shape, and finish metals and other materials.

Of these methods, **chemical milling**[193] is the most widely used on metal aircraft and missile parts. In chemical milling, a mask is placed over areas of a metallic workpiece where metal is *not* to be removed. The metal workpiece is then placed in a chemical bath that etches metal away from the unmasked areas. This process is not subject to export controls, and is well within PRC capabilities.

**Electrochemical machining**[194] employs a negatively-charged, shaped electrode to remove material from a positively-charged metal workpiece in a conductive chemical fluid (electrolyte). This process is more complex than chemical milling, and can be used to produce complex shapes with deep cavities.

**Electric discharge machining (EDM)** removes electrically conductive material by means of controlled, repeated electric discharges.[195] The chips are removed by flushing with a dielectric fluid. When EDM is used for grinding, the workpiece is fed into a negatively-charged rotating wheel. This type of EDM is not subject to export controls. In another form of EDM, a moving wire is brought to within arcing distance of the metal part being cut in a dielectric fluid. This type of EDM is subject to export controls. Both types of EDM are on the U.S. Militarily Critical Control Technologies List (MCTL) if the number of rotary axes for contour control exceeds five (for the wire type), or two (for the nonwire type).

**Laser beams** are also used for cutting metals and other materials.[196] Either solid-state lasers or gas lasers may be used for this purpose, including:

- **CO2 lasers**
- **Ruby lasers**
- **Neodymium lasers**
- **Neodymium-YAG lasers**

Export controls apply to laser tools, and these tools are listed in the Missile Control Technology List (MCTL) if they have two or more rotary axes that can be coordinated simutaneously and have positioning accuracy better than 0.003 degrees. However, lasers of the types and power levels useful in most material machining applications are widely available worldwide, and to the PRC.

**High velocity water jets** generated by pressures of 60,000 pounds per square inch and above are also used for cutting materials, especially plastics and composites.[197] A related process is **abrasive water-jet machining**, in which abrasive particles such as silicon carbide are added to the water to increase the material removal rate.

Export controls apply to water-jet machine tools, and are noted in the MCTL if they have two or more rotary axes that can be coordinated simultaneously and have a positioning accuracy of better than 0.003 degrees.

## The Use of Computers for Machine Control

Much of the recent improvement in machine tool capabilities is attributable to advances in the use of computers for machine control. Moreover, further advances in machine control technology are in the offing.

Although there is some uncertainty as to the level of PRC technology in this area, there has been no credible evidence that it is up to the state of the art of the highly-developed nations (the United States, Japan, and Western Europe).

The PRC's inability to achieve state-of-the-art in computer-control system technology for machine tools is not due to a lack of theoretical knowledge. PRC engineers regularly attend, and present papers at, meetings dealing with most of the frontier developments in machine tools and their control systems.[198]

Rather, the PRC has been inhibited by shortcomings in its industrial infrastructure. The PRC also lacks the ability to integrate the contributions of the many disciplines that are required to utilize the rapidly emerging new technologies. The PRC system is unable to keep up with these basically new approaches.

Control system technology for machine tools is rapidly starting to change. Among the most important changes on the horizon is the emergence of "open architecture" control systems. These systems use personal computers for machine control.

**While PCs of sufficient capability for the control of sophisticated machine tools are now available in the PRC, and it is believed that motion-control boards needed for this purpose are also generally available, software for machine control is the other necessary element.** The PRC would need specialized software to achieve a highly capable machine tool control system. At present, export controls are imposed on software for machine tool control that can be used to contour control independently and simultaneously on more than four axes.

In addition, there are controls on software that can adaptively use the measurement of at least one physical variable through a computational model to change one or more machining instructions.

Capabilities to produce software for PCs are widely diffused throughout the world, and are growing steadily in the PRC itself. As a result, these controls on software may not be as effective in the future, as these new trends in machine tool control develop.

An important aspect of advanced software for machine tools is that it can be used to compensate for a machine tool's mechanical errors, if the errors are repeated. This is done by mapping the machine's performance against a known standard, and then compensating for positioning errors.

As machine control systems move increasingly toward becoming PC-based, these "open architecture" systems will make error correction systems easier to implement, and more widely used.

## Fiber Composite Materials and Structures

Since the early 1970s, there has been a trend toward replacing metals with fiber composites in the primary structure of aircraft.[199]

The main reason for the adoption of fiber composite materials and structures is that they weigh less than metals, but provide the same or better stiffness and strength. In addition, composite materials and structures usually last longer (that is, they have a greater time-to-failure under repeated or cyclic loading) than metal parts designed for the same maximum static loads. They also vibrate less.[200]

A disadvantage of composite materials and structures is that the manufacturing processes to use them are more complicated, and consequently they add costs. They also require more advanced nondestructive evaluation techniques for quality control and field maintenance. In light of these factors, the trend toward replacing metals with composites has thus far proceeded much more rapidly in military aircraft than in civil aircraft.

For helicopters and other vertical take-off and landing aircraft,[201] however, the trend toward fiber composites began earlier and proceeded faster. Initially, fiberglass composites were the material of choice, even though they have much lower strength and stiffness properties than the boron and carbon/graphite composites that were later utilized in fixed-wing aircraft. The reason that fiberglass composites were attractive for helicopters (and other vertical take-off and landing aircraft) is that structural weight savings on these aircraft have a relatively higher payoff in performance than on fixed-wing, horizontal take-off aircraft. Moreover, the load intensities on a helicopter's non-rotating parts tend to be lower than on high-speed fixed wing aircraft.

Among the advantages of composite structures is that a structural part can be designed to have different strength properties in different directions. That is, it can be stiffer in one direction, and more flexible in another. This permits it to be tailored to the loading conditions of specific applications.

For this reason, fiber composite structures are especially well adapted to the application of radar signature reduction techniques. It should be noted that the use of composites in and of itself is not enough to give an aircraft stealth properties; a fiber composite structure aircraft without radar signature reduction features will not necessarily have a lower radar cross-section than a metal structure.[202] The subject of stealth in relation to composite construction is discussed more fully under the heading "*Stealth and Composite Techniques*," later in this *Technical Afterword*.

Although fiberglass composite materials have been used in aircraft manufacturing since the early 1950s, most of the applications of this material originally were for secondary structure not considered critical for flight safety. (A notable exception was the use of fiberglass/epoxy resin composites for helicopter rotor blades — experimentally in the 1950s, and then in production in the late 1970s.) Fiberglass/epoxy resin composites using S-glass, although of high strength and stiffness relative to most homogeneous plastics, did not begin to approach the strength and stiffness of aluminum alloys, much less those of high-strength steel alloys. But they could be used in secondary structures for their weight and sometimes manufacturing cost advantages relative to alternatives.

**A turning point in the application of fiber composites to aircraft, rockets, and ballistic missiles** took place in the early 1960s, with the discovery and development of the high strength and stiffness properties of boron fibers. Single boron fibers in tension (that is, subjected to stress in one direction) were found to be stronger and stiffer than the best available high-strength steel alloys.

The use of a boron/epoxy resin composite then followed. It can be used for aircraft, rocket, and ballistic missile structural elements that are designed to take multi-directional loads, such as are typically encountered in aircraft primary structures. Boron-epoxy resin composites are formed and cured in autoclaves (essentially, pressure cookers) under controlled high temperatures and pressures, in much the same way as the earlier fiberglass/epoxy resin composites were made. Boron-epoxy resin composites are just as strong and stiff as aluminum and steel alloy structures, if not better, and weigh less.

Very shortly after the introduction of boron fibers, carbon/graphite and Kevlar fibers were introduced. Depending on the particular application and type of loading, these offered material properties and unit weights comparable to boron fibers, and at lower cost.[203]

It required some years of development, including ground and flight testing of experimental structural components, before boron/epoxy resin composites were first used in the primary structures of production aircraft. Their first use was in the horizontal tail surfaces of the Navy F-14A aircraft, in the early 1970s. This was followed shortly by the F-15A, which used boron/epoxy composites for both its horizontal and vertical tail surface structures.

Since then, there has been a steadily increasing trend toward the use of the various high-strength, high-stiffness fiber composites, particularly graphite/epoxy, in primary structures in military aircraft. The same trend is underway, albeit at a slower rate, in civilian aircraft.

The progression in composite usage in primary structures has been as follows:[204] [205]

**High-Tech Fiber Composites in Military and Civil Aircraft**

| Military Aircraft | Percentage of Primary Structure | Civil Aircraft | Percentage of Primary Structure |
|---|---|---|---|
| **F-15A** | 4-5% | **Boeing 767** | 3-4% |
| **F-16** | 12% | **Airbus A300-600** | 4% |
| **FA-18E/F** | 19% | **Airbus A310-300** | 8% |
| **AV-8B** | 26% | **MD-11** | 5% |
| **F-22** | 35% | **Boeing 777** | 9% |
| | | **Airbus A-340** | 12% |

## Composite Structure Fabrication Technologies

The manufacture of fiber composite structures generally begins by combining the fiber with epoxy resin, or some other so-called "matrix" material. The resulting prefabricated sheets are called *prepreg.* Successive layers of these *prepreg* sheets are then placed in a mold that is shaped to the form of the part being fabricated.

The fiber directions in successive prepreg layers are diagonal to one another, in a fashion tailored to the load and stress field to which the part will be subjected. The stack of prefabricated sheets — called a "layup" — is then cured in an autoclave (essentially, a pressure cooker) under controlled high temperature and pressure.

Initially, the task of making the layups in molds was done by hand. Later, beginning with simple, near two-dimensional parts, computer-controlled automated layup machines became available. Today, automated layup machines are capable of handling ever more complex parts.

Attachments between fiber composite structural elements have, for the most part, been made with bolts. In some cases, adhesive bonds have been used, in much the same manner as with metal parts. More recently, the layups for two or more parts have been joined in the curing process — this is called *cocuring*.

These fiber composite fabrication processes permit the manufacture of parts in nearly final form ("near net shape"). However, some cutting, drilling, and other machining and finishing operations are usually required.

Much of this is done with conventional machine tools. But the tool shape and hardness, and the cutting speeds, must be adapted to the fiber composite material being worked. Laser cutting and water jet/hydroabrasive cutting are also used extensively in finishing operations for fiber composites.

**For axially-symmetrical parts — such as rocket motor cases — filament winding is used (for example, in the Minuteman missile's upper stage).** Filament winding has also been used to manufacture fiberglass/epoxy helicopter rotor blades. In addition, long parts of constant cross-section can be made by the **pultru-**

**sion** process: pulling the fibers and matrix material through a die. This is the analogue of the extrusion process for metals.

Most of the fiber composite structures produced to date have employed polymer matrix materials that cannot be subjected to severe temperature environments. This has been a strict limitation on the kinds of structures for which fiber composites can be used. But newly-developed composite materials do not have this limitation. These new materials include:

- **Metal matrix composites**
- **Ceramic matrix composites**
- **Carbon/carbon composites**

These new fiber composites can be used in higher-temperature applications such as rocket engines, hypersonic aircraft, and ballistic missiles.[206] [207]

**The PRC has been seeking to acquire or develop composite materials and structures technologies.** One route has been through seeking co-production relationships for subassemblies of commercial aircraft and helicopters that have significant composite parts.[208] There are also reports of indigenous development as well.

A wide range of composite materials and structures fabrication equipment is included in the Missile Control Technology List (MCTL), and is subject to export control regimes at some threshold of capability. These include:

- **Composite filament winding**
- **Tape laying**
- **Weaving**
- **Prepreg**
- **Fiber production equipment**

The more advanced Western methods of composite structure fabrication for complex three-dimensional shapes are extremely sophisticated robotic machines — some with as many as nine axes of motion. It is not believed that the PRC has been able to develop or acquire machines of this capability as yet.

## Stealth and Composite Technologies

What is stealth? Simply put, stealth is the ability to conceal an attacker from a defender's detection and defensive systems, and successfully accomplish the mission.[209] Stealth does not make the attacker invisible, only more difficult to detect.[210] To avoid detection, it is necessary to reduce or eliminate the attacker's "signature."

The "signature" is composed of five primary elements:

- **Visual signature**
- **Infrared (heat) signature**
- **Acoustic (noise) signature**
- **Radio transmission signature**
- **Radar signature**[211]

The first three signatures are relatively short range.[212] The radar signature is the most important, because it can be detected at the longest range — up to 400 miles away.[213]

In a stealth vehicle, attention is paid to all five signature sources.[214] To reduce the infrared and acoustic signatures of an aircraft, the engines are buried inside the fuselage or wings. Special non-reflective paints and paint schemes reduce the visual signature. The radio transmission signature can be reduced or eliminated by secure communications or radio silence.

Defeating radar detection is relatively simple in principle.[215] It involves designing the vehicle so that the incoming radar signal is reflected away from the defender's radar receiver, or absorbed by the vehicle itself using radar-absorbing materials.[216] Radar stealth is accomplished in five ways:

- **Designing the vehicle so that there are no surfaces pointing directly back to the source radar**
- **Using radar-absorbing materials on surfaces that could reflect back to the source radar**

- **Removing surface roughness by making the surface of the vehicle as smooth as possible**
- **Designing engine inlets to reduce reflection**
- **Burying engines and weapons inside the vehicle**[217]

The F-117 and B-2 aircraft represent the cutting edge in manned stealth aircraft, because they combine all of the elements of design, materials, and manufacturing technology to achieve stealth, including radar and infrared invisibility.[218]

Why is stealth so important to the military? Stealth vehicles are difficult to counter by a defender.[219] In military terms, stealth insures a greater probability of completing a mission and increased survivability of U. S. forces.[220] Other benefits include:

- **The ability to range over a greater area of enemy territory without being detected**
- **Reduced mission cost**
- **Increased effectiveness of other radar-jamming systems, such as chaff**[221]

The PRC probably cannot build stealth aircraft or missiles with the same capabilities as the F-117 and B-2, now or in the near future. But the PRC is likely to try to acquire most of the key elements necessary to build them.

Even acquisition of these elements will be insufficient to permit the PRC to build effectively stealthy aircraft or missiles. System integration of stealth is a major additional task facing the PRC.

## The PRC's Acquisition of Stealth Design Technology

The PRC's efforts to solve the stealth design problem received a major boost when the PRC was able to import both high performance computers, and software packages known generically as “finite element” software. This software is used to assess aerodynamic forces and stresses on three-dimensional structures.

"Finite element" software also has the capacity to solve complex sets of Maxwell's equations. These equations relate to electromagnetic radiation (that is, radar) around a structure.

With high performance computers and "finite element" software, the PRC now has the capability to design aircraft which are aerodynamically feasible and then evaluate their stealth capabilities, too.

The Department of Defense has sought tighter export controls on "finite element" software.[222] This software is distinctly dual-use, with civilian applications including automobiles, off-shore oil drilling platforms, and the design of nuclear reactor plants. One of the main concerns of the Defense Department, however, is its use in stealth applications. The software is also critical for anti-submarine warfare.[223]

## The PRC's Acquisition Of Composite Materials Technology

Building composite structures for aircraft is, in some ways, similar to building a fiberglass boat: the rigid fiberglass is technically a composite material, made up of layers of fiberglass fabric and epoxy resin. In composite structures for aircraft, the fabric is woven from ceramic, polymer, or carbon/carbon materials, instead of fiberglass.[224]

Large rolls of the fabric are run through machines that apply a coating of uncured resin to the fabric (known as *prepreging* the fabric). This material bonds together, forming the composite structure.

In stealth aircraft structures, radar-absorbing layers and coatings are integrated into the composite structure.

**Some PRC joint ventures are adding to the PRC's ability to produce composite airframes:**

- **British Petroleum America proposed to sell to the PRC proprietary technology for resins and reinforcing materials,** as well as the technology and training to operate a facility.[225] The company also planned to sell the methodology for translating manufacturing requirements into optimized semi-finished materials. BP America specifically sold the PRC technical data for hot-melt prepreg formulations,[226] and for an acrylonitrile plant.[227] The prepreg technical data was sold to the AVIC China Helicopter Corporation.[228]

- **Hexcel was willing to supply the PRC with high-temperature curing resins and the production equipment and training** to apply the resin to fabric materials.[229] Specifically, Hexcel planned to give the PRC the technology for 250 F and 350 F epoxies.[230] The company planned to transfer to the joint venture a solution-impregnation coating tower for fabrics, and hot-melt impregnating equipment for tapes.[231] The joint venture was supported by exports of carbon epoxy prepreg to the Chengdu Aircraft Industry Corporation[232] and the Xian Aircraft Company.[233] In addition, Hexcel was going to transfer Boeing Aircraft Company's specifications for advanced composites,[234] graphite,[235] Kevlar,[236] and conductive fabrics.[237]

Kevlar is used to make high-strength smooth surfaces on stealth aircraft. The graphite and conductive fabrics are used for radar-absorbent surfaces of stealth aircraft. In addition to their uses for stealth technology, the growing importance of composite structures in all aircraft construction provides an incentive to the PRC to acquire this technology even for non-stealth aircraft — military and civilian.

## The PRC's Acquisition of Composite Structures Manufacturing Technology

Obtaining the design capability and the materials-production capability were still not sufficient for the PRC to build aircraft with composite structures. The missing element of the Chinese puzzle was the ability to manufacture aircraft parts with consistent performance time after time.

The answer to this question was found in a joint venture with the Sikorsky Aircraft Company.[238]

The Sikorsky Aircraft Company joint venture with the PRC proposed to build the composite tail section of the civil S-92 helicopter.[239] Sikorsky would teach the PRC to design and fabricate the tail section using proprietary technology to meet Federal Aviation Agency standards of quality and performance.

The project included teaching the PRC to fabricate aircraft components using carbon fiber materials (which are also used in stealth aircraft).[240] In addition to showing the PRC how to use the materials, Sikorsky also taught the PRC about:

- **Bag molding**
- **Mold releases**
- **Die manufacturing**[241]

The key requirements the PRC expected to obtain from the venture were precision tooling, repeatability, and a high production rate.[242]

## Overall Assessment

The PRC acquisition of composite technology is an interesting case study. It indicates a broad-based set of joint-venture initiatives directed toward providing for the PRC a state-of-the-art composite materials/aerospace structure capability.