DEPARTMENT OF DEFENSE

MILITARILY CRITICAL TECHNOLOGIES LIST

SECTION 12: PROCESSING AND MANUFACTURING TECHNOLOGY

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PREFACE

The Militarily Critical Technologies List (MCTL) Program provides a systematic, ongoing assessment and analysis of goods and technologies to identify those that are critical to the Department of Defense (DoD). It characterizes the technologies (including quantitative values and parameters) and assesses worldwide technology capabilities.

The MCTL is a compendium of goods and technologies that DoD assesses would permit significant advances in the development, production, and use of the military capabilities of potential adversaries. It includes goods and technologies that enable the development, production, and employment of weapons of mass destruction (WMD). Goods and technologies are considered critical if their acquisition and exploitation by a potential adversary would either significantly negate or impair a major military capability of the United States or significantly advance a critical military capability of the adversary. A leading edge technology that has a high potential for advanced military application can be included even if it is not currently embedded in a U.S. system.

Technologies are identified through the deliberation and consensus of Technology Working Groups (TWGs) whose members are subject matter experts from government, industry, and academia. TWG chairpersons continually screen technologies and nominate items to be added or removed from the MCTL. Working within an informal structure, the TWGs strive to produce precise and objective analyses across the technology areas and to update these assessments periodically.

The legal basis of the MCTL stems from the Export Administration Act (EAA) of 1979, which assigned responsibilities for export controls to protect technologies and weapons systems. It established the requirement for DoD to compile a list of militarily critical technologies. The EAA and its provisions, as amended, have been extended by Presidential Directives.

The MCTL is not an export control list. Items on the MCTL may not be on an export control list, and items on an export control list may not be on the MCTL. The MCTL is designed to be used as a reference for evaluating potential technology transfers and for reviewing technical reports and scientific papers for public release. Technical judgment must be used when applying the information. The MCTL should be used to determine whether the proposed transaction would result in a transfer that would give potential adversaries access to technologies whose specific performance levels are at or above the characteristics identified as militarily critical. It should be used with other information to determine whether a transfer should or should not be approved.

An Index of MTCL Technology Data Sheets is provided with each MCTL section. Separate documents contain a Glossary and a list of Acronyms and Abbreviations.

This document, MCTL Section 12: Processing and Manufacturing Technology, supersedes MCTL Part I, Section 10: Manufacturing and Fabrication Technology, June 1996.

SECTION 12—PROCESSING AND MANUFACTURING TECHNOLOGY

Scope

Highlights

- Various fabrication technologies are critical in manufacturing military hardware (e.g., fabricating aircraft and missile parts, antiarmor weapons, and nuclear applications).
- Various types of bearings are used in engines, gyroscopes, drive trains, tracking systems, and so forth.
- Measuring and inspection equipment is necessary for the performance and reliability of hardware and for the interchangeability of parts.
- Nondestructive test and evaluation (NDT&E) equipment is necessary to maintain a high level of quality control.
- Equipment for the subtractive manufacture of military equipment (e.g., turning, milling, and grinding machines) is essential for the manufacture of most military equipment.
- Coating equipment and technologies improve the capabilities of a wide range of military hardware.

OVERVIEW

This section describes the technologies required for the production of important military equipment. In most cases, the technologies, the equipment, and the know-how are dual use and affect civil applications where considerations of costs, flexibility, competitiveness, and so forth have become major concerns. In some cases, these technologies are not state of the art. In others, the United States is not the world leader in the technology. All countries engaged in the production of military weapons, munitions, and systems possess, to some degree, the know-how in the technology areas indicated in the “Highlights” box above. A country’s level of technology directly affects the quality, cost, and reliability of its military hardware. U.S. concerns are directed at preventing exports to countries or areas where the receipt of such equipment could cause destabilization or could assist in producing weapons of mass destruction (WMD). Therefore, the level of concern for the machine-tool technology necessary to meet the U.S. antiproliferation goals is less than the state-of-the-art machine tools.

The section addresses several different technologies associated with a modern industrial base. These technologies include bearings, certain nondestructive evaluation and inspection equipment, and many types of production equipment. For manufacturing technology, Section 14 of the MCTL addresses design, manufacturing, and testing and maintenance that is aided by computers [computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided testing (CAT)].

BACKGROUND

For years, manufacturing and fabrication equipment has been a mainstay of industrial societies. This equipment was instrumental in bringing about the Industrial Revolution in the 18th century, the continued development of a wider range of machines in the 19th century, and the development of the concept of automation in the early part of the 20th century. The mid-to-late 20th century witnessed a rapid expansion, with the introduction of both automatic control of the machining axes and the incorporation of additional axes of motion. Indeed, one can trace the development of our present industrial society, as well as the sophistication of military hardware, to the development of manufacturing and fabrication equipment.

While rudimentary machines have been used throughout history, machines as we know them today were first developed in England and the United States. In England in 1775, John Wilkinson invented a precision horizontal-boring machine to bore out cylinders for the newly invented steam engine. In the United States in 1798, Eli Whitney invented machinery to produce interchangeable parts for the assembly of army muskets. The 19th century marked the development of milling and turning machines (for rifle stocks) (both in 1818), gear-cutting machines, sewing machines, harvesters, grinding machines, and automatic screw machines.

The early part of the 20th century witnessed the development of automation. This development, coupled with the existing machines, opened the world to mass production. As a result, products could be manufactured in higher volume and at much lower cost, and the world experienced the mass-market appeal of automobiles and numerous other consumer products. Consumer products became affordable to a much wider range of the population. During World War II, the military used this capability to produce tanks, planes, and ships in unprecedented numbers and at costs previously unheard of. Such machines were critical for the manufacture of engine parts and nuclear weapons.

However, automation alone was not sufficient to meet some of the post-World War II military needs because more sophisticated weapons were developed—weapons that required not only high accuracy, but also high repeatability. From this need came the development (in 1952) of a three-axes machine with the rudiments of numerical control (tape instructions). Development continued with the introduction of automatic tool changing, four- and five-axes machines, and computer numerical controllers. Most subsequent improvements involved materials, better cutting tools, more accurate raceways, and faster and more stable spindle assemblies.

At the same time, as these later developments were being introduced, composite materials were developed. To make best use of these new materials, new machines were developed (e.g., tape-laying and filament-winding machines). This revolutionized the production of a wide range of commercial and military products (e.g., strong and lighter aircraft assemblies, automobile and tank parts, and so forth).

Along with these continued improvements in manufacturing technology came an increased awareness of the importance of quality and reliability. Quality was addressed in many aspects of the manufacturing process, and equipment was developed to measure the final product to verify that it met the design parameters. Much of this equipment was also computer controlled to allow for accurate and rapid measurement. The coordinate measuring machine (CMM) is a prime example of such equipment. The issue of reliability was addressed with the development on nondestructive test and measurement equipment (i.e., equipment that could measure various characteristics of the final product without affecting the operational capability of the end item).

The technology for coating various substrates has also experienced rapid growth and development during this century. In earlier centuries, coatings were mainly applied for surface protection, and the most common media were paints or similar coatings. The perfection of equipment to produce vacuum environments rapidly increased the range of coating materials and technologies. Technologies moved from simple vacuum evaporation to chemical vapor deposition (CVD), plasma spraying, sputter deposition, ion implanting, and so forth. The refinement of these various technologies resulted in faster, more reliable jet aircraft (improved gas turbine engines); improved canopies for aircraft; longer-life bearings for applications in jet engines, machine tools, and drive-trains of automobiles, trucks and tanks; specially designed dielectric layers and wear coatings for optical systems and sensors; and coatings for low observability of weapon systems.

Bearings have experienced similar developments. Although bearings, in their simplest concept, have been used for many years, it was not until the 19th century and the introduction of machine tools that they were recognized as individual, important components. In the mid 20th century, the development of tapered bearings, high-speed bearings, and miniature bearings were instrumental in the improvement of automotive drive trains, high-speed machine tool spindles, navigation systems, and gyroscopes.

SECTION 12.1—ADVANCED FABRICATION AND PROCESSING

Highlights

- Fabrication equipment includes equipment that changes the shape of a material to form the desired shape for a specific application (e.g., nose cones, missile skins, engine fan blades, and so forth).
- Processing equipment includes high-temperature furnaces used to produce graphite, high-temperature alloys, titanium, and single-crystal turbine blades and technologies used to produce composite structures for military hardware (e.g., filament-winding machines, tape-laying machines, and so forth).

OVERVIEW

This section includes equipment for manufacturing structures by means of various advanced manufacturing techniques (e.g., fabricating structures using spin-, flow-, and shear-forming machines and superplastic forming/diffusion bonding; processing a final product using high-temperature furnaces and heaters; and stretch-forming machines that involve actions such as bending and/or stretching finished material to form a desired shape or rolling material over mandrels to form curvilinear or cylindrical cross-section parts).

BACKGROUND

Some of these technologies that have been developed in recent years have their roots in antiquity. Technology to fabricate composite structures began in the early 1940s, with work on propeller blades, and composite structures for space applications were developed in the early 1960s. Since then, refinements in processes and equipment have resulted in some of the equipment addressed in this section.

Various forms of casting had their beginnings in antiquity. Gold objects were cast in 5000 B.C., and copper objects were cast some time later. From these beginnings, the technologies developed during World War II. These applications, using harder metals, depended on the development of new mold materials that could handle the newer metals.

Vacuum and environmental furnaces, as we know them today, developed from the furnaces used in the early 20th century to harden the blades and combs used in commercial applications. Other applications followed, ranging from bicycle and automotive parts to engine and weapons parts.

LIST OF MCTL TECHNOLOGY DATA SHEETS
12.1. ADVANCED FABRICATION AND PROCESSING

MCTL DATA SHEET 12.1-1. SPIN-, FLOW-, AND SHEAR-FORMING MACHINES

Critical Technology Parameter(s)	Having the following characteristics: equipped with numerical or computer controls; having > 2 axes (active or guiding) that have contouring control; and capable of applying a roller force > 60 kN.
Critical Materials	Mandrel; computer numeric(al) control (CNC).
Unique Test, Production, Inspection Equipment	Nondestructive test and inspection equipment to evaluate the end product.
Unique Software	Finite element methods for determining the manufacturing program; software algorithms for the control of the rollers and mandrels to obtain the desired shape.
Major Commercial Applications	Used in manufacturing cookware, wheels for automobiles, electrical fixtures, seamless cylinders, pipe fittings, turbine shafts, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; MTCR 3; NDUL 1.1; CCL 2B.

BACKGROUND

These processes form parts with rotational symmetry:

- **Spin-forming.** The material is formed on a spinning mandrel with no change in the thickness of the original blank.
- **Flow-forming.** This process involves rotating the object on a mandrel and using a forming tool to move metal from one location on the object to another, which results in variable thickness of the object.
- **Shear-forming.** The deformation is carried out by a roller on the spinning mandrel, and the thickness of the part is dependent on the angle and pressure of the roller.

MCTL DATA SHEET 12.1-2. SUPERPLASTIC FORMING/DIFFUSION BONDING (SPF/DB)

Critical Technology Parameter(s)	Capable of bonding certain alloys (primarily titanium, nickel, aluminum, and titanium aluminides) in a single heat cycle.
Critical Materials	Superplastic forming is most often used with aluminum, nickel, titanium, or titanium aluminides, either as bulk materials or as composites.
Unique Test, Production, Inspection Equipment	Mondestructive test and inspection equipment to evaluate the end product.
Unique Software	Software algorithms for the control of the parameters.
Major Commercial Applications	Structural panels, bridge structures, aircraft landing gears, turbine engine fan blades, and so forth.
Affordability Issues	SPF results in weight and cost savings in comparison with more conventional manufacturing methods, such as machining the solid.
Export Control References	WA 1B; CCL 1B.

BACKGROUND

The technologies:

- **SPF.** This technology uses the superplasticity properties of certain materials to produce parts of complex shape in a mold at high temperatures. It allows the formation of unique, complex shapes and the fabrication of components from a single piece of material. SPF material, including a range of materials (e.g., aluminum alloys, titanium, ceramics, and so forth) is used extensively in manufacturing airframes for military aircraft.
- **SPF/DB.** This is a manufacturing option for joining dissimilar superplastic materials and for making the components with critical property continuity requirements. Unlike other joining processes, the DB process preserves the base-metal microstructure at the interface. More importantly, no localized thermal gradient is present to induce distortion or to create residual stresses in the component.[1]

[1] Lawrence Livermore National Laboratory (LLNL) Web site: http://www.llnl.gov/.

MCTL DATA SHEET 12.1-3. VACUUM OR CONTROLLED-ENVIRONMENT INDUCTION FURNACES

Critical Technology Parameter(s)	Induction coils having a diameter □ 600 mm, capable of operating at temperatures >□850 °C, and designed for power inputs of 5 kW or greater.
Critical Materials	Vacuum system or controlled atmosphere.
Unique Test, Production, Inspection Equipment	Mondestructive test and inspection equipment to evaluate the end product.
Unique Software	Software algorithms for the control of the temperature, power, and vacuum.
Major Commercial Applications	Used in manufacturing high-grade steels (many commercial applications) and depleted uranium for use in counterweights, isotope shields, and radiographic cameras.
Affordability Issues	Not an issue.
Export Control References	NDUL 1.4; CCL 2B.

BACKGROUND

Vacuum or controlled-environment induction furnaces are used in melting, casting, and forging high-grade steel and other metals. Heating metal parts in a vacuum or a controlled environment is common practice wherever the prevention of surface oxidation or removal of surface contaminants (e.g., traces of lubricant) produces a justifiably improved surface.

MCTL DATA SHEET 12.1-4. VACUUM OR CONTROLLED-ATMOSPHERE METALLURGICAL MELTING AND CASTING FURNACES

Critical Technology Parameter(s)	Arc melt and casting furnaces with consumable electrode capacities > 1,000 cm^3 and < 20,000 cm^3 and operating at temperatures > 1,700 °C; electron-beam melting and plasma atomization and melting furnaces with power ≥ 50 kW and temperature > 1,200 °C.
Critical Materials	Vacuum system or controlled atmosphere.
Unique Test, Production, Inspection Equipment	Nondestructive test and inspection equipment to evaluate the end product.
Unique Software	Software algorithms for the control of the temperature, atmosphere, and power.
Major Commercial Applications	These furnaces are used in the production cycle for a very wide range of civil applications, including engine parts (automotive and aeronautic), cookware, bridge beams, and so forth.
Affordability Issues	Not an issue.
Export Control References	NDUL 1.8; CCL 2B.

BACKGROUND

Heating metal parts in a vacuum or a controlled environment is a common practice wherever the prevention of surface oxidation or removal of surface contaminants (e.g., traces of lubricant) produces a justifiably improved surface.

MCTL DATA SHEET 12.1-5. EQUIPMENT FOR PRODUCING PREPREGS BY THE HOT-MELT METHOD

Critical Technology Parameter(s)	Ability to manufacture the following prepregs: • Carbon, with a specific tensile strength $> 17 \times 10^4$ m and a specific modulus $> 10.15 \times 10^6$ m • Organic, with a specific modulus $> 12.7 \times 10^6$ m and a specific tensile strength $> 23.5 \times 10^4$ m • Inorganic, with a specific modulus $> 2.54 \times 10^6$ m and a melting, softening, or sublimation point > 1,922 K (1,649 °C).
Critical Materials	Specific fibers and resin for the composite material.
Unique Test, Production, Inspection Equipment	Test: Fourier Transform Infrared Spectroscopy; rheometrics.
Unique Software	Software algorithms for the control of the parameters.
Major Commercial Applications	Civil aircraft, automobiles, boats, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 1B; CCL 1B.

BACKGROUND

Prepregs are defined as reinforcing or molding material already impregnated with a synthetic resin. They are an essential constituent of composite materials. Hot-melt-method equipment is used to form these prepregs by impregnating fibers with a suitable resin. This process is followed by a curing process.

MCTL DATA SHEET 12.1-6. HOT ISOSTATIC PRESSES (HIPs)

Critical Technology Parameter(s)	A chamber cavity whose inside diameter is ≥ 406 mm and has a working pressure > 204 MPa; thermal environment > 1,500 K; or hydrocarbon impregnation and removal of gaseous products.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Nondestructive test and inspection equipment to evaluate the end product.
Unique Software	None identified.
Major Commercial Applications	Forming metallic and ceramic powders into billets or near-net shapes; densification of castings and weld joints to improve radiographic-quality mechanical properties and pressure tightness after machining; diffusion bonding of metals and ceramics; rejuvenation of service-affected components.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

The HIP is primarily used to eliminate voids in sintered electronic ceramic, making a more structurally sound unit. Densification of ceramic materials is achieved by means of temperature and pressure.

In HIPs, the pressurizing medium is typically either a gas or glass, and the process is carried out at elevated temperatures for specific time periods. HIP is used to densify parts fabricated by a cold isostatic press (CIP) or by more conventional methods, to heal casting defects and voids, to bond similar or dissimilar materials, and to form net or near-net shapes from metal, ceramic, cermet, and graphite powders.

MCTL DATA SHEET 12.1-7. SINGLE-CRYSTAL (SC) ALLOY CASTING EQUIPMENT

Critical Technology Parameter(s)	Capable of producing cooled turbine blades with stress rupture life exceeding 400 hours at 1,273 K (1,000 °C) at a stress of 200 MPa.
Critical Materials	Nickel alloys.
Unique Test, Production, Inspection Equipment	Investment casting equipment; X-ray equipment for examination of the final product.
Unique Software	CAD programs to design turbine-blade shape; software programs to control the time, temperature, pressure of the melt.
Major Commercial Applications	Commercial jet aircraft engines and industrial gas turbines.
Affordability Issues	Not an issue.
Export Control References	WA Cat 9B; CCL 9B.

BACKGROUND

SC alloy casting is a manufacturing process in which molten material is poured or injected into a mold (or cavity) and allowed to freeze and take the form of the mold. The cooling rate must be carefully controlled to produce SCs.

MCTL DATA SHEET 12.1-8. PYROLYTIC DEPOSITION EQUIPMENT

Critical Technology Parameter(s)	Ability to produce pyrolytically derived materials (e.g., pyrolytic graphite), from precursor gases which decompose in the 1,300 to 2,900 °C range, at pressures of 1 mm Hg to 150 mm Hg.
Critical Materials	Specific gases for the desired end product.
Unique Test, Production, Inspection Equipment	Each part to be fabricated requires special mandrels and flow nozzles. The deposition gases and rates of delivery are also specific to the part being produced. This very proprietary area is closely controlled by the manufacturer.
Unique Software	Software algorithms for the control of the parameters.
Major Commercial Applications	Sputtering targets, ion beam grids, crucibles for high-vacuum, ion-implant hardware, and so forth.
Affordability Issues	Not an issue.
Export Control References	MTCR 7; ITAR 121.16.

BACKGROUND

Pyrolytic deposition involves the decomposition of a gas and/or gases in a high-temperature furnace and their densification into a solid form on a mandrel or mold. It is often used in the formation of graphite. Pyrolytic graphite is a form of graphite manufactured by the decomposition of a hydrocarbon (most often, methane) at a very high temperature in a vacuum furnace. The result is an ultra pure, highly anisotropic product that is near the theoretical density.

MCTL DATA SHEET 12.1-9. COMPOSITE FILAMENT-WINDING EQUIPMENT

Critical Technology Parameter(s)	Two or more coordinated axes, including one linear and one rotary, so controlled that the filament can be laid on the mandrel in its predescribed patterns (similar equipment to composite tape-laying equipment).
Critical Materials	Mandrel; polyesters; vinyl esters; epoxies; carbon composite fiber; phenolics.
Unique Test, Production, Inspection Equipment	Nondestructive test and inspection equipment to evaluate the end product.
Unique Software	Software algorithms for the control of the parameters.
Major Commercial Applications	Drive shafts, tubing, pressure vessels, tool handles, golf clubs, bicycle forks, and so forth.
Affordability Issues	Products manufactured with this equipment are less expensive than products machined from metal. Filament winding is one of the most efficient techniques to produce high-quality, complex composite structures.
Export Control References	WA Cat 1B; CCL 1B; NSG 3.4; MTCR Item 6.

BACKGROUND

Filament winding consists of winding resin-impregnated fibers or rovings of glass, aramid, or other materials on a mandrel in predetermined patterns (including noncylindrical and nonspherical shapes), curing the resin, and removing the mandrel. This method provides great control over fiber placement and uniformity of structure. This technique results in a composite structure that is exceptionally strong and does not require the interior supports necessary for aluminum frames, thus resulting in a structure that offers more usable space within the structure.

MCTL DATA SHEET 12.1-10. COMPOSITE TAPE-LAYING EQUIPMENT

Critical Technology Parameter(s)	Two or more coordinated axes.
Critical Materials	Mandrel; polyesters; vinyl esters; epoxies; carbon composite fiber; phenolics.
Unique Test, Production, Inspection Equipment	Nondestructive test and inspection equipment to evaluate the end product.
Unique Software	Software algorithms for the control of the parameters.
Major Commercial Applications	Civil aircraft wing sections, nose cones for launch vehicles, automotive parts, sports equipment, and so forth.
Affordability Issues	Products manufactured with this equipment are less expensive than products machined from metal. Tape laying is one of the most efficient techniques for producing high-quality, complex composite structures.
Export Control References	WA Cat 1B; CCL 1B.

BACKGROUND

Tape-laying machines lay tape 75 mm to 150 mm wide with extreme precision along curved paths on a mandrel to create complex geometries. The tape is heated and compressed onto the mandrel to ensure the compactness of the final structure. This technique results in a composite structure that is exceptionally strong and does not require the interior supports necessary for aluminum frames, thus resulting in a structure that offers more usable space within the structure.

MCTL DATA SHEET 12.1-11. COMPOSITE WEAVING, STITCHING, OR INTERLACING EQUIPMENT

Critical Technology Parameter(s)	Ability to perform multidirectional and multidimensional weaving, stitching, or interlacing.
Critical Materials	Mandrel; polyesters; vinyl esters; epoxies; carbon composite fiber; phenolics.
Unique Test, Production, Inspection Equipment	Nondestructive test and inspection equipment to evaluate the end product.
Unique Software	Software algorithms for the control of the parameters.
Major Commercial Applications	Automotive, civil aircraft, boats, and other commercial applications.
Affordability Issues	Products manufactured with this equipment are less expensive than products machined from metal. Composite weaving and interlacing is one of the most efficient techniques to produce high-quality, complex composite structures.
Export Control References	WA Cat 1B; CCL 1B.

BACKGROUND

These machines are used in the first step in manufacturing composite structures. Fabrics (e.g., carbon-tow materials) are weaved or interlaced into the desired shape, and then stiffening elements are stitched into the skin. When the stitching is complete, the resin is added and autoclaved to form the final composite structure.

MCTL DATA SHEET 12.1-12. EQUIPMENT FOR MANUFACTURING MICROELECTROMECHANICAL DEVICES (MEMS)[2]

Critical Technology Parameter(s)	Ability to manufacture microelectromechanical devices with dimensions □ 1 □.
Critical Materials	Silicon wafers, thick photo resist; SiC substrates; piezoelectric thin films; thin-film polysilicon; ultra-pure gases.
Unique Test, Production, Inspection Equipment	Material removal and assembly equipment including lithography; electron and ion beam milling, grinding, etching, and polishing machines; CVD and etching equipment; and tooling and fixturing equipment, SEM, cluster tools, and molecular beam epitaxy, metal-organic chemical vapor deposition (MOCVD) equipment.
Unique Software	Software algorithms for the process, system, and package simulation.
Major Commercial Applications	MEMS devices and macro systems will have broad commercial applications ranging from biomedical, diagnostics, gyroscopes, automotive, robots, sensors, communications, and aerospace to printers.
Affordability Issues	MEMS devices will be smaller and consume less power than comparable parts and will also be able to be manufactured in bulk quantities, thus reducing the cost.
Export Control References	WA Cat 3B; CCL 3B.

BACKGROUND

"MEMS" means batch-fabricated miniature devices that convert physical parameters to or from electrical signals and that depend on mechanical structures or parameters for their operation. MEMS devices are fabricated using conventional semiconductor manufacturing equipment.

2 This includes lithography equipment; electron and ion beam milling, etching, grinding, and polishing machines; CVD equipment; and etching equipment.

MCTL DATA SHEET 12.1-13. RAPID PROTOTYPING MANUFACTURING (RPM)

Critical Technology Parameter(s)	This technology can be used not only to manufacture prototypes much faster than with more conventional techniques, but also to manufacture end products when only small quantities are required. Some early users of this technology report time reductions of 5 to 1 and cost reductions of 10 to 1. This is an ongoing program in a wide range of civil and military facilities. Another potential application is the manufacture of end products with varying material composition (e.g., gradient devices). This approach has the potential of significantly enhancing the material properties of military hardware.
Critical Materials	The materials depend on the RPM procedure used, including such materials as photopolymer epoxy resins, acrylates, polycarbonates, nylon, elastomers, certain metals, thermoplastics, polyester, ceramic powder, and so forth.
Unique Test, Production, Inspection Equipment	Laser stereolithography, laser sintering equipment, polymer extrusion equipment, printers, and computers (for CAD).
Unique Software	Simulation, modeling, and CAD programs.
Major Commercial Applications	Aerospace product that is produced in small volume; molds for items produced in large volume (e.g., automotive); superior materials for applications requiring improved mechanical properties (e.g., engine parts).
Affordability Issues	Allows for a quick fabrication of three-dimensional (3-D) prototypes of a design to allow the evaluation of the design before the beginning of production; allows rapid production of small volume products, spare parts, and so forth.
Export Control References	None identified.

BACKGROUND

Rapid prototyping is a process that automates the manufacture of 3-D, solid objects from raw materials. It is carried out through an “additive process” in which layers of the product are built up by one of at least three techniques: the deposition of a liquid that is solidified by light; the deposition of a solid material that is hardened by either a laser or a typical sintering process; or building up of the structure by using an adhesive-backed material.

SECTION 12.2—BEARINGS

Highlights
• Several types of bearings have significant military importance.
• High-speed bearings are essential in gas turbine engines and auxiliary equipment in ships, tanks, and aircraft.
• Antifriction bearings are necessary components of guidance equipment and other equipment where smoothness of motion is essential.
• Solid tapered roller bearings are used in applications that require radial and thrust load capacity (e.g., helicopter, tank, and truck drive trains).
• Active magnetic bearings are used in applications where reduced friction and mechanical wear are essential (e.g., inertial wheels, weapon tracking and pointing systems, and so forth).
• Aerostatic and hydrostatic bearings are used in applications where extremely low friction is required.

OVERVIEW

This section covers various types of bearings and the technology required for their development and manufacture. Bearing types have proliferated as the applications for their use have developed, particularly in advanced machines where the relative motion between two parts must occur smoothly, quietly, reliably, and with a long time between failures. In general, bearings can be categorized as either:

- **Sliding surface.** Sliding bearings can incorporate self-lubricating materials or introduce a lubricant between the moving parts. When load capacity is obtained because of the dynamic motion within the bearing, it is known as a hydrodynamic bearing.
- **Rolling-element.** Rolling bearings can use either balls, cylindrical rollers, tapered rollers, spherical rollers, or needle roller elements. The lubricant, bearing design, materials, and operating environment are usually important parameters in the development of a thin lubricant film between the rolling elements and the mating surfaces within the bearing.
- **Magnetic.** Magnetic bearings are manufactured using magnetic materials and operate in a mode in which the surfaces do not physically slide or roll on each other, but are separated by the strength of the magnetic field.

Bearings addressed in this section include the following types:

- **Sliding bearings.** Fluid film, gas film, and fabric lined.
- **Rolling element bearings.** Precision, hostile environment element antifriction, low-torque antifriction, and extreme precision.
- **Magnetic bearings.** Active.
- **Aerostatic bearings.** Extremely low-friction bearings.
- **Hydrostatic bearings.** Extremely low-friction bearings.

BACKGROUND

Bearings had their beginnings in ancient times. The Egyptians moved heavy stones and statues by sliding them on wooden planks. The planks were lubricated with water or some oil. This technique is known as friction bearings and is commonly used today in spindles and car engines. The more common roller bearings also had their start in antiquity when logs were placed under heavy loads, allowing the loads to move over the rolling logs. Later, wood rollers were used in the axles of carts. These wooden rollers were effective in reducing the effort to pull the cart but could not handle heavy loads. The advent of metal rollers and the further development of the techniques to produce spherical balls led to the rapid development of bearings.

LIST OF MCTL TECHNOLOGY DATA SHEETS
12.2. BEARINGS

MCTL DATA SHEET 12.2-1. HIGH-SPEED BEARINGS, BALL OR SOLID ROLLER, EXCEPT TAPERED

Critical Technology Parameter(s)	Having lubrication elements or modifications that enable operation at speeds >1.0 million DN.[3]
Critical Materials	Tungsten carbide; synthetic sapphire; Monel; beryllium; M50 NiL steel; Stellite; Inconel; beryllium copper; silicon nitride; lubricant.
Unique Test, Production, Inspection Equipment	Grinding, lapping, and honing machines and fixtures; gauging and metrology equipment for curved geometry measurement.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability Issues	Not an issue.
Export Control References	None identified.

BACKGROUND

The main components of a rolling bearing are the inner ring, the outer ring, the rolling elements, the cage, and the seals. The inner ring is mounted on the shaft of the machine and is, in most cases, the rotating part. The outer ring is mounted in the housing of the machine and, in most cases, does not rotate. The cage separates the rolling elements, preventing contact between them that would cause poor lubrication conditions during operation. Seals protect the bearing from contamination and are essential for a long and reliable life of the bearing. Bearings with integral seals are becoming increasingly popular.[4]

3 DN is where D is the diameter of the bore in mm and N is speed in rpm (i.e., diameter of the bearing in mm times the speed in rpm).

4 See http://www.skf.co.uk/Products/products1.htm.

MCTL DATA SHEET 12.2-2. LOW-TORQUE, ANTIFRICTION BEARING, BALL OR SOLID ROLLER, EXCEPT TAPERED

Critical Technology Parameter(s)	For 0.5 in. pitch-diameter bearings with 5×10^{-4} radial play, operate at slow speed (1–4 rpm) 400-g thrust load friction torque < 0.6 g/cm; for other sizes, loads, or clearances, a starting torque < 4,500 mg/mm.
Critical Materials	Stainless steel; super alloys; beryllium copper; ceramics; lubricant, and so forth.
Unique Test, Production, Inspection Equipment	Grinding, lapping, and honing machines and fixtures; gauging and metrology equipment for curved geometry measurement.
Unique Software	None identified.
Major Commercial Applications	Gyroscopes, tachometers, and so forth.
Affordability Issues	Not an issue.
Export Control References	None identified.

BACKGROUND

The main components of a rolling bearing are the inner ring, the outer ring, the rolling elements, the cage, and the seals. The inner ring is mounted on the shaft of the machine and is, in most cases, the rotating part. The outer ring is mounted in the housing of the machine and, in most cases, does not rotate. The cage separates the rolling elements, preventing contact between them that would cause poor lubrication conditions during operation. Seals protect the bearing from contamination and are essential for a long and reliable life of the bearing. Bearings with integral seals are becoming increasingly popular.[5]

[5] See http://www.skf.co.uk/Products/products1.htm.

MCTL DATA SHEET 12.2-3. PRECISION BALL BEARINGS AND SOLID ROLLER BEARINGS

Critical Technology Parameter(s)	Having tolerances of Annular Bearing Engineering Committee (ABEC) 9, ABEC 9P, International Standards Organization (ISO) Standard Class 2 or 2A, or better.
Critical Materials	Tungsten carbide; synthetic sapphire; Monel; beryllium; M50 NiL steel; 52100 steel Stellite; Inconel; beryllium copper or silicon nitride; lubricant.
Unique Test, Production, Inspection Equipment	Grinding, lapping, and honing machines and fixtures; gauging and metrology equipment for curved geometry measurement.
Unique Software	None identified.
Major Commercial Applications	Aerospace, precision machine tools, sensitive measuring equipment, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2A; CCL 2A.

BACKGROUND

The main components of a rolling bearing are the inner ring, the outer ring, the rolling elements, the cage, and the seals. The inner ring is mounted on the shaft of the machine and is, in most cases, the rotating part. The outer ring is mounted in the housing of the machine and, in most cases, does not rotate. The cage separates the rolling elements, preventing contact between them that would cause poor lubrication conditions during operation. Seals protect the bearing from contamination and are essential for a long and reliable life of the bearing. Bearings with integral seals are becoming increasingly popular.[6]

Bearings with a rating of ABEC 9 are precision bearings, and the term ABEC 9 refers to the tolerance standard of the bearing. ABEC 9 is the highest tolerance standard of the Annular Bearing Engineering Committee or ABEC. See the hyperlink for an explanation of the production.[7]

6 See http://www.skf.co.uk/Products/products1.htm.

7 See http://www.hooverprecision.homasregister.com/olc/hooverprecision/prodproc.htm.

MCTL DATA SHEET 12.2-4. BEARINGS, SOLID TAPERED ROLLER

Critical Technology Parameter(s)	Having tolerances of American National Standards Institute (ANSI)/Anti-Friction Bearing Manufacturers Association (AFBMA)/ISO Class 0 inch or ANSI/AFBMA Class B/ISO Class 4, or better, with lubrication elements allowing speeds > 0.5 million DN and a fracture toughness of 45 ksi square root inches; or Having tolerances of ANSI/AFBMA/ISO Class 0 inch or ANSI/AFBMA Class B/ISO Class 4, or better, for operation at temperatures < –54 °C or > 150 °C and having a fracture toughness of 45 ksi square root inches.
Critical Materials	Manufactured from M50 NiL steel, or silicon nitride, with lubrication elements allowing speeds > 2.3 million DN, and lubricant.
Unique Test, Production, Inspection Equipment	Grinding, lapping, and honing machines and fixtures; gauging and metrology equipment for curved geometry measurement.
Unique Software	None identified.
Major Commercial Applications	Heavy equipment drive trains, automotive drive trains, jet engine parts, and so forth.
Affordability Issues	Not an issue.
Export Control References	None identified.

BACKGROUND

The tapered roller bearings embody four basic components. These are the inner race (cone), the outer race (cup), tapered rollers, and a cage (roller retainer). Under normal operating conditions, the inner race, outer race, and rollers carry the load while the cage spaces and retains the rollers. The inner race roller and cage are referred to as the “inner race assembly,” and this is usually separable from the outer race, facilitating equipment build.

The extensions of the raceways and rollers of a tapered roller bearing are designed to converge at a common point on the axis of rotation. This results in true rolling motion of the rollers on the raceways at every point along the roller body. The angled raceways allow the tapered roller bearing to carry combinations of radial and thrust loads. The greater the angle between the outer race and bearing centerline, the greater the ratio of thrust to radial load capacity. Long line roller/race contact gives the tapered roller bearing a high load-carrying capacity. This and the capability to carry radial loads, thrust loads, or any combination of the two make tapered roller bearings an ideal choice for many applications. For a given bore, selecting an especially light or heavy section to meet application load/duty requirements is possible.[8]

[8] Industrial Technology, http://www.industrialtechnology.co.uk/1998/jun/timken.html.

MCTL DATA SHEET 12.2-5. BEARINGS, NEEDLE ROLLER

Critical Technology Parameter(s)	Having a fracture toughness of 45 ksi square root inches.
Critical Materials	M50 NiL steel; lubricant.
Unique Test, Production, Inspection Equipment	Grinding, lapping, and honing machines and fixtures; gauging and metrology equipment for curved geometry measurement.
Unique Software	None identified.
Major Commercial Applications	Automotive; consumer products; construction; agriculture; general industrial goods.
Affordability Issues	Not an issue.
Export Control References	None identified.

BACKGROUND

Needle roller bearings are similar to cylindrical roller bearings but have long, thin rollers, which gives them a very compact cross section. These bearings are lightweight and small in size but have high rigidity and a great load capacity.

MCTL DATA SHEET 12.2-6. BEARINGS, GAS-LUBRICATED FOIL

Critical Technology Parameter(s)	Operation at temperatures > 288 °C and a unit load capacity > 15 psi (1 MPa).
Critical Materials	Gas (e.g., helium); lubricant.
Unique Test, Production, Inspection Equipment	Grinding, lapping, and honing machines and fixtures; gaging and metrology equipment for curved geometry measurement.
Unique Software	None identified.
Major Commercial Applications	General aviation small turbine engines, cryogenic turbopumps, pipeline compressors, machine tools, and so forth.
Affordability Issues	Not an issue.
Export Control References	None identified.

BACKGROUND

In gas-lubricated foil bearings, the shaft rests on the bearing housing only at rest. As the shaft begins to rotate, it is lifted from touching the outer shell and rotates free of the friction of normal bearing systems. As a result, foil bearings have been reported to operate at greater than 2.5 million DN. Although foil bearings are presently used only in certain applications, research is continuing to improve the load capacity of the bearings.

MCTL DATA SHEET 12.2-7. BEARINGS, ACTIVE MAGNETIC

Critical Technology Parameter(s)	Having flux densities of 2.0 Teslas, or greater and yield strengths > 414 MPa; having all electromagnetic 3-D homopolar bias designs for actuators; or having high-temperature position sensors [450 K (177 °C) or higher].
Critical Materials	High-saturation flux-density magnetic materials (e.g., Vanadium Permandur, Hiperco□27).
Unique Test, Production, Inspection Equipment	Grinding, lapping, and honing machines and fixtures; gauging and metrology equipment for curved geometry measurement.
Unique Software	None identified.
Major Commercial Applications	Turbomachinery, auxiliary power units, machine tools, vacuum systems, trains, gas turbine engines, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2A; CCL 2A.

BACKGROUND

In magnetic bearings, the rotating element does not contact the stator during operation. The rotor (ferromagnetic) is levitated by the action of a series of electromagnets so that the rotor is free to rotate in free-space, thus reducing friction and mechanical wear.

MCTL DATA SHEET 12.2-8. AEROSTATIC BEARINGS

Critical Technology Parameter(s)	Quantitative parameters have not been published; however, such bearings should run longer, with more precision, at either high or low speeds, with significantly reduced noise. Stiffness is a present problem that is being researched.
Critical Materials	Gas to maintain pressure within the bearing structure.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	CAD of bearing structure.
Major Commercial Applications	Machine tools, linear aerostatic bearings for use in positioning systems, inspection equipment (e.g., CMMs), and so forth.
Affordability Issues	High-speed spindles for machine tools.
Export Control References	None identified.

BACKGROUND

In aerostatic bearings, gas is supplied through an opening in the bearing case and into the bearing gap. The pressure inside the gap creates the load carrying properties that maintain spacing between the rotating bearing and the bearing case. As a result, aerostatic bearings do not suffer from friction-induced wear and do not experience starting and stopping friction.

Their primary application is in precision machines. In some areas, their application is limited because of their inherent stiffness (e.g., they are used in diamond turning machines, microgrinders, and coordinate measuring machines but have limited use in standard milling and turning machines). Much effort is being expended worldwide to solve the stiffness limitation. If the research is successful and the product reaches the machine tool industry (aerostatic bearings are in competition with hydrostatic bearings for this application), their use would result in higher speed spindles.

MCTL DATA SHEET 12.2-9. HYDROSTATIC BEARINGS

Critical Technology Parameter(s)	Quantitative parameters have not been published; however, such bearings should run longer, with more precision, with greater stiffness (> 100 psi) and damping capability, at either high or low speeds, all with significantly reduced noise. The development of these bearings is an important step in the development of 75,000 to 100,000 rpm spindles.
Critical Materials	Liquid to maintain pressure within the bearing structure.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	CAD programs for 2-D and 3-D designs.
Major Commercial Applications	Machine tools, turbo pumps, air conditioners, telescope mounts, gear systems in helicopters, engines, and so forth.
Affordability Issues	Affordability issues include reduced maintenance and the application to high-speed spindles for machine tools.
Export Control References	None identified.

BACKGROUND

In hydrostatic bearing systems, a fluid, usually oil, is pumped into the bearing case, and the pressure of the fluid centers the rotating shaft within the bearing structure. This results in no wear on internal parts. In addition, because of the inherent high damping ratio of the oil, hydrostatic bearings can be used in applications where the ability to support large weights is important (large telescope mounts) and where better surface finishes are required in a machining operation. These spindles also have a very high stiffness, so they can be used in milling and turning machine tools.

SECTION 12.3—METROLOGY

Highlights

- Coordinate measuring machines provide the capability to inspect not only standard shapes and sizes, but also a wide range of irregular shapes, such as gears, camshafts, and so forth.
- Linear and angular displacement equipment is critical for measuring small, very precise parts before these parts are assembled into the hardware.
- Equipment for measuring optical properties is essential for applications such as laser mirrors and infrared (IR) guidance systems, where the spectral characteristics are important.

OVERVIEW

This section covers the technologies for dimensional measuring systems and the equipment needed for the precise determination of the dimensions of manufactured parts, machine tools, and inspection machines. Included are systems for in-process measurement and post-manufacture inspection. This technology area is of paramount importance for the construction of systems incorporating mechanical or electrical components built to exacting tolerances, whether such hardware is military or civil. This technology area is highly dependent on sensors, positioners, feedback systems, digital computers, and associated components and hardware. Included in the list of metrology equipment are coordinate-, linear-, and angular-measurement machines, using laser, standard light, photogrammetry, and noncontact techniques. The tolerances of parts measured range from ±1 nm (corresponding to an optical surface finish prepared by diamond turning, with ion-beam polishing) to ±10 μm (corresponding to more traditional metal machining).

BACKGROUND

The reliability of military hardware depends on the quality of the manufacturing processes that produces the hardware. Sophisticated equipment has been developed to inspect hardware during the manufacturing process and to inspect the finished hardware. Such inspections are critical to guarantee not only the delivery of a usable and reliable product, but also to guarantee that spare parts will have the same proper fit-and-function as that of the original equipment.

LIST OF MCTL TECHNOLOGY DATA SHEETS
12.3. METROLOGY

MCTL DATA SHEET 12.3-1. COORDINATE MEASURING MACHINE (CMM)

Critical Technology Parameter(s)	Having ≥ two axes and a one-dimensional (1-D) length measurement uncertainty 1.25μm.
Critical Materials	Granite base; CNC of coordinating axes, slides, and rails, and feedback systems.
Unique Test, Production, Inspection Equipment	Laser interferometer measuring equipment with accuracies < 1 μm.
Unique Software	Software algorithms for controlling the measuring tool and for comparing the measured values against the design values.
Major Commercial Applications	Most civil hardware, either on every piece or on a sample basis.
Affordability Issues	An affordability issue because the use of metrology equipment reduces the probability of “out-of-spec” material being incorporated into hardware.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

A CMM is a programmable robotic device with a sensor that accurately records dimensional data at predetermined points on a manufactured part. The sensor can be a “ouch-probe, non contact probe, or a laser.

MCTL DATA SHEET 12.3-2. LINEAR AND ANGULAR DISPLACEMENT MEASURING DEVICES

Critical Technology Parameter(s)	Non-contact type with a resolution ≥ 0.2 μm within a measuring range of 0.2 mm. Having a linear voltage differential transformer system with both of the following: 1. Linearity of 0.1% or better within a range of up to 5 mm. 2. Drift of 0.1% or better per day at a test temperature of ±1 K. Having all of the following and laser: 1. Maintaining for at least 12 hours, over a temperature range of ±1 K around a standard temperature and a standard pressure, both of the following: a. A resolution over their full scale of 0.1 μm or less. b. A measurement uncertainty ≤ 0.2 + L/2000:m (L is the measured length in millimeters).
Critical Materials	CNC of coordinating axes, slides, and rails, and feedback systems.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software algorithms for controlling the measuring tool and comparing the measured values against the design values.
Major Commercial Applications	Metrology equipment is used in manufacturing most civil hardware, either on every piece or on a sample basis.
Affordability Issues	An affordability issue because the use of metrology equipment reduces the probability of “out-of-spec” material being incorporated into hardware.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

Linear and angular displacement equipment is critical for measuring small, very precise parts before these parts are assembled into the hardware. Metrology equipment is used in manufacturing most civil hardware, either on every piece or on a sample basis.

MCTL DATA SHEET 12.3-3. METROLOGY EQUIPMENT FOR SPECTRAL CHARACTERIZATION OF REFLECTANCE, TRANSMISSION, ABSORPTION, AND SCATTER

Critical Technology Parameter(s)	Capable of measuring reflectance/transmission to better than 1 part in 1,000 with absolute accuracy or absorption/scatter to better than 1 part in 100,000 with absolute accuracy.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Most equipment with these capabilities requires computer control with specific algorithms to control its performance.
Major Commercial Applications	Nonmilitary space optics, laser mirrors, telescope optics, and so forth.
Affordability Issues	Not an issue.
Export Control References	None identified.

BACKGROUND

Optical coatings are used on a wide range of military hardware, including space-surveillance optical elements, laser mirrors, domes, IR guidance systems, coatings for laser eye protection, and so forth. The metrology equipment necessary to maintain quality control of these coatings is critical.

MCTL DATA SHEET 12.3-4. LASER LOCATION SYSTEMS

Critical Technology Parameter(s)	Automated, laser measuring system that uses optical triangulation to achieve high accuracy of 3-D positions, with the capability to measure ≥ 15 points per second.
Critical Materials	Lasers, optical mirrors, and so forth.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Most equipment with these capabilities requires computer control with specific algorithms to control its performance.
Major Commercial Applications	None identified.
Affordability Issues	Not an issue.
Export Control References	None identified.

BACKGROUND

Optical triangulation requires three parts: a light source (e.g., a laser), sensors, and electronic instrumentation. The laser light is projected onto an object at a known angle and is reflected back to the sensors. It is then sent to a signal processor. As the source and sensors are spatially changed relative to the object, the output is a 3-D presentation of the object.

SECTION 12.4—NONDESTRUCTIVE INSPECTION (NDI) EQUIPMENT

Highlights

- Used to analyze material properties and to locate and characterize flaws within materials, fabricated parts, and assemblies.
- Used also to examine the internal and external condition of materials, fabricated parts, and assemblies.
- Results in an increase in the quality and reliability of delivered hardware.

OVERVIEW

This section covers technologies for the nondestructive detection and characterization of flaws, such as cracks, porosity, inclusions, and delaminations and for the nondestructive measurement or prediction of mechanical properties, such as bond strength or elastic moduli in materials, components, or structures. The technologies also involve the means for interpreting the significance of detected flaws so that either an immediate accept/reject decision can be made, or changes can be made to correct a flawed or out-of-control process. In many instances, these technologies provide the basis for the design, determination of reliability, and maintenance requirements for military systems, including ordnance, vehicles, ships, submarines, aircraft, and missiles.

BACKGROUND

The optimal use of structural materials, as well as the introduction of high-performance systems for military applications, depends the ability to detect and characterize strength-limiting flaws and defects. The technologies addressed in this section are used in developing new materials and in manufacturing hardware. They are unsurpassed in detecting problems in design and manufacture and in minimizing latent failures in delivered hardware systems (i.e., they minimize the risk of structure failure by permitting rapid, accurate, and cost-effective testing). The technology makes possible the calculation of fracture residual-life prediction and, on occasion, the life extension of mechanically critical components in aircraft, ships, and vehicles, thus enhancing military readiness.

LIST OF MCTL TECHNOLOGY DATA SHEETS
12.4. NONDESTRUCTIVE INSPECTION (NDI) EQUIPMENT

MCTL DATA SHEET 12.4-1. DIGITAL SHEAROGRAPHY

Critical Technology Parameter(s)	Provides a large area, quantitative analysis of stress concentrations that result from the vibration of a structure or exist in composite materials in aging aircraft. Inspection speed of an order-of-magnitude higher than conventional ultrasonic techniques.
Critical Materials	Lasers, CCD cameras, and so forth.
Unique Test, Production, Inspection Equipment	Laser system; charged-coupled device (CCD) camera; image processor.
Unique Software	Software algorithm to process information.
Major Commercial Applications	Useful in a wide range of commercial hardware, particularly aging aircraft.
Affordability Issues	Improved shearography would result in reduced costs for performing some NDI tests.
Export Control References	None identified.

BACKGROUND

Digital shearography is a laser-based digital interferometry system that uses full-field observation (i.e., does not require scanning). It is used to detect stress concentrations caused by anomalies in materials.

MCTL DATA SHEET 12.4-2. ULTRASOUND NONDESTRUCTIVE TESTING

Critical Technology Parameter(s)	Ability to scan test material with air-coupled transducers and detect imperfections of >□0 mm.
Critical Materials	Sound transmitter; sensors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software algorithm to process information.
Major Commercial Applications	Similar to the military, but in commercial hardware (e.g., composite structures: quality control of commercial aircraft, automobiles, tires, concrete, and so forth; bearings: pumps, machine tool spindles, and so forth).
Affordability Issues	Improved quality and reliability are indirect cost savings.
Export Control References	None identified.

BACKGROUND

Ultrasonic testing uses the transmission of high-frequency sound waves into a material to detect imperfections within the material.

MCTL DATA SHEET 12.4-3. DIGITAL HOLOGRAPHIC NONDESTRUCTIVE TESTING

Critical Technology Parameter(s)	Real-time processing of information (< 5 s); resolution (in plane) 0.1 mm; and resolve stress strain of < 2,000 psi.
Critical Materials	Laser light source; sensors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software algorithm to process information.
Major Commercial Applications	Stress measurement of bolting two parts together (engine block); identification of disbanding, cracks, or delamination flaws in composites, tires, and so forth; vibrational analysis of automotive disk brakes and jet engine turbine wheels); determination of corrosion.
Affordability Issues	Improved quality and reliability are indirect cost savings.
Export Control References	None identified.

BACKGROUND

Optical holography is an imaging technique that records the amplitude and phase of laser light reflected from an object as an interferometric pattern, thus allowing a 3-D image of the object. When used as a nondestructive testing tool, two holographic images are taken—one before a stress is applied to the object and one after a stress is applied to the object. The resulting interference pattern reflects the deformation caused by the stress and defects that result in distortions of the pattern, either on the surface or subsurface. It can be also used with film as a recoding medium or with a detector (e.g., a CCD) and a computer. In the latter, it is referred to as digital holography.

MCTL DATA SHEET 12.4-4. COMPUTED TOMOGRAPHY (CT)

Critical Technology Parameter(s)	Resolution—< 5 µm; capable of imaging steel objects up to 8 in. thick.
Critical Materials	X-ray source; sensors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software algorithm to process information.
Major Commercial Applications	Medical applications (X-ray scans of the human body); mapping voids in castings; inspection of composite material for impact damage; measurement of variations in density of solid objects; inspection of high explosives; inspection of pressure vessels for cracks and voids around welds.
Affordability Issues	Improved quality and reliability are indirect cost savings.
Export Control References	None identified.

BACKGROUND

CT was first used, and is still extensively used, in the medical profession and is normally referred to as a “Cat-Scan.” CT inspection produces a 2-D density map of a cross-sectional slice of an objects interior. To accomplish this, a beam of penetrating radiation (X-ray) is projected through an object and is detected by multiple detectors that count photon interaction between the radiation and the object matter. This scan data, taken in small electronic slices, is then reconstructed. Information of the internal part of the object under study can be determined. CT provides important benefits for industrial NDT&E.

SECTION 12.5—PRODUCTION EQUIPMENT

Highlights

- The equipment and software in this section are the workhorses in reducing raw material, metals, composites, and ceramics into a final product.
- Ultra-precision machine tools are critical for manufacturing military items that require the greatest precision.
- Multitasking machines can reduce costs and increase the accuracy of the final product.

OVERVIEW

This section addresses machine tools used for the production of military systems and components. The individual machine tools provide the foundation of a manufacturing base. The equipment includes both numerically controlled (NC) and non-NC machines. NC machines are computer controlled so that the motions of the various axes are simultaneously and continually coordinated, thereby maintaining a predetermined (programmed) path. This includes turning, milling, and grinding machines, electrical discharge machines, water and liquid jet machines, and electron beam and laser cutting machines. The non-NC machines include single-point diamond cutting and fly-cutting machine tools. Such tools have wide application in the production of optical-quality surfaces.

BACKGROUND

Modern weapon systems require a variety of production equipment to manufacture the necessary components. For example, turning, milling, and grinding machines are required for fabrication a range of items, from large structures to small parts for gyroscopes, engine parts, and so forth. This equipment has matured over the years, moving from manual machines to computer-controlled machines, from low-speed spindles to high-speed machining, and from machines with rather coarse accuracy to machines with accuracies in the low-micrometer range.

LIST OF MCTL TECHNOLOGY DATA SHEETS
12.5. PRODUCTION EQUIPMENT

MCTL DATA SHEET 12.5-1. MILLING MACHINE WITH FIVE OR MORE AXES FOR REMOVING OR CUTTING METALS, CERAMICS, OR COMPOSITES

Critical Technology Parameter(s)	Five or more axes that have simultaneous contouring control, including rotary axes.
Critical Materials	CNC of coordinating axes, rotary axis, rotary table, slides and rails, and feedback systems.
Unique Test, Production, Inspection Equipment	Circular and irregular path measuring equipment and ballbar to measure the positioning accuracy of the machine tool.
Unique Software	Software for CNC.
Major Commercial Applications	Used in manufacturing a very wide range of civil items (e.g., commercial aircraft, automobiles, farm equipment, and so forth).
Affordability Issues	Not an issue. However, the use of four- and five-axes machines can often reduce the costs of machining parts with three-axes machines.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

Milling is the process of producing machined surfaces by progressively removing a predetermined amount of material from the work piece. The material is removed by a rotating cutting tool and, in modern milling machines, both the work piece and the cutting tool can be moved in several directions (axes). The work piece is situated on a table that may be capable of being rotated or tilted. The cutting tool is mounted in a spindle that has X, Y, and Z coordinate motion and may be capable of being tilted in one or two perpendicular directions.

MCTL DATA SHEET 12.5-2. MILLING MACHINE WITH THREE LINEAR AXES AND EITHER ONE ROTARY AXIS OR A ROTATING TABLE, FOR REMOVING OR CUTTING METALS, CERAMICS, OR COMPOSITES

Critical Technology Parameter(s)	Three linear axes (X, Y, Z), plus either one rotary axis or a rotating table, which have simultaneous contouring control and either: 1. A positioning accuracy of better than 6.0 µm (ISO 230/2). 2. An aerostatic spindle.
Critical Materials	CNC of coordinating axes, rotary axis, rotary table, slides and rails, and feedback systems.
Unique Test, Production, Inspection Equipment	Circular and irregular path measuring equipment and a ballbar to measure the positioning accuracy of the machine tool.
Unique Software	Software for CNC.
Major Commercial Applications	Used in manufacturing a very wide range of civil items (e.g., commercial aircraft, automobiles, farm equipment, and so forth).
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

Milling is the process of producing machined surfaces by progressively removing a predetermined amount of material from the work piece. The material is removed by a rotating cutting tool and, in modern milling machines, both the work piece and the cutting tool can be moved in several directions (axes). The work piece is situated on a table that may be capable of being rotated or tilted. The cutting tool is mounted in a spindle that has X, Y, and Z coordinate motion and may be capable of being tilted in one direction.

MCTL DATA SHEET 12.5-3. TURNING MACHINE WITH TWO OR MORE AXES FOR REMOVING OR CUTTING METALS, CERAMICS, OR COMPOSITES

Critical Technology Parameter(s)	Two or more axes that have simultaneous contouring control and a positioning accuracy or better than 6.0 µm (ISO 230/2).
Critical Materials	CNC of coordinating axes, slides and rails and feedback systems.
Unique Test, Production, Inspection Equipment	Circular and irregular path measuring equipment and ballbar to measure the positioning accuracy of the machine tool.
Unique Software	Software for CNC.
Major Commercial Applications	Used in manufacturing a very wide range of civil items (e.g., commercial aircraft, automobiles, farm equipment, and so forth).
Affordability Issues	Most CNC two- and three-axis machines have the ability for automatic tool changing. This significantly reduces the machining time.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

The turning machine (lathe) can be designed to operate as either a horizontal or a vertical machine. The part is rotated against a tool that can be moved along the axis of the part, cutting to a programmed depth. The lathe is primarily used to cut parts with a circular cross section; however, with the addition of live tooling and a third axis, cutting flat sections is possible.

MCTL DATA SHEET 12.5-4. ULTRA-PRECISION MACHINE TOOLS: SINGLE-POINT DIAMOND TURNING (SPDT) MACHINES, FLY-CUTTING MACHINES, AND MICROGRINDERS

Critical Technology Parameter(s)	SPDT machines capable of producing a surface finish of 0.01 µm R_a or better; fly-cutting machines capable of producing a surface finish of 0.01 µm R_a or better; microgrinders capable of producing a surface finish of 0.01 µm R_a or better.
Critical Materials	CNC of coordinating axes, aerostatic or hydrostatic spindles, and feedback systems.
Unique Test, Production, Inspection Equipment	Circular and irregular path measuring equipment and ballbar to measure positioning accuracy of machine tool.
Unique Software	Software for CNC.
Major Commercial Applications	Used in manufacturing lasers, lenses for lithographic equipment, civil space systems, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

This entry describes three different types of machines:

- **The SPDT.** The SPDT can operate as either a horizontal or a vertical machine. The substrate rotates under the diamond point. The diamond point is moved up and down as it moves across the rotating surface, resulting in a preprogrammed surface. The diamond turning machine can cut spherical or aspherical shapes. It cannot be used on glass.
- **The fly-cutting machine.** The fly-cutting machine operates as a vertical machine. It is used to impart extremely smooth surfaces on flat surfaces (i.e., it does not do contouring).
- **The microgrinder.** The microgrinder uses a deterministic or magnetorheological approach to producing spherical or aspherical surfaces on optical substrates. The microgrinders can be used on glass.

MCTL DATA SHEET 12.5-5. DEEP-HOLE DRILLING MACHINES

Critical Technology Parameter(s)	Computer controlled and having a maximum depth-of-bone > 5,000 mm.
Critical Materials	CNC of coordinating axes, slides and rails, and feedback systems.
Unique Test, Production, Inspection Equipment	Circular and irregular path measuring equipment and ballbar to measure positioning accuracy of machine tool.
Unique Software	Software algorithms for the control of the parameters.
Major Commercial Applications	Power generators; off-road equipment; nuclear research, marine systems; hydraulic cylinders.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

Deep-hole drilling machines are capable of drilling cylinder type end products that have length to diameter ratios in the range of 30:1 to 50:1.

MCTL DATA SHEET 12.5-6. GRINDING MACHINE WITH THREE OR MORE AXES, FOR REMOVING OR CUTTING METALS, CERAMICS, OR COMPOSITES

Critical Technology Parameter(s)	Two or more axes that have simultaneous contouring control and a positioning accuracy < 4 μm.
Critical Materials	CNC of coordinating axes, rotary axis, rotary table, slides and rails, and feedback systems.
Unique Test, Production, Inspection Equipment	Circular and irregular path measuring equipment and ballbar to measure positioning accuracy of machine tool.
Unique Software	Software for CNC.
Major Commercial Applications	Most all parts created by a machining process have a grinding operation as one of the final steps. This would include parts for commercial aircraft, automobiles and trucks, impellers for pumps, ship propellers, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

Grinders are power-operated machines designed with abrasive wheels or discs for grinding metals, ceramics, or composites.

MCTL DATA SHEET 12.5-7. ELECTRODISCHARGE MACHINES OF WIRE-FEED TYPE

Critical Technology Parameter(s)	Five or more axes for contour control.
Critical Materials	CNC of coordinating axes, rotary axis, and feedback systems.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software for CNC.
Major Commercial Applications	Turbine discs; gears; dies; motor components; medical devices; molds; stamping dies; extrusion dies; forging dies; tool fixtures; gauges.
Affordability Issues	Not an issue.
Export Control References	CCL 2B.

BACKGROUND

Electrical discharge machining (EDM) is a high-precision metal-removal process that uses an electrical discharge from a thin wire to vaporize and achieve fine cuts through hard metal parts.

MCTL DATA SHEET 12.5-8. ELECTRODISCHARGE MACHINES OF NONWIRE TYPE

Critical Technology Parameter(s)	Two or more rotary axes that can be coordinated simultaneously for contour control.
Critical Materials	CNC of coordinating axes and feedback systems.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software for CNC.
Major Commercial Applications	Aircraft part production; medical parts; molds; stamping dies; extrusion dies; forging dies; tool fixtures; gauges.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

EDM is a high-precision metal-removal process that uses thermal energy from a fine, accurately controlled electrical discharge (spark) to erode (vaporize) metals. In the EDM plunge (or ram) process, the inverted image of the tool electrode is gradually impressed in the workpiece. EDM is particularly effective in machining very hard materials.

MCTL DATA SHEET 12.5-9. MACHINE TOOLS FOR REMOVING METALS, CERAMICS, OR COMPOSITES BY MEANS OF WATER, OTHER LIQUID JETS, ELECTRON-BEAM (E-BEAM), OR LASER BEAM

Critical Technology Parameter(s)	Two or more rotary axes that can be coordinated simultaneously and have a positioning accuracy of better than 0.003 deg.
Critical Materials	Computer control of the coordinating axes; water-jet machining: high-pressure water source, abrasive material (when required); laser machining: CO_2 or Nd:YAG lasers.
Unique Test, Production, Inspection Equipment	Circular and irregular-path measuring equipment and ballbar to measure positioning accuracy of machine tool.
Unique Software	Software for CNC.
Major Commercial Applications	Automotive, aerospace, pump components, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

A "waterjet" cutting system uses a narrow stream of water under extremely high pressure to "erode" a precise and narrow path through material to be cut. A cutting table placed over a capture/recycling tank holds the workpiece in place while a cutting nozzle directs a water stream that impacts material at speeds faster than the speed of sound. The entire cutting assembly travels along a CNC track that is controlled by CAD software. Nonmetals and relatively soft materials can be cut using pure water. For harder materials, such as metals and stone, a garnet abrasive is added to the water to augment its cutting ability.

In an E-beam cutting tool, electrons are accelerated to a high velocity and focused on the substrate to be machined. The heat generated by the E-beam melts the target, removing small amounts of the substrate. E-beams must be used in a vacuum and, as a result, are limited to the machining of small items.

A laser beam is a high-intensity beam of light that can be tightly focused onto a spot only 0.005 in. in diameter. Laser light is produced by passing electrical energy through a lasing medium. In gas lasers, CO_2 is mixed with helium and nitrogen to make the lasing medium. In solid-state lasers, yttrium-aluminum-garnet (YAG) crystals containing neodymium ions are used as the medium.

Laser processing systems are made of five basic components: the laser, beam-focusing optics, the material-handling system, the heat exchanger, and the control computer. The heat exchanger cools the laser and optical components.

Cutting is material removal in one or more axes to produce material separation. Many machines of this type have only X, Y, and Z axes and are used, to a great extent, in cutting plates or drilling holes in plates. However, some equipment has an additional rotary axis, giving them five-axis capability. This facilitates the manufacture of 3-D structures.

MCTL DATA SHEET 12.5-10. SPINDLE ASSEMBLIES, CONSISTING OF SPINDLES AND BEARINGS, SPECIALLY DESIGNED FOR MACHINE TOOLS

Critical Technology Parameter(s)	Run-out or camming < 0.0006 mm (0.6 μm) in one revolution of the spindle.
Critical Materials	ABEC 9 bearings; aerostatic bearings; hydrostatic bearings; lubricant.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Very accurate machine tools; coordinate measuring machines; astronomical telescope movements.
Affordability Issues	Not an issue.
Export Control References	CCL 2B.

BACKGROUND

Spindles are the mechanism that both holds a cutting tool in a machine tool and rotates, thus imparting a cutting (machining) capability to the machine. Spindles can use ball bearing, aerostatic, or hydrostatic support. Aerostatic and hydrostatic bearings are primarily used on precision machines.

MCTL DATA SHEET 12.5-11. LINEAR POSITION FEEDBACK UNITS (e.g., INDUCTIVE-TYPE DEVICES, GRADUATED SCALES, OR LASER SYSTEMS)

Critical Technology Parameter(s)	An overall accuracy < $[(800 + (600 \times L \times 10^{-3}]$ nm, where L is the effective length in millimeters.
Critical Materials	Accurately ruled substrates.
Unique Test, Production, Inspection Equipment	Equipment to make the scale masters and to measure the graduations.
Unique Software	None identified.
Major Commercial Applications	Motion control of machine tools, inspection equipment, semiconductor manufacturing equipment, radio and optical telescopes, radar pedestals, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

A linear encoder consists of a linear scale, made of glass or tape, a light source, and a photoreceptor. It works on the principle of counting pulses as a series of graduations that move past a detector. This device is used to convert linear position information into an electrical output signal that is used to control the movement and position an object.

MCTL DATA SHEET 12.5-12. ROTARY POSITION FEEDBACK UNITS (e.g., INDUCTIVE-TYPE DEVICES, GRADUATED SCALES, OR LASER SYSTEMS)

Critical Technology Parameter(s)	An accuracy < 0.00025 deg.
Critical Materials	Accurately produced radial gratings.
Unique Test, Production, Inspection Equipment	Equipment to make the scale masters and to measure the graduations.
Unique Software	None identified.
Major Commercial Applications	Motion control of machine tools and inspection equipment.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

Rotary encoders are used in machine tools to control the motion of the ball screw from the servo drive and to control the movement of a rotary head and in metrology equipment to control the movement of the measuring apparatus, with the goal of providing a superior positioning accuracy of the machine. These encoders operate by converting a pattern on a rotary disc into an electrical signal that can be processed to determine angular position.

MCTL DATA SHEET 12.5-13. LINEAR GUIDE ASSEMBLIES FOR MACHINE TOOLS AND INSPECTION EQUIPMENT

Critical Technology Parameter(s)	Yaw, pitch, or roll < 2 sec. of arc total indicated reading (TIR); horizontal straightness < 2 mm/300 mm length; and vertical straightness < 2 mm/300 mm length.
Critical Materials	Precision bearings; surface finish; no backlash.
Unique Test, Production, Inspection Equipment	Bearing manufacturing equipment; fine lapping; polishing machines.
Unique Software	None identified.
Major Commercial Applications	Machine tools and precision inspection equipment.
Affordability Issues	Not an issue.
Export Control References	None identified.

BACKGROUND

Linear guides are used in machine tools to control the movement of the machine body, with the goal of providing a superior positioning accuracy of the machine. They provide smooth, low-friction rolling motion, with added rigidity and interchangeable components.

MCTL DATA SHEET 12.5-14. DIAMOND CUTTING TOOL INSERTS

Critical Technology Parameter(s)	Flawless and chip-free cutting edge when magnified 400 times; cutting radius from 0.1–0.5 mm, inclusive; cutting radius out-of-roundness < 0.002 mm TIR.
Critical Materials	Industrial diamond.
Unique Test, Production, Inspection Equipment	Inspection equipment to examine the quality of the tool cutting edge.
Unique Software	None identified.
Major Commercial Applications	High-speed machining; machining of graphite; machining of optical materials.
Affordability Issues	Use of a diamond cutting tool can speed up the machining of aluminum.
Export Control References	None identified.

BACKGROUND

Diamond cutting tool inserts are used in single-point diamond turning machines and are critical components in producing products that have mirror-like surfaces and in various machining applications, such as machining of graphite and high-speed machining.

MCTL DATA SHEET 12.5-15. SOFTWARE FOR ELECTRONIC DEVICES THAT HAVE GREATER THAN OR EQUAL TO FOUR-AXIS SIMULTANEOUS CONTOURING CONTROL

Critical Technology Parameter(s)	The ability to control a machine tool having ≥ four axes, such that the movement on each axis can be simultaneously contour controlled. Capability extends as high as eight to nine axes.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	The software itself.
Major Commercial Applications	Many commercial operations, including aircraft, automobiles, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2B; CCL 2B.

BACKGROUND

This software is used for the numerical control of five-or-more-axes machine tools.

MCTL DATA SHEET 12.5-16. MULTITASK MACHINE TOOLS

Critical Technology Parameter(s)	Capability to perform turning and milling operations in the same machine and having two or more axes that can be coordinated simultaneously for contouring control.
Critical Materials	CNC of coordinating axes, slides and rails, and feedback systems.
Unique Test, Production, Inspection Equipment	Circular and irregular path measuring equipment and ballbar to measure positioning accuracy of machine tool.
Unique Software	Software for CNC.
Major Commercial Applications	Used in manufacturing a wide range of civil items·(e.g., commercial aircraft, automobiles, farm equipment, and so forth).
Affordability Issues	A reduction of total machines necessary to produce the same parts; operations that can be performed with less moving and setup of the part, resulting in reduced cost and increased accuracy.
Export Control References	WA Cat 2B; CCL 2B. (Only controlled if either the turning or milling characteristics exceed the control parameters.)

BACKGROUND

In this context, multitask machine tools refer to machines that can perform more than one machining function (e.g., both turning and milling operations without physical intervention by the operator).

MCTL DATA SHEET 12.5-17. CUBIC-BORON-NITRIDE (CBN) GRINDING WHEELS FOR HARDENED STEEL GEARS AND BEARINGS

Critical Technology Parameter(s)	Important for grinding steel gears (diamond-coated wheels are of limited value in grinding hardened steel) to improve power density of gearbox.
Critical Materials	CBN.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Helicopters, engines, and so forth.
Affordability Issues	CBN-coated wheels will last much longer than conventional wheels.
Export Control References	None identified.

BACKGROUND

CBN is next only to diamond in hardness and is ideal for use as an abrasive. CBN is specifically used for grinding ferrous materials (containing iron, nickel, or cobalt).

MCTL DATA SHEET 12.5-18. MICROELECTROMECHANICAL SYSTEMS (MEMS)

Critical Technology Parameter(s)	No quantitative parameters are available; however, the general concept is to build extremely small machines (devices) that can perform the same tasks—albeit on a miniature scale—as conventional machines. In short, MEMS devices should be smaller, less expensive, and more reliable than more conventional devices.
Critical Materials	Silicon wafers; other materials used in microelectronics fabrication industry.
Unique Test, Production, Inspection Equipment	Standard semiconductor manufacturing equipment, including photolithographic equipment, dry etchers, deposition equipment, and systems for reactive ion etching; LIGA[9]; wafer-to-wafer bonding; and so forth.
Unique Software	None identified.
Major Commercial Applications	Unlimited applications. Present uses include accelerometers for airbag deployment in automobiles; micropressure sensors, medical microfluidic systems; micromirrors for projectors; nozzles for inkjet printers; fluid flow sensors.
Affordability Issues	MEMS fabrication is less costly than the fabrication of traditional components. MEMS-based systems often have improved performance or reduced size and weight, which lead to further savings.
Export Control References	None identified.

BACKGROUND

MEMS is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. While the electronics are fabricated using integrated circuit (IC) process sequences [e.g., complementary metal oxide semiconductor (CMOS) or bipolar complementary metal oxide semiconductor (BICMOS) processes], the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices.

9 LIGA is a German term: lithographie, galvanoforming und abformung (lithography, electroplating, and moulding).

MCTL DATA SHEET 12.5-19. CBN-COATED CUTTING TOOLS

Critical Technology Parameter(s)	Tools have coatings, with a hardness of 5,000 knoop[10] (second only to diamond), a thermal conductivity of 13 W/cm (K), and a heat resistance of 1,000 °C.
Critical Materials	Boron and nitrogen compounds.
Unique Test, Production, Inspection Equipment	CVD equipment; sputter equipment; physical vapor deposition (PVD) equipment for deposition; IR spectroscopy to characterize films.
Unique Software	None identified.
Major Commercial Applications	Wide application in materials requiring surface protection from erosion. Also, should have wide application in the production of superior cutting tools, dies, and molds.
Affordability Issues	Increased production rates result from a much longer useful life and higher metal removal rate. The former saves the cost of frequent tool-changing operations, thus speeding the machining operation. CBN-coated cutting tools are significantly more expensive than other cutting tools.
Export Control References	None identified.

BACKGROUND

Cutting tools are used in both milling and turning operations. CBN coatings are of great interest for several reasons. They possess great hardness and rigidity, chemical resistance (does not react with iron-based metals as do diamond films), and high thermal conductivity.

Polycrystalline cubic boron nitride (PCBN) blanks are manufactured from CBN crystals using an advanced high-temperature, high-pressure process. The CBN crystals are sintered together with a binder phase and integrally bonded to a tungsten carbide substrate. The binder phase, usually either a metallic or ceramic matrix, provides chemical stability, enabling the PCBN qualities to be utilized in high-speed machining environments.

10 "Knoop" hardness is a method of measuring a material's hardness by its resistance to indentation.

SECTION 12.6—COATING EQUIPMENT AND TECHNOLOGY

Highlights

- Improve the high-temperature capability of turbine engines and missile reentry cones.
- Improve the wear capabilities of engine parts, bearings, domes, and IR windows.
- Improve the corrosion resistance of hardware.
- Improved optical coatings for antireflection and bandpass filters.

OVERVIEW

This section includes the equipment for applying coating materials and the technology for the development, refinement, and production of nonorganic coatings for nonelectronic substrates. Such substrates include metal, ceramics, various composites, and optical systems. The technologies cover all pertinent coating design features, such as coating formulation, substrate and source material preparation, and post-coating treatments. Of concern are coatings to protect substrate materials from oxidation, hot corrosion, wear, erosion, and fatigue; coatings to reduce heat input to the substrate; or coatings to modify the reflectance or transmittance of light from or in the substrate material.

This section also addresses developing technologies in coating (e.g., nanophase coating; CBN coating; and multi-laser surface modification/coating).

BACKGROUND

Coatings are the only means to alter substrates to meet specified military requirements. Mechanical coatings are required for radiation hardening, wear and corrosion resistance, and extended-life requirements of items such as sensor systems, structures, power systems, gas turbine engines, bearings, and other components operating in hostile environments. Optical coatings are used to tailor aircraft or missile surfaces as a means of avoiding radar detection.

LIST OF MCTL TECHNOLOGY DATA SHEETS
12.6. COATING EQUIPMENT AND TECHNOLOGY

MCTL DATA SHEET 12.6-1. CHEMICAL VAPOR DEPOSITION (CVD) EQUIPMENT

Critical Technology Parameter(s)	Modified for pulsating CVD, controlled nucleation thermal decomposition (CNTD), or plasma-enhanced or -assisted CVD. Having high vacuum rotating seals (□ 0.01 Pa) or *in situ* coating thickness control.
Critical Materials	Ultrapure gaseous form of material to be deposited.
Unique Test, Production, Inspection Equipment	Mass spectrometer to analyze decomposed gas in the deposition chamber; scanning electronic microscope (SEM) equipment for defect detection; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity of deposited layer.
Unique Software	Software algorithms for controlling the temperature, atmosphere, and deposition rate.
Major Commercial Applications	Coatings deposited by CVD are used to improve the hardness and life of cutting tools, drills, jet/nozzles, bearings, medical devices, sunglasses, computer discs, metal matrix carbon-carbon composites, fibers or whiskers for composites materials, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA 2B; CCL 2B.

BACKGROUND

CVD is a coating or surface-modification process wherein a metal, alloy, composite, or ceramic is deposited on a substrate. The gaseous reactants are decomposed or combined in the vicinity of the substrate, resulting in the deposition of the desired material on the substrate.

MCTL DATA SHEET 12.6-2. PHYSICAL VAPOR DEPOSITION (PVD) EQUIPMENT

Critical Technology Parameter(s)	Electron-beam PVB (EB–PVD): deposition rate on the order of 100 μm/hour; laser PVD: deposition rate > 0.1 μm/pulse and capability of depositing > 2 μm films.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Mass spectrometer to analyze decomposed gas in the deposition chamber; equipment to measure thickness of deposited layer.
Unique Software	Software algorithms for controlling the temperature, atmosphere, and deposition rate.
Major Commercial Applications	Engine parts; turbine blades on commercial aircraft; automobile bodies; medical devices.
Affordability Issues	Not an issue.
Export Control References	WA 2B; CCL 2B.

BACKGROUND

EB–PVD is an overlay coating process conducted in a vacuum with a pressure less than 0.1 Pa where a source of thermal energy (electron beam) is used to vaporize the coating material. This process results in the condensation, or deposition, of the evaporated species on to appropriately positioned substrates.

Laser PVD is an overlay coating process conducted in a vacuum with a pressure less than 0.1 Pa where a source of thermal energy [pulsed or continuous-wave (CW) laser beam] is used to vaporize the coating material. This process results in the condensation, or deposition, of the evaporated species on to appropriately positioned substrates.

MCTL DATA SHEET 12.6-3. ION-IMPLANTATION PRODUCTION EQUIPMENT

Critical Technology Parameter(s)	Accelerating voltage >200 keV; beam current ≥ 5 mA for metal ions at 100 kV; capable of high-energy implant into a heated target; positional control of the workpiece; stored program controlled.
Critical Materials	Surface finish; outgassing properties; hardness; dimensional stability; chemical inertness of metal components.
Unique Test, Production, Inspection Equipment	SEM equipment for defect detection.
Unique Software	Software algorithms for controlling the temperature, atmosphere, and deposition rate.
Major Commercial Applications	Ion implantation has wide commercial applications, including surface hardening of tools, dies and molds, bearings, increased corrosion resistance of stainless steel, improved biocompatibility of medical implants, and so forth.
Affordability Issues	Significant cost savings are possible in commercial and military machining operations by using cutting tools whose surface was modified by ion implantation. Cost savings estimates run as high as 400% for extended tool life, plus savings in time to machine the end product. Ion implant surface modification also extends the life of dies and molds.
Export Control References	WA 2B; CCL 2B.

BACKGROUND

Ion implantation is a surface modification process in which the element to be implanted is ionized, accelerated through a potential gradient, and implanted into the surface of the substrate.

MCTL DATA SHEET 12.6-4. ION-ASSISTED RESISTIVE HEATING VAPOR DEPOSITION (ION PLATING) PRODUCTION EQUIPMENT

Critical Technology Parameter(s)	Vacuum of 10^{-3} torr, or better; a substrate to plasma potential of 15 to 20 V; an overall capability to deposit film with a uniformity of ±1.0% over the substrate surface.
Critical Materials	High-purity source gases.
Unique Test, Production, Inspection Equipment	SEM equipment for defect detection; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	Software algorithms for controlling the temperature, atmosphere, and deposition rate.
Major Commercial Applications	Wide range of commercial applications, including diesel engine parts, gas turbine engines, cutting tools, home appliances, jewelry, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA 2B; CCL 2B.

BACKGROUND

Ion plating is a form of PVD in which a material vaporized from a source is transported through a vacuum or low-pressure gaseous or plasma to the negatively biased substrate where it condenses.

MCTL DATA SHEET 12.6-5. SPUTTER DEPOSITION EQUIPMENT

Critical Technology Parameter(s)	Capable of current densities ≥ 0.1 mA/mm^5 at a deposition rate ≥ 15 mm/hr.
Critical Materials	High-purity source targets.
Unique Test, Production, Inspection Equipment	SEM equipment for defect detection; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	Software algorithms for controlling the temperature, atmosphere, and deposition rate.
Major Commercial Applications	Cutting tools for machine tools, knife edges; optical films for antiglare characteristics, corrosion protection for aircraft components, tribological applications, films to enhance visual characteristics (decoration), and so forth.
Affordability Issues	Not an issue.
Export Control References	WA 2B; CCL 2B.

BACKGROUND

Sputter deposition is an overlay process based on a momentum-transfer phenomenon, where positive ions are accelerated by an electric field toward the surface of the target (coating material). The kinetic energy of the impacting ions causes the target surface atoms to be released (sputtered) and deposited on an appropriately placed substrate.

MCTL DATA SHEET 12.6-6. THERMAL SPRAY EQUIPMENT

Critical Technology Parameter(s)	Power levels > 150 kW, gas velocities of 3,000 m/s; spray rates of > 15 kg/h.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Digitally controlled atomization of molten coating material and automatic rastering of mandrel; SEM equipment for defect detection; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	None identified.
Major Commercial Applications	Jet engine compressor blades, combustor components in power-generation plants, drive rollers in commercial printers, EMI shielding coatings for ignition parts, medical prostheses, molds; corrosion resistance for marine applications, diesel engine parts, and so forth.
Affordability Issues	Many thermal spray systems are portable so that the equipment can be taken to the object to be coated. This saves not only the time of transporting objects, but in the case of large articles (e.g., aircraft), the article may be able to be coated without having to be disassembled before coating. Thermal coating equipment is used in many commercial airline repair depots throughout the world.
Export Control References	WA 2B (Plasma spray only); CCL 2B (Plasma spray only).

BACKGROUND

Thermal spray is a process of applying coatings to a substrate in which the material to be deposited is heated to a molten or semi-molten state and propelled toward the substrate by either process gases or atomization jets. Thermal spraying includes plasma spray, flame spray, high-velocity oxy-fuel (HVOF), low-pressure plasma spray, and electric wire arc spray.

MCTL DATA SHEET 12.6-7. HIGH-TEMPERATURE PROTECTION COATINGS FOR ENGINE PARTS

Critical Technology Parameter(s)	Reduce temperature of underlying layer by 150 °C, or greater, or allow operation at 2,000 °C.
Critical Materials	$ZrO2 + Y2O2$; silicides; ceramics (e.g., alumina and magnesia).
Unique Test, Production, Inspection Equipment	CVD, PVD, pack cementation, thermal spraying and sputter deposition for deposition of film; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	Software algorithms for controlling the parameters.
Major Commercial Applications	Commercial aircraft.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2E; CCL 2E.

BACKGROUND

High-temperature protective coatings make advanced heat engines more efficient because the engine parts (e.g., turbine blades and pipes) can run at higher temperatures (for military aircraft, this can be as high as 1,400 °C). The efficiency and power of the aircraft is increased at higher temperature operation.

MCTL DATA SHEET 12.6-8. TECHNOLOGY FOR CORROSION AND HIGH-TEMPERATURE PROTECTION COATINGS FOR ENGINE PARTS

Critical Technology Parameter(s)	Reduce temperature of underlying layer by 150 °C, or greater, or allow operation at 2,000 °C.
Critical Materials	ZrO2 + Y2O2; silicides; ceramics (e.g., alumina and magnesia), aluminides; McrAlY.
Unique Test, Production, Inspection Equipment	CVD, PVD, pack cementation, thermal spraying, sputter deposition, and slurry deposition; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	Software algorithms for controlling the parameters.
Major Commercial Applications	Commercial aircraft.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2E; CCL 2E.

BACKGROUND

The alloys used in the compressor sections of turbines in aircraft engines and electric power plants are highly resistant to corrosion, but they still can deteriorate because of a buildup of reactive materials in the gas stream. Certain coatings, when applied to a substrate, decrease the subatrate's susceptibility to corrosion**.**

MCTL DATA SHEET 12.6-9. TECHNOLOGY FOR INCREASED-WEAR COATINGS FOR ENGINES

Critical Technology Parameter(s)	Hardness ≥ 9,000 kg/mm^2.
Critical Materials	Chromium; nitrides; CBN; carbides.
Unique Test, Production, Inspection Equipment	CVD, thermal vapor deposition, sputtering equipment, and slurry deposition for deposition of film; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	Software algorithms for controlling the parameters.
Major Commercial Applications	Commercial aircraft.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2E; CCL 2E.

BACKGROUND

Moving parts generally result in surface wear. This wear increases gaps between the moving parts and decreases the operating efficiency of the product. Certain hard coatings can minimize the wear.

MCTL DATA SHEET 12.6-10. TECHNOLOGY FOR INCREASED-WEAR COATINGS FOR DOMES AND MISSILE-SEEKER WINDOWS

Critical Technology Parameter(s)	Hardness ≥ 9,000 kg/mm^2.
Critical Materials	DLC; diamond.
Unique Test, Production, Inspection Equipment	CVD, PVD, and sputtering equipment for deposition of film; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	Software algorithms for controlling the parameters.
Major Commercial Applications	Optical scopes, IR lenses, eyeglasses, sunglasses, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2E; CCL 2E.

BACKGROUND

Domes and missile seeker windows are not made of hard materials and thus are subject to deterioration caused by the high speeds of the aircraft or missile through the atmosphere. In many applications (e.g., a missile-seeker window), the surface quality is important to the operation of the seeker system. Hard coatings are applied to these surfaces to protect them from wear. In some applications, the optical absorption of the coating is important. For example, in an IR seeker, it is critical that the coating not absorb IR radiation.

MCTL DATA SHEET 12.6-11. TECHNOLOGY FOR WEAR-RESISTANCE COATINGS AND SURFACE MODIFICATION FOR BEARINGS

Critical Technology Parameter(s)	Increase of 300% in surface hardness, with concurrent reduction in sliding friction by a factor of 3.
Critical Materials	TiC; carbon; diamond; DLC; chromium; tantalum; tin; TiN.
Unique Test, Production, Inspection Equipment	CVD, RF plasma coating, spray coating, ion-beam assisted deposition for deposition of the film; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	Software algorithms for controlling the parameters.
Major Commercial Applications	Jet engines, automotive engines, machine tools, solar panels, radar antennae, gyroscope platforms, and so forth.
Affordability Issues	Coated bearings should extend the life of the bearings and the equipment using the bearings.
Export Control References	WA Cat 2E; CCL 2E.

BACKGROUND

Moving parts generally result in surface wear. This wear increases gaps between the moving parts and decreases the operating efficiency of the product. Certain hard coatings can minimize the wear.

MCTL DATA SHEET 12.6-12. TECHNOLOGY FOR ANTIREFLECTION OPTICAL COATINGS FOR GUIDANCE SYSTEMS

Critical Technology Parameter(s)	Antireflection films that resist rain, sand, erosion, and oxidation at temperatures >700 °C and reduce reflection to 2–3%.
Critical Materials	Mg F2 is most often used for single-layer antireflection coating. Multilayer coatings are more common, but the specific layer makeups are proprietary.
Unique Test, Production, Inspection Equipment	CVD, EB-PVD, ion-assisted resistive heating-PVD, laser evaporation, and sputter deposition for deposition of the film; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	Software algorithms for controlling the parameters.
Major Commercial Applications	Camera lenses, mirrors, laser optics, optical systems for lithographic equipment, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2E; CCL 2E.

BACKGROUND

Antireflection films are used to reduce the amount of light lost to reflection at the surface of optical transmission elements. This is particularly important in compound lenses, which have many interfaces from one lens element to another. In compound lenses, the amount of light lost by reflection can be reduced from 10–15 percent to 2–3 percent by using high-efficiency multilayer antireflection coatings.

MCTL DATA SHEET 12.6-13. TECHNOLOGY FOR BANDPASS COATINGS FOR SENSORS

Critical Technology Parameter(s)	Filters that have selectable or variable bandpass in 0.2–20 μm spectral range.
Critical Materials	Oxides; fluorides; sulfides.
Unique Test, Production, Inspection Equipment	CVD, EB-PVD, ion-assisted resistive heating-PVD, laser evaporation, and sputter deposition for deposition of the film; spectroscopic ellipsometer; spectrophotometer for measurement of film thickness and uniformity.
Unique Software	Software algorithms for controlling the parameters.
Major Commercial Applications	Laboratory equipment, motion sensors, robotic control, temperature measurement, automotive IR systems, and so forth.
Affordability Issues	Not an issue.
Export Control References	WA Cat 2E; CCL 2E.

BACKGROUND

Optical coatings for sensors either allow selective wavelength to be transmitted to the sensor or reject unwanted wavelengths, depending on the wavelength of concern and the sensor wavelength response.

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INDEX OF MCTL TECHNOLOGY DATA SHEETS

INDEX OF MCTL TECHNOLOGY DATA SHEETS