Chapter 12
Manufacturing Technology During New Era

Manufacturing industry is the "never fall sun", one of the pillars of contemporary civilization. It is both the basis and also the frontier, both an old craftsman and also a young scholar. It is the foundation of sustainable development of national economy.
—Yang Shuzi (Chinese academician, 1933–)

We first make a comparison of the typical manufacturing technologies in the 2nd Industrial Revolution against that in the New Era (Table 12.1).

Without further explanation, the great progress made during the 3rd Technological Revolution is clearly seen.

12.1 Introduction

12.1.1 Challenges in New Era

12.1.1.1 Higher Productivity

After WWII, the world was in peace again and the economy around the world resumed quickly. The desire for higher living standard drove up the demand for almost all products. Taking automobiles as an example, Table 12.2 shows statistics of the number of vehicles per 1000 inhabitants in several counties (ANON 2017). In the U.S. every 1000 people owned 797 motor vehicles in 2014; however, this number was only about 143 in 1924.

To meet the dramatically increased demand for motors, more machine tools along with other types of production machines, such as stamping presses, were needed. Also, productivity of these machines needed to be improved, driving the development of new technologies, including high-speed machining, computer-aided process planning (CAPP), group technology, as well as digital manufacturing.

C. Zhang and J. Yang, *A History of Mechanical Engineering*,
https://doi.org/10.1007/978-981-15-0833-2_12

Table 12.1 Comparison of manufacturing technologies between the 2nd industrial revolution and new era

	Traditional technology (in the second industrial revolution)	Contemporary technology (in the new technological revolution)
New machine tools	Grinding machine, gear cutting machine, etc.	CNC machine, machining center, ultra precision and ultra high speed machine tools
Tool material	High-speed steel, carbide	Carbide, ceramic tools
Cutting speed	100 m/min or more	The highest speed is more than 1000 m/min
Automation	Mechanical and electrical automation, single machine automation, rigid automation	Flexible automation, towards to intelligent automation
Production mode	Mass production	Multi-variety and small-batch production, customized production
Processing	Machining	Machining, non-traditional processing, additive manufacturing
Environment	Less considered	Green manufacturing
Management	Taylor’s management	Computer integrated manufacturing system, network manufacturing, virtual property
Distribution of resources	Labor intensive, equipment intensive	Information intensive, knowledge intensive

Table 12.2 Number of road motor vehicles per 1000 inhabitants

Australia	The U.S.	Italy	Poland	Japan	S. Korea	Russia	China	Vietnam
736	797	679	537	591	459	293	205	23
(2016)	(2014)						(2015)	(2013)

12.1.1.2 Higher Accuracy

Newly emerged technologies and large complicated engineering systems, such as space shuttles, airplanes, and mechatronic products, greatly lifted the requirement on machining accuracy. For example, the micro-robots used in gene manipulation have a motion range in the scale of nanometre, requiring the accuracy as high as 0.1 nm (Zhu 2001).

To meet the high requirement in accuracy, ultraprecision machining technologies appeared, which have a precision level to the atomic scale in the order of 0.2–0.4 nm. For this reason, the ultraprecision machining is also called nanomachining (Joshi 2012).

12.1.1.3 Change in Manufacturing

Machine building became an industrial sector in Britain during the 1st Industrial Revolution. Since then manufacturing has experienced fundamental changes.

Initially, machines were built by craftsmen in workshops. In this case, products were with very little variation, and production quantity was small. The year 1914 saw a fundamental change when H. Ford introduced an assembly line to his factory (Hounshell 1984). With this assembly line, large number of coincident cars were manufactured efficiently. This new way of production is termed as high production or mass production. Mass production uses dedicated machines and various automated equipment; thus, automation of this type is called rigid automation or Detroit type automation. Mass production and rigid automation dominated the manufacturing in about half a century, being a symbolic achievement in mechanical engineering in the 20th century.

Changes came again during the 1960s and 1970s. Mass production met the common demand of most people. However, personal preferences and special requirements on products stood out after the basic demand was met, leading to the change of market need from large number, but coincident products to smaller number, but more variant products. To meet this changed market requirement, manufacturers changed the mass production back to a job shop style in which a variety of products could be made. It was reported that job shop production has been the dominant in the U.S. where 90% of the products in the market was manufactured with less than 50 items (Xu et al. 2001).

This also caused changes to the manufacturing system. Mass production was implemented through rigid automation in which automated machines and manipulators are the main players. In the job shop production, however, flexible manufacturing systems are needed to make smaller number of, but more variation in, the products. Programmable machines and robots are the center in such a production style.

12.1.1.4 Crisis of Natural Resources and Energy

The crisis of energy and natural resources was already discussed in 9.2.2. The manufacturing industry has been the largest consumer of energy and natural resources for a long time. In the New Era, market needs dramatically increased while product life was generally shortened, putting an ever high need for energy and almost all natural resources. The United States Department of Energy predicted in its International Energy Outlook 2001 that the consumption of energy would increase by 60% in 20 years.

To address the challenge, Kenneth Boulding, an American economist, proposed the concept of circular economy in 1966. The Club of Rome published a report in 1972 titled as “The limits to growth”, warning that the global system of nature, which we all live in, could not support the rates of economic and population growth beyond the year 2100 (Meadows et al. 1972). In 1987 the United Nations World Commission on Environment and Development released the Brundtland Report, in which the concept of sustainable development was defined the first time (Brundtland Commission 1987). In 1992, the Agenda 21 was issued on the UN Conference on Environment and Development as an action plan for sustainable development, calling all the nations to draw their own plans in national and local level in order to achieve global sustainable development.

The crisis in energy and natural resources significantly affected every aspect of mechanical engineering. To reduce energy consumption, light-weight design became a trend. Lighter materials, such as ceramics, started to replace metals in making some mechanical components. The introduction of new materials brought challenges to both design and manufacturing. Also, for light-weight purpose, thin-walled parts were used more often, which might be an issue for machining. These manufacturing challenges, in turn, led to the invention of non-traditional machining technologies.

12.1.1.5 Environmental Crisis

It is reported that more than 70% of the total pollutant discharge all over the world comes from the manufacturing industry. Thus, it is an urgent challenge faced by the world to find greener and more sustainable manufacturing technologies (Eccleston and March 2010).

The challenges from natural resources and energy crisis, as well as ecosystem and environmental degradation directly inspired the development of green manufacturing.

12.1.1.6 New Materials

New materials have been continuously developed and applied in mechanical engineering. Structural ceramics have been used to make many mechanical parts, such as bearings and cylinders of internal combustion engines. Compared with metals, ceramics are harder, and more brittle; thus, more difficult to machine. On the other hand, however, the requirement on accuracy of manufacturing was not compromised.

Titanium alloys, super-alloys and various reinforced plastics are widely used as materials for fuselage and wings of airplanes. These materials are all hard to machine.

To address the machining problems of these new materials, one effort was to adopt traditional machining methods to these materials. The other route was to

Fig. 12.1 Installation of generator rotor in Three Gorges Hydropower Station, China

develop specialized technologies for the hard to machine materials, the so called non-traditional machining technologies.

12.1.1.7 Extreme Dimension

During this period, machines developed toward two extremes in terms of size, very large and very small.

Three Gorges Dam, for example, is the largest hydro-power complex project all over the world. Its power generating units are so large that the outer and inner diameter of the generator are 22 and 20 m, respectively (Fig. 12.1). Despite the huge size, the requirement on accuracy of manufacturing is very tight; the dimension deviation of the inner diameter is within 1 mm.

The other extreme is the manufacturing and fabrication of integrated circuit, micro-scale machines, as well nano-machines. As their names imply, these machines are extremely small. The micro-scale machines normally range from 1 to 100 μm in size. The nano-machines are even smaller, being measured in nanometers (Wang 2013). Some details of manufacturing this types of objects are given in Sect. 10.4.4.

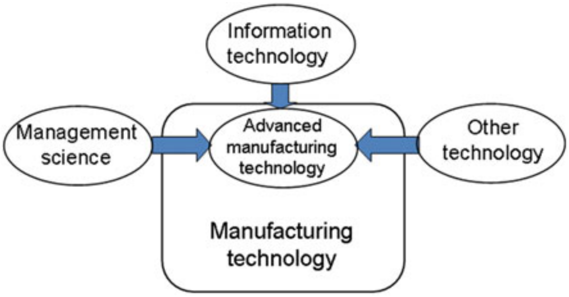


Fig. 12.2 Advanced manufacture technologies

12.1.2 Developments of Manufacturing Technologies in New Era

Along with the change in production from large quantity, less variation to small quantity, more variation, flexible and intelligent manufacturing systems were gradually replacing the traditional rigid ones.

GT, CAD/CAM, CAPP, NC machining, machining centers, and FMS, which are all based on information technology, make up the main contents of the so-called advanced manufacturing technologies. These technologies played a big role in reducing labor working intensity, lifting productivity and improving machining accuracy.

In addition, progresses were also made in this period in ultra-high-speed machining, ultra- high-precision machining, non-traditional manufacturing as well as additive manufacturing technologies.

With the advent of the knowledge economy era, the manufacturing industry changed from labor and machine intensive to information and knowledge intensive (Wang 2004).

The advanced manufacturing technologies were a result of incorporation of information technologies, management and several other disciplines (Yang and Wu 2003) (Fig. 12.2).

In 1951 the Foundation of the International Institution for Production Engineering was established, which later changed to the International Academy for Production Engineering Research (shortened as CIRP).

12.2 Automation: Backbone of Advanced Manufacturing

Automation is the backbone of the advanced manufacturing technologies. Given that CIMS covers a wider scope including the whole system in a manufacturing enterprise, CIMS is introduced in a dedicated section in this chapter.

12.2.1 NC Machining and NC Machine Tools

Since Christopher Spencer invented the first fully automatic turret lathe of the world in 1873, interest in automated machining has never stopped. Before the WWII, automation was mainly achieved through cams, hydraulic transmission and relay control. However, real automation in machining was not accomplished until the advent of computers.

12.2.1.1 Birth of NC Machine Tool

Parsons Corp., an American manufacturing company, and MIT were widely credited as the pioneers in developing NC machine tools. John Parsons first used a "computer" in manufacturing in 1946 (Olexa 2001); however, the computer he used was not more than a punched card calculator. In 1948, Parsons got a contract from the U.S. Air Force to develop a machine for construction of jet-plane wings. However, he quickly realized in the process of building this machine he and his staff did not have the necessary knowledge and resources. Thus Parsons subcontracted part of the machine to the Servomechanisms Laboratory at MIT. In 1950, the Servomechanisms Laboratory bought a surplus "Hydro-Tel" mill from Cincinnati Milling Machine Company for development, and signed a new contract directly with the Air Force without Parsons. The MIT's machine was widely credited as the first generation of NC machine tools, and was publicly demonstrated in 1952. Nevertheless, Parsons already filed a patent earlier. The control system of the MIT machine consisted of vacuum tubes and relays.

12.2.1.2 Further Development of NC Machine Tools

During 1952–1958, the collaboration between MIT and the U.S. Air Force continued. The initial NC system was programmed by hand and it was very time consuming. John Runyon at the MIT attempted to automatize the process. In 1956, D. Ross, a researcher at the Servo-lab, made main improvement to the programming solution, which eventually evolved to the Automatically Programmed Tool (APT). At this time, NC became CNC (computer numerical control). Besides the milling machines, NC technology was expanded to other types of machine tools, including boring machines, drilling machines and lathes. Obviously, MIT made ground-breaking contribution to the development of CAM, computer-aided manufacturing (Reintjes 1991).

To 1959, the second generation of numerical control (NC) technology, characterized with transistors and printed circuit boards, became dominant. To 1965, The third generation of NC technology was adopted, represented by the much smaller, more reliable and energy-efficient integrated circuits. On the International Machine Tool Show 1970, at Chicago NC systems with general minicomputers were demonstrated for the first time. This system is referred as the fourth generation of NC system or CNC system. With the appearance of microprocessors, NC technology advanced to the 5th generation, featured with much cheaper and more reliable large scale integrated circuit technology.

Now CNC has been a mature technology. Allen-Bradley, FANUC and Siemens are the largest three CNC providers of the world (Wang 2004).

The first commercial machining center of the world, Milwaukee-Matic II as shown in Fig. 12.3, was successfully developed at Kearney & Trecker Corp., the U. S., in 1958 (Makely 2005). It added automatic tool changer and automatic work positioning to a NC milling machine; thus, multiple operations, such as milling, drilling, reaming and broaching etc., could be performed with one setup. A machining center is normally equipped with multiple tool options. Machining centers greatly improved the productivity due to the automation of work and the reduction of non-productive time. In the 1966 Chicago Machine Tool Show machining centers were displayed the first time and immediately attracted wide interest from various industries. Following that was a rapid development.

The first effort of using one computer to control multiple machine tools, group control, was made in 1966 as the direct numerical control (DNC) technology. With the number of CNC machine installation grew during the 1970s and 1980s, DNC evolved into a new form as distributed numerical control (DNC).

Military aircrafts are normally produced with low quantity, but high quality requirements. The U.S. Air Force and its aircraft providers paid great attention to the development of NC machine tools. Manufacturing of aircrafts was always faced

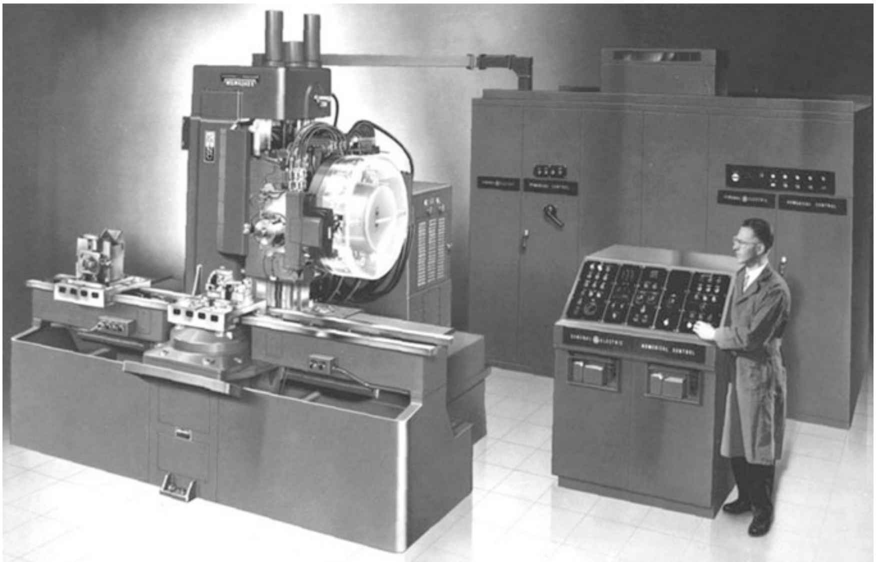


Fig. 12.3 Milwaukee-Matic II, the first machining center

with new challenges; to addresses the challenges often inspired the creation of new technologies. The Air Force collaborated widely with universities, and provided abundant research funding to support fundamental research as well as technical development with regard to NC machining. Correspondingly, many innovations in this field were tied, directly or indirectly, to the U.S. Air Force. This fact combined with the America's leading position in electronic and computer technology made the U.S. one of the top NC machine producers.

Now NC technology has been applied to lathes, milling machines, EDM machines, and various gear cutting machines. Compared with conventional machine tools, NC machine tools have a series of advantages, such as flexibility of operation, ability to produce complex shapes, high productivity, as well as high product quality. Due to these features, they have been widely accepted by the manufacturing industry.

12.2.2 Process Planning

12.2.2.1 Group Technology

With the batch production becoming dominant, two needs came forward. One was to improve the productivity, and the other to integrate design and manufacturing into a higher level. Group technology (GP) is a methodology that takes advantage of the design and processing similarities among the parts to be produced. It is especially beneficial to the above two needs. Machines may vary in types and functions; however, the individual components within the machines can be grouped into several part families. Individual parts within each part family bear great similarity in design or manufacturing. A gearbox, for example, can be divided into a housing, shafts, gears, and seals etc. Improvement in productivity is achieved by arranging the manufacturing equipment into machine groups or cells and each cell specializes in the production of a part family.

The origin of GT is traced back to a paper by R. Flanders, an American engineer, in 1925 in which he proposed a way to organize manufacturing. In 1937, A. Sokolovsky (А. Соколовский), a scholar from Soviet Union, described the essential features of GT. S. Mitrofanov (Сергей Митрофанов), also a Soviet Union scholar, published a book in 1959 entitled *Scientific Principles of Group Technology*. H. Opitz in Germany developed the well-known part classification and coding system, the Opitz Classification System (Groover 2001). After these developments, application of GT also significantly expanded in many countries, including UK, Japan, China and the U.S.

GT, combined with computer technology, is critical in many design and manufacturing activities nowadays, such as CAD, CAM, CAPP and FMS. In the U.S. Air Force project, Integrated Computer Aided Manufacturing (ICAM) (see Sect. 12.8.1), the design, manufacturing and management were connected through the GT technology.

12.2.2.2 Computer-Aided Process Planning

Computer-aided process planning (CAPP) is the use of computer technology to aid in the process planning of a part or product to be manufactured.

Process planning involves determining the most appropriate manufacturing processes and the sequences for producing a given part or product according to the specification set forth in the design documentation. It used to be accomplished by engineers who were familiar with the manufacturing process, equipment and machining tools required. Process planning was time consuming, and the quality of the planning heavily relied on the knowledge level and experience of the planner. CAPP is a more efficient and reliable alternative way of the above process planning.

The earliest research on CAPP was in 1965 (Niebel 1965). The earliest CAPP system, AUTOPROS, was developed in Norway in 1969 and was available in market in 1973 (Sun 2004). Among the many CAPP systems, the CAM-1 Automated Process Planning, developed by CAM-1, is a landmark.

CAPP stands as a bridge in the integration between CAD and CAM.

12.2.3 Integration of CAD/CAPP/CAM

The three computer-aided technologies significantly improved the efficiency in design and manufacturing. However, they were developed following the conventional engineering practice in which engineering drawings were prepared by designers and draftsman and later used by manufacturing engineers to implement the design. The design and manufacturing were separated from each other in this practice, creating duplication of work by design and manufacturing personnel and being of low efficiency. Thus, during the 1970s and early 1980s, effort was made to integrate the three into one CAD/CAPP/CAM system, in which the design and manufacturing were directly linked. The goal was to automate not only design and manufacturing, but also the transition between the two. In an ideal system, the design specifications of a product embedded in the CAD data base can be directly accessed by the CAPP to convert into process plan and by the CAM to generate the NC part program.

It is worth mention that the GT was also integrated into the system in some cases.

The integration of the three technologies laid the foundation for computer integrated manufacturing systems (CIMS).

12.2.4 Flexible Manufacturing Systems

Flexible manufacturing systems (FMS) was a technology developed starting from the 1960s (Toni and Tonchia 1998).

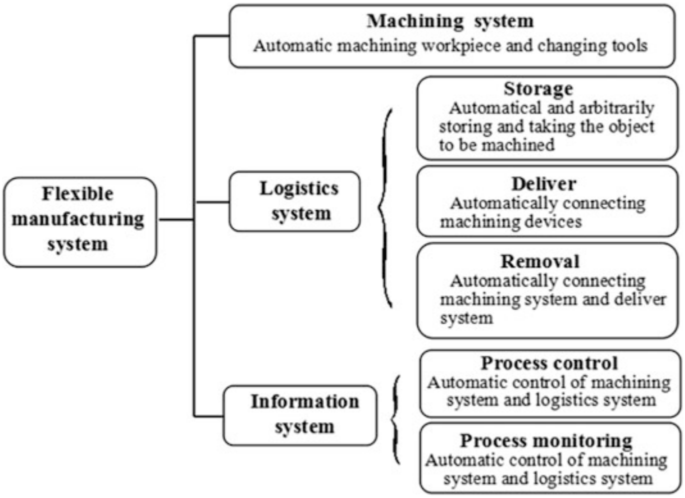


Fig. 12.4 Flexible manufacturing system

Mass production relies on dedicated equipment and production lines, featuring high efficiency and low manufacturing cost. However, mass production systems tolerate very little, or not at all, product variation. Traditional production of low and medium quantity had certain capacity to deal with product flexibility through using general purpose machine tools and equipment. The drawback was low productivity and high production cost.

A flexible manufacturing system (FMS) consists of processing workstations, usually CNC machine tools or machining centers, interconnected by automated material handling and storage systems and is controlled by distributed computer systems. It has high productivity, and a certain level of flexibility at the same time (Fig. 12.4).

The first FMS concept was proposed for machining by David Williamson, an engineer at Molins, UK. He was granted the patent in 1965 (Maleki 1991). His concept was named system 24, because the system was expected to work 24 h/day, 16 h of which unattended by human workers.

One of the first FMS installation in the U.S. was the Omniline I system at Ingersoll-Rand Company in Roanoke, Virginia, in 1967. This system was installed by Sunstrand, and consisted of two five-axis machining centers, two four-axis machining centers and two four-axis drilling machines. In 1976, Japan's Fanuc Ltd. exhibited the flexible manufacturing cell (FMC) consisting of machining centers and industrial robots. West Germany and Soviet Union also installed FMS shortly after in 1969 and 1973 respectively.

FMS approached technical maturity around the late 1970s, and gained increased acceptance all over the world. By 1990, about 1500 FMS were installed throughout the world.

Benefits of FMS include reduction of overall product cost, labor and machines required, shortening of lead time as well as possibility of unattended production.

12.2.5 Robots in Manufacturing

The beginning of robotics in the U.S. was closely related to the auto-industry. The Unimate, the first commercialized product of Unimation, was installed in an assembly line of GM (see Sect. 10.3).

By the late 1960s, robots were widely applied in Japan for automotive production. After 1980, industrial robots gained further popularity. Now all the main auto-makers of the world have adopted robots in their production systems.

Assembly was the first operation to use robots (Fig. 12.5). Other operations in which robots are applied include conveying, welding and painting.

In the first half of the 20th century, manipulators were used in fixed production systems for moving work parts between machine tools. A manipulator differs from a robot essentially. A manipulator is an automated machine which has fixed moving sequences. It does not contain a computer. While a robot contains computers in its control system and its moving sequences can be changed through programming. Thus, a robot can accomplish multi-tasks, and is particularly good at medium and low quantity production dealing with certain level of product variations.

Industrial robots have become an integrated part of FMC.

Parallel robots are the basis of parallel machine tools, details of which are given in Sect. 10.3.2.

Fig. 12.5 ABB robots work at an automobile manufacturing facility in Tianjin (http://usa.chinadaily.com.cn/weekly/2012-10/05/)

12.3 Progress of Machining Technology

In the New Era, machining technologies also progressed fast. The demand for high productivity, and high machining precision as well as the advent of various new materials are among the main driving forces to the progress.

12.3.1 Tool Materials

To meet the requirement of high-speed machining and machining difficult-to-machine materials, many innovations were made in tool materials, amongst which the development of hard coating technology and ceramic materials was the most representative (Kane 1982; GSHCAS 1985).

During the 1970s, the chemical vapor deposition (CVP) and physical vapor deposition (PVP) technology were used to engineering tool surface. Through applying coating of TiC, TiN, HfC, Al_2O_3 on surface of high-speed steel and cemented carbide, the tool's performance and durability were greatly improved.

Market needs pushed the development of new tool materials, also improved the existing ones. These needs mainly include improving productivity, improving machine tool structure and NC machine tools performance, and machining of difficult-to-machine materials etc. It is estimated that difficult-to-machine materials now make up above 50% of total materials requiring machining. Cemented carbides are not satisfactory in machining some of the difficult-to-machine materials. In addition, the current market demand for cemented carbides is already very large, consuming huge amount of tungsten, cobalt, tantalum and niobium. It is estimated that the resources of these precious elements on earth will run out in several decades if the current consumption rates continue.

Ceramics tools were developed as an alternative solution to the above challenge (Kane 1982; Ai and Xiao 1988; GSHCAS 1985).

The effort of making tools from ceramics first happened in UK and Germany during the early 20th century. However, the high brittleness prevented its application. In 1922, ceramic tools were used to cut plastics and nonferrous metals in the Soviet Union. The U.S. also conducted study on ceramic tools during the 1930s and 1940s. However, the real breakthrough did not occur until the mid-1950s. Due to the lower strength and toughness, ceramic tools were only used for uninterrupted finishing or semi-finishing operations. In 1950, the 2nd generation ceramic, Al_2O_3-TiC, was developed in the U.S., which significantly improved the strength and toughness on the basis of aluminum oxide. Tools made of the 2nd generation aluminum-based ceramics were developed in 1968, which greatly expanded the scope of application of ceramic tools. Silicon nitride tools were developed around the end of the 1970s. Silicon nitride has better toughness and hot strength than aluminum oxide, and is categorized as the 3rd generation of ceramic tool material. Its application is fast growing in the main industrialized countries.

12.3.2 High-Speed Machining (HSM)

High speed machining (HSM) means using cutting speed that are significantly higher than those used in conventional machining. There is not a consistent definition of HSM so far. One definition is based on the DN ratio, the bearing bore diameter (mm) multiplied by the maximum spindle speed (rev/min) (Groover 2007). According to this definition, if the DN ratio is in between 500,000 and 1,000,000, the machining is referred as HSM. HSM is the 2nd landmark after the NC technology in machining.

With the application of NC, machining centers, and FMS, the idle time in machining, such as that for tool changing, loading and unloading works, was significantly reduced. During the 1980s, it was realized that the room to further increase productivity through reducing idle time almost exhausted. In this case the effort was directed to reduce the direct machining time through increasing the cutting speed and feed.

The early effort toward HSM is traced to Carl Salomon, a German scholar. He filed the first patent of HSM in 1931 (King and Vaughn 1984; Flom et al. 1984). He concluded through measuring tool temperature that there existed a critical cutting speed for each material at which the temperature reached maximum and beyond which the temperature dropped rapidly. However, his conclusion was not verified by later classical analysis of M. Merchant (Groover 2002). Partially due to this reason, Solomon's work was not publicized until many years later (Schulz et al. 2010).

One pre-requisite for HSM is good tool materials. During the period from 1920s to 1950s, the application of carbides as tool materials doubled the cutting speed in every decade.

Starting from the 1950s, studies on HSM were started with using ceramics as tool materials. The 1970s saw intensive research activities extending to many aspects of detailed applications. To the early 1990s, HSM technology approached mature. HSM has remained a highlight in all trade shows on machine tools since the EMO 1995 at Milan. Commercialization started from the late 1990s when many machine tools of HSM became available in the market. Applications typically are in the space, mold, optical, auto, and home appliance manufacturing industries. The U.S., Japan and Germany are the world leaders in research and development of HSM technology. After the 21th century, HSM became the mainstream machining technology in almost all industrialized countries.

Compared with traditional machining, HSM has the following advantages.

(1) Higher productivity: Material removal rate is generally 3–6 times of that of traditional machining.
(2) Possibly lower vibration: The high excitation frequency may be well beyond the primary natural frequencies of the system, thus, the vibration of the system may be lower.

(3) Lower cutting force: This is especially good for machining of thin-walled parts.
(4) Lower temperatures of cutting tools and work pieces: Shorter cutting time makes more cutting heat removed by chips.

The surface meter per minute (Flom et al. 1984) for machining steel and aluminum has reached 1000–1500 m/min and 7500 m/min respectively.

12.3.3 Precision and Ultra-Precision Machining

Beginning in the 1960s, precision and ultraprecision machining (UPM) technologies were developed in response to the requirement of higher manufacturing accuracy. These technologies are critical to the manufacturing of components and systems in space shuttles, satellite and many other high-tech systems.

Precision machining means the machining technologies with a precision level between 1 and 0.1 μm. Ultraprecision machining has even higher level of precision characterized by the following: less than 0.1 μm in linear error of the workpiece, less than 0.025 μm in surface finish of Ra, and 0.01 μm in programming input resolution (Solon 2012). UPM belongs to micrometer scale manufacturing. Driven by the development of MEMS technology, Nanometer scale manufacturing technologies are also under development (Yuan 2008).

Traditional precision machining depends mainly on grinding. UPM, however, includes a number of non-traditional machining technologies relying on different energy sources, such as electrical, magnetic, optical, chemical and nuclear etc.

The U.S., Britain and Japan are the leaders of the world in UPM technologies. The U.S. started development of the UPM technology in the 1950s mainly for the space industry. Diamond cutting tools and UPM machines with only air and oil bearings were both firstly invented in the U.S. Japan, although starting later than the U.S., is catching up quickly. Different from the U.S., Japan put more effort to applying UPM in civil products. One representative example is in manufacturing of the micro scale components in optical and graphical devices (Ikawa 1991). Japan has been a leader in grinding and polishing of ultraprecision mirrors and lenses, especially in ultraprecision grinding and polishing of free-form and aspheric surfaces in large optical mirrors. Ultraprecision grinding is also used in the manufacturing of the silicon wafer in large scale integrated circuit. The wafer requires very high in surface finish and flatness. Surface scratch is not tolerated.

Other precision and ultraprecision grinding and polishing methods include magnetic fluid polishing, bonnet polishing and stressed lap polishing etc.

12.3.4 Machining of Difficult-to-Cut Materials

From the view point of machining, difficult-to-cut materials can be divided into two categories (Fu 2010).

(1) High strength, high toughness materials

These include high strength steel, titanium alloys, and super-alloys. Large cutting force, high temperature and excessive tool wear are the common challenges encountered in machining these materials.

Titanium was discovered in 1791, but titanium alloys were not commercialized until the 1950s. Titanium alloys have very high corrosion resistance and high strength-to-weight ratio, making them very attractive in making airplane parts, jet engines, racing cars and submarine hulls and medical devices. Boeing and General Motor started the research on machining of titanium alloys very early. Super-alloys are also called high-temperature alloys which found wide applications in making the combustor and turbine sections of the aero-engines. Britain and the U.S. are the leaders in super-alloys.

(2) Hard, brittle materials

This group includes engineering ceramics, optical glass, and silicon. Surface scratch caused by the built-up edge and cracks are the main problems in machining these materials.

Engineering ceramics have a series of excellent characteristics, such as high compressive strength and hardness, resistance to wear and corrosion, low density and thermal expansion etc. They have found numerous applications in many industries, one of which is in internal combustion engines installed on civil and military vehicles. Ceramic components make higher operating temperature possible which means higher efficiency of the combustion of fuel. From the 1970s, many countries, including the U.S., Japan, Germany, Italy, and China, attempted to make ceramic components of internal combustion engines. The common parts which can be made with ceramics include cylinders, cams, combustors, rotors etc. some examples are shown in Fig. 12.6.

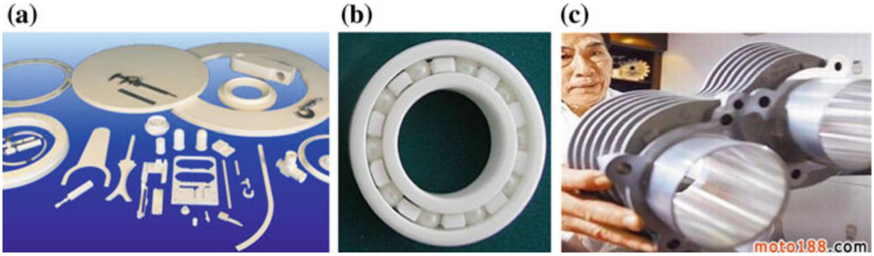


Fig. 12.6 Structural ceramic parts. **a** Various parts, **b** ceramic bearing, **c** ceramic cylinder body

Although these materials have superior properties, machining is still a big challenge. Thus, many companies keep the technologies of machining difficult-to-cut materials as business secret. Some countries even treat it as national critical technologies.

Machining of difficult-to-cut materials has some overlap with high speed machining and ultraprecision machining. Machining of difficult-to-cut materials, as any modern technology, involves cutting tools, machines and process. On the one hand, requirement of machining difficult-to-cut materials inspired the development of new cutting tools and tool materials. On the other, some non-traditional machining techniques often find applications in machining these type of materials.

12.3.5 Near-Dry and Dry Machining

Cutting fluids are used extensively in machining for purpose of reducing friction and wear, cooling the cutting zone, protecting the machined surface and flushing away the machining chips. However, issues related with cutting fluids, including the cost and contamination of environment, have caught more attention since the 1990s.

It was estimated that cutting fluids made up only 3% of the overall cost of machining 20 years ago. However, this number climbed up to 13–17% in recent years, well exceeding the cutting tool cost of 2–5%.

To alleviate the environmental impact and control the cost, near-dry and dry machining technologies have been a trend in the world since the mid-1990s (Ren et al. 2013). In the near-dry machining, a fine mist of air-fluid mixture containing very small amount of cutting fluids is applied. While in the dry machining, cutting fluids are completely removed.

Dry machining has a high requirement on the hot-hardness and toughness of the cutting tools. The advance in cutting tools has make dry machining feasible and effective in various machining operations, such as turning and milling, of various materials including steels, steel alloys and cast irons. In the dry machining, the chips have to be removed through pressurized air which is applied through the tool shank.

12.3.6 Vibration Control of Machining

The machine, cutting-tool and the work piece constitute an elastic system. The machining process itself, transmission of the machine tool and the surroundings create excitations. Thus the elastic system will vibrate under these excitations. The vibration in machining process has several detrimental effects, including reduction of machining accuracy and surface finish, life reduction of machine tool and cutting tools, and generation of noise etc.

Machining vibration was noticed very early; however, systematic study did not start until WWII (see Sect. 7.7.3). With the increase of machining speed, vibration became more severe. This is especially true in precision machining, high-speed machining and machining of difficult-to-cut materials.

12.3.6.1 Chatter and Machine Tool Dynamics

Vibration of machining systems is very complicated, involving three types of vibrations, namely free vibration, forced vibration and self-excited vibration.

Chatter, the form of self-excited vibration in machining systems, is induced and maintained by the forces generated by the cutting process itself. It is the main problem limiting the productivity of machining.

Carbides used as tool material greatly increased the cutting speed of machining. By the 1930s, the cutting speed had reached hundreds of meters per minute. Early researchers on machining chatter were almost all from three countries, the U.S., UK and Germany. The reason behind is that military production in these countries required higher cutting speed.

Research on chatter in theory did not start until the mid-1940s. The earliest report on chatter was made in 1945 (Stone 2014). Since then, many models and methods have been established, laying the foundation of machine tool dynamics. The book by Stephen Tobias (Tobias 1965), a German scholar, was the landmark of machine tool dynamics, in which the sources of vibration, modeling and analysis of vibration, mitigation of vibration as well as dynamic design of machine tools are systematically treated.

Starting in the 1960s, ultrahigh speed machining technologies were tested and developed in the U.S., Germany and Japan (星·鐵太郎 1977). In this effort the control of chatter in machining process was the key. Development of machine tools, cutting tools and relevant process for the ultrahigh speed machining then went into a booming period. Application of ultrahigh speed machining greatly improved productivity.

Machine tools are very complicated in structure and chatter is a complicated vibrational phenomenon caused by multi-factors. Early studies of machine tool chatter based on linear theory were not able to explain nonlinear phenomena. As a result, the early models were not widely accepted, being depicted as "models are to be used, but not to be believed" (Stone 2014). Chatter is self-excited vibration in nature, which can be better treated with nonlinear theory.

12.3.6.2 Up-to-Date Development in Research of Chatter

By the end of the 20th century, the machining technology had reached such a point that controlling chatter vibration of machine tools became critical. Specifically the important driving forces to the study of chatter came from the following aspects.

(1) Ultraprecision machining requires higher level vibration control due to the higher requirement on machining accuracy and surface finish.
(2) Ceramics are widely adopted as materials of tools, which are much more brittle with less resistance to impact.
(3) Ultra high-speed machining and heavy-duty machining increase the possibility of chatter to happen in machining.
(4) Lighter and thin-walled workpieces also increase the possibility of chatter.
(5) Machining centers and FMS put forward a requirement of real-time monitoring of operation because the multi-operations are enclosed in a limited area.

In recent years, two trends became obvious in the study of chatter. (1) Linear theory was replaced with nonlinear theory, (2) real-time monitoring was under fast development.

Linear models of chatter were first developed by S. Tobias during the late 1960s. After the 1990s, chaos and bifurcation, typical nonlinear vibration phenomena, were observed in several machining methods (Gradisek et al. 1997).

Shi Hanmin, a Chinese scholar, made outstanding contribution in the study of chatter with nonlinear theory. He explained theoretically some important nonlinear phenomena which were not well understood before, and discovered the stable machining zone under high speed. This finding fundamentally changed the traditional opinion that mitigation of chatter must be at the cost of sacrificing productivity. More importantly, all his theoretical findings were validated with experiments (Shi 2003).

Chatter is essentially a problem of stability. With dynamic models the border between stable and unstable cut, termed stability lob diagram (SLD), can be determined. Then chatter can be, at least in theory, avoided through properly choosing cutting parameters. However, there are some technical difficulties in practice. These include (Quintana and Ciurana 2011):

(1) The dynamic models are not accurate enough to construct the lobs accurately due to the extreme complexity and diversity of machining operation.
(2) The mechanisms of chatter for different types of machine tools and machining operations are different.
(3) In some cases, the SLD and the system cutting tool, machine tools and the workpiece are changing continuously; thus, it is difficult to predict in advance.

Due to the above reasons, online chatter detection technologies have been developed after the late 1970s through monitoring signals like vibration, sound, and power etc. These technologies fit particularly well into modern manufacturing systems, such as FMS and CIMS.

Since the 1990s, some new algorithms and technologies, such as neutral network, expert systems, wavelet analysis, and smart materials and structures etc., have been adopted in chatter detection (Jia et al. 2006).

12.3.7 Advance in Machine Tools

With the advent of NC technology, CNC Machine tools, machining centers and FMS became the mainstream of machine tools. At the same time, some other progresses were also made in response to the development in high speed machining, heavy-duty machining and precision machining.

Ball screw was first developed in the 1930s, and applied to machine tools in 1955. Without ball screws, precision linear motion, a critical component in NC machine tools for precision machining, would be impossible.

In high-speed machining, the spindle RPM and feed speed are as high as 10 times of that in conventional machining. Besides, acceleration and deceleration normally happen in very short times. All of these put forward very high requirements on both dynamic and static performance of the machine tools. Some new technologies, such as electric spindles and high speed linear motor, were developed in addressing these issues.

As a relatively new technology, electric spindles integrate the main spindle and the motor into one set as shown in Fig. 12.7, eliminating the transmissions from the motor to the spindle. Thus, acceleration can be achieved quickly and very high spindle speed can be reached. In addition, the elimination of the transmission also get rid of the several factors embedded in the transmission, such as the elastic deformation, clearance, and friction losses related to the transmission. In summary the benefits of electric spindles can be stated as high spindle speed, high power, high rigidity, high accuracy and high reliability.

Only are a few countries in the world, including Switzerland and Germany, able to make electric spindles. Although already being installed on aircraft carriers for aircraft launching in 1945, Linear motors were not applied in machine tools until the end of the 20th century. Compared with ball screws, linear motors are of smaller inertial, simpler in structure, and more accurate. Thus, they are more suitable for machine tool drives. Japan, the U.S. and China are some of the countries in the leading position of this technology (Ye 2000).

Lathes and milling machines were first developed for Ultra-precision machining. In 1983, the Large Optics Diamond Turning Machine (LODTM) was constructed in U.S. for manufacturing large optics with complex surface. The LODTM used a

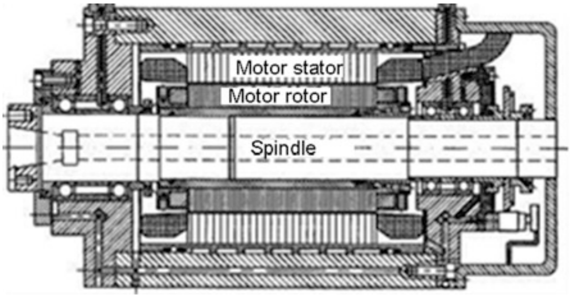


Fig. 12.7 Electric spindle

Fig. 12.8 Impeller of an aero engine (http://compressedairducation.com/tag/centrifugal/)

series of then advanced technologies, reaching a unimaginable accuracy level of 0.05 μm in spindle rotation (Yuan 2008; Yuan and Wang 2016).

12.4 Machining of Free-Form Surfaces

12.4.1 Free-Form Surface

Irregular surfaces are widely used in many industries, such as space, energy, military and automotive. Impellers in airplane engines (Fig. 12.8), screw propellers in large ships (Fig. 12.9), and stamping molds of auto-body panels are among the most representatives.

In CAD or computer graphics, these irregular surfaces are termed free-form surfaces, indicating that the surfaces can not be represented by the basic features, such as cylinders, cones, spheres and planes etc.

An important application of free-form surfaces is the "optical free-form surfaces". Spherical surfaces are most commonly used in traditional optical systems; however, more complex surfaces, such as those without rotational symmetry or

Fig. 12.9 Screw propeller (https://www.ebay.com.au)

more generally free-form surfaces, began to be used in some special optical systems, such as colorful displays and some cameras (Li 1998).

The lenses in some large telescopes are as large as meters in diameter. Some others under construction are even larger.

Machining and fabrication of free-form surfaces are very challenging.

Before the 1970s, free-form optical surfaces were made in two main steps. First the rough geometry of the surface was copied by various molding processes, such as injection molding. Then the refined surface was obtained through manual grinding and polishing. This method was very low in productivity, and had been used in manufacturing telescopes since Newton's time. The mold shaping processes in this method have pretty good repetitive accuracy, moderate production cost, being suitable for production of large quantity of optical surfaces of medium and low accuracy (Cheng and Tan 2013). However, the difficulty of making free-form surfaces was not really solved. It simply transferred the difficulty from making the optical component to making the mold.

The NC technology was invented in 1952 for manufacturing blades of helicopters. Research on automated machining of complex surfaces started in the 1960s. Now the manufacturing of free-form optical surfaces is gradually converged to multiple-axis CNC machining (Li 1998; Neo 2017).

Free-form surface allows more freedom for the optics designers to focus on the product's functional, aesthetic and ergonomic requirements. However, the manufacturing is more difficult. The common operations in manufacturing include CNC milling, grinding, polishing, measurement, and corrective polishing. The accuracy requirement on free-form optical surfaces is very high, sometimes in the order of sub-micron in dimension and sub-nanometer in surface finish. The materials, such as glass, of the optical components generally fall in category of difficult-to-cut materials.

Free-form surfaces are hard to be mathematically represented. In practice, CAD and CAM in particular, they are modeled by control points, degree, and the number of segments with spline curves which is commonly described by the Non-uniform rational B-splines (NURBS). NURBS is elegant and has the required flexibility in defining the surface. It has been adopted in the mainstream CAD/CAM packages, including UG and Pro-E.

The current trend is to integrate the design, manufacturing and measurement of complex parts with free-form surfaces into one system (DEMS 2010).

12.4.2 Machining of Spiral Bevel Gears

Among the many types of gears, spiral bevel gears have the most complicated geometry and are the hardest to manufacture. In this section we introduce the evolution of two typical manufacturing methods with an intention to illustrate the interaction of different technologies.

Spiral bevel gears are widely used in automotive differentials. The fast growth of automotive and space industries created a very high demand on spiral bevel gears and hypoid gears of high accuracy. This demand in turn inspired the development of corresponding gear manufacturing technologies (Hotchkiss 1969; Maiuri 2007).

William Gleason, an Irish immigrant to the U.S., founded a machine shop in New York in 1865 to build gear-cutting machine tools. This was the origin of the later Gleason Corporation, a prominent machine tool maker in the world. At the beginning, only machines for cutting spur gears were made in this company. In 1913, Gleason invented a method for cutting spiral bevel gears with face milling as shown in Fig. 12.10. This is the well know Gleason method, a single indexing method. The tooth trace of the bevel gear in the Gleason method is a circular arc and the tooth depth at the larger diameter is larger than that at the smaller diameter (tapered teeth). The Gleason method can also be used in grinding and lapping. In 1927, the company successfully developed the process of manufacturing hypoid gears.

In 1946, Oerlikon, a Swiss company, developed a continuous indexing method of cutting spiral bevel gears, called Oerlikon method as shown in Fig. 12.11. The tooth trace of the gear in this method is elongated epicycloid and the tooth depth along the face width is constant.

Spiral bevel gears made from different methods cannot be engaged. This is different from spur gears.

The Oerlikon method was actually coincident with a patent of Gleason in 1914.

The continuous indexing Oerlikon method is obviously more productive than the single indexing Gleason method. One may wonder why Gleason did not develop its own continuous indexing method based on the patent. The following two reasons

Fig. 12.10 Gleason process

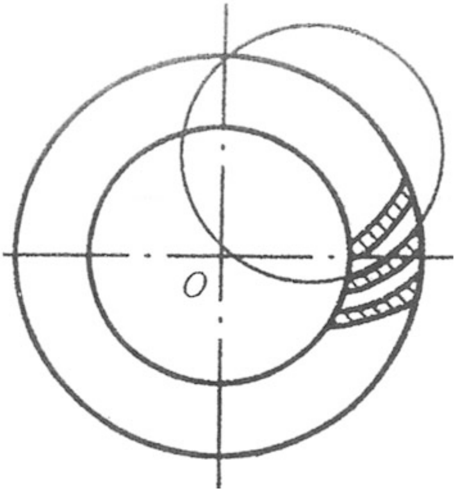
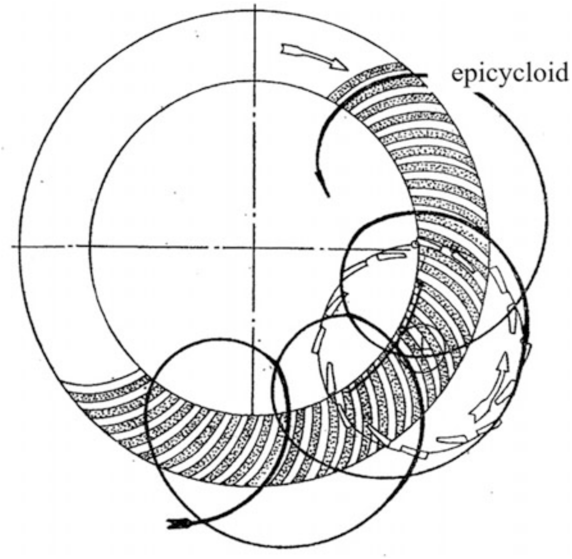


Fig. 12.11 Oerlikon process



may be responsible for this fact. First, gears made through the Oerlikon method could not be ground; ground gear set had to be manufactured exclusively in a single indexing process. However, the spiral bevel gears used in the automotive and space industries required grinding because of their hardened surface. Secondly, the constant tooth depth of the Oerlikon gears was not in agreement with the equal-strength rule. These factors made the Gleason's machines dominant in the market for several decades.

After invented in the 1950s, the NC technology quickly found application in milling, turning and grinding machines. To the 1970s, spiral gear cutting machines adopted the NC technology. This was a fundamental step making the Gleason's machine be able to cut Oerlikon gears, and vice versa. To this point the two spiral gear manufacturing methods, which used to be separated with each other with clear borders, were merged together.

In 1993, the Oerlikon Geartec AG was acquired by Klingelnberg, a Germany based company. To the 1990s, a turning point was brought to the Oerlikon method. (1) grinding of gears using the continuous indexing method became possible and economical with the advent of CNC technology. (2) drying cutting process for bevel gears was invented in 1997 and was applied to the C 28 machine.

In the year of 2002, the spiral bevel gear cutting machines from Klingelnberg-Oerlikon became the market leader for the first time in history.

12.5 Non-traditional Machining

Conventional machining processes use a sharp cutting tool to remove materials from the workpiece. While non-traditional machining methods achieves the material removal by means of mechanical, thermal, electrical or chemical energy sources.

Non-traditional machining processes have been developed since WWII when the demand for hard material components of complicated geometry came up. The machining of these parts could not be achieved through traditional machining technologies. Thus, alternative processes had to be sought. The challenges raised can be summarized as below (Bai et al. 2014).

(1) Some very hard materials, such as cemented carbides, titanium alloy, diamonds, and hardened steels, are impossible to be machined through traditional cutting and grinding.
(2) Very brittle materials, such as heat-treated alloys, glass, ceramics, and powder-metallurgy parts, are difficult to be machined without damage to the part.
(3) Some parts have complex shapes, including such features as internal and external profiles or holes with high length-to-diameter ratios.
(4) Some workpieces are too flexible or slender to withstand the forces in machining or grinding, or the parts are difficult to clamp in fixtures and work-holding devices.
(5) Special surface finish and dimensional tolerance requirements cannot be met by other manufacturing processes or are uneconomical.

There are many types of machining methods in this group, including electric discharge machining (EDM), electrochemical machining, ultrasonic machining, electron beam machining (EBM) and photochemical machining etc. In most of these machining methods no mechanical contact with the workpiece happens; thus, the above challenges do not constitute an issue.

12.5.1 Thermal Energy Processes

Machining processes based on thermal energy include electric discharge machining (EDM), laser beam machining (LBM) and electron beam machining (EBM) etc.

12.5.1.1 Electric Discharge Machining (EDM)

EDM is based on the erosion of metals by spark discharges. In this process, the tool and workpiece are connected to a DC power supply and placed in a dielectric fluid. The two main processes in this category include EDM, and wire EDM.

In 1770, an English physicist, Joseph Priestley, found the erosive effect of electric discharges on metals for the first time in history. Further research was conducted almost simultaneously in the Soviet Union and the U.S. at the beginning of WWII.

B. Lazalenko and N. Lazalenko (Лазаленко), two Soviet scientists, were assigned to exploit the destructive effect of electric discharges on tungsten, but accidently discovered that the erosive effect of electric discharges could be precisely controlled. In 1943, a spark machining process, thus called at that time, was developed.

In the U.S., a research team led by Harold Stark developed a sparking machine around the same time for the removal of broken taps and drills from cast aluminum bodies of hydraulic valves. The initial machine created sparks at a frequency of 60 times per second. Later vacuum tubes were used in the circuit, increasing the frequency up to thousands of sparks per second (Jameson 2001).

The time for the evolution of wire EDM is not as clear as the EDM, roughly covering the period from the early 1960s to the early 1970s.

In 1967, a wire EDM machine was manufactured in the Soviet Union. During the 1960s, a research group in the U.S. led by David Dulebohn developed an optical line following system. In 1974, a wire EDM machines controlled by the optical line following system was constructed. Later in 1976, a CNC wire EDM machine was developed using the same computer program (Jameson 2001).

12.5.1.2 Laser Beam Machining (LBM)

In LBM, the source of energy is a laser. It focuses optical energy on the surface of the workpiece. Although the theory of laser was known very early, the first actual working laser was created by Theodore Maiman, an American physicist, in May of 1960 (Maiman 1960). In 1961, the first commercial laser was put in the market. In the Soviet Union, N. Basov (Николай Басов) proposed the idea of semiconductor laser in 1959 and built a device in 1963.

Shortly after Maiman's demonstration of a working laser, Western Electric of the U.S. developed a laser machine for drilling holes in diamond dies in 1965. In 1967, a German scientist, Peter Houldcroft, designed a laser cutting nozzle to cut 1 mm thick steel sheet with a focused CO_2 laser beam. By the 1970s, laser cutting machines with a power of several KW were developed and used in high speed cutting of various materials. Some example parts made from laser processing are shown in (Fig. 12.12)

12.5.1.3 Electron Beam Machining (EBM)

The energy source in EBM is high-velocity electrons, which strike the workpiece surface and generate heat. The theory of electron beam technology appeared in the late 19th century. The idea of using EB to build a furnace for melting, sintering and

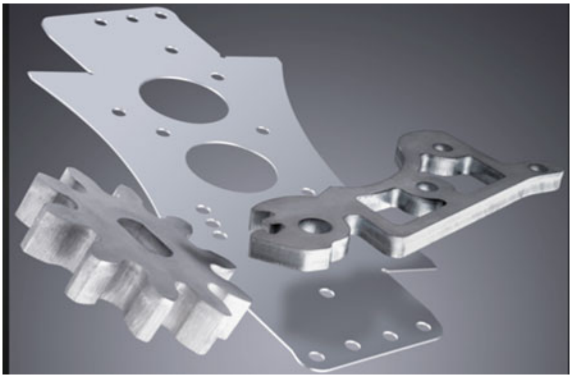


Fig. 12.12 Parts with laser processing (http://images.fabricatingandmetalworking.com)

joining was first mentioned in a paper published in 1904, and was patented in 1906 (Steigerwald 2007). Machining with EB, however, was not advanced until 1949 when Dr. Karl-Heinz Steigerwald, a German scientist, used EB to make very fine holes. The power of the EB in the first machine was only somewhere in between 100 and 200 W. Then around 1952, He built another two machines to make holes as small as 80 μm in diameter on watch bearing. In 1958, an EB machine was developed for welding based on the previous drilling model.

EB has high power density, and is able to be controlled precisely. Thus, EBM is well suited for welding, accurate machining and surface treatment.

12.5.2 Mechanical Energy Processes

Ultrasonic machining and water jet machining both use mechanical energy other than a sharp cutting tool to achieve machining.

12.5.2.1 Ultrasonic Machining (USM)

Ultrasonic machining (USM) is suitable for machining various metals, such as stainless steel and titanium, and brittle non-metal materials, such as glass, ceramics, and carbides etc.

Two American scientists first noted the application of high frequency sound wave for machining in 1927. The first patent of USM was issued in 1945 to Lewis Balamuth who found that ultrasonic wave could effectively machine various brittle materials (Balamuth 1964). In 1951, he built the first physical USM machine. Since then until the 1970s, almost all patents of USM granted in the U.S. were owned by Balamuth and his group.

Fig. 12.13 Thick steel plate cut with water jet (www.allsetengineering.com)

12.5.2.2 Water Jet Machining

Use of water jet is traced back to coal mining in the mid 19th century. Paper Patents, a company in the U.S., developed a low-pressure water jet system to cut paper in 1933.

In 1956, Carl Johnson, an engineer in Luxembourg, developed a method for cutting soft plastic shapes using a thin stream, high-pressure waterjet. In 1958, Billie Schwacha, an aviation engineer, developed a system that used ultrahigh pressure (690 MPa) liquid jet to cut steels. This was a landmark indicating that water jet technology reached a critical point of cutting hard materials. During the 1960s, several companies joined the stream to further refine water jet systems (Fig. 12.13).

In 1982 an Egyptian-born American engineer, named Mohamed Hashish, published his results based on several year research. He concluded that steel and concrete could be cut with water jet by adding abrasives to the water. This was a real breakthrough in this technology (Hashish 1984). He continued his work to develop a commercially viable abrasive water jet nozzle in 1983 for cutting hard materials. Soon this technology was used in cutting very thick glass (12 in.) for space optics mirror cores. Since then water jet has been widely used in cutting hard and brittle materials, including stainless steels, titanium, stone, ceramics, glass etc.

In 1993, OMAX Corporation was established in the U.S. specializing in abrasive water jet machining. The VP of the company, John Olsen, developed the PC controller specifically designed for abrasive jet machining.

12.5.3 *Electrochemical Machining*

Electrochemical machining (ECM) uses electrical energy in combination with chemical reactions to accomplish material removal. ECM is less sensitive to the hardness and toughness of the material than the conventional machining; thus, it has gained wide applications in industry. Typical processes of ECM include deburring, grinding, polishing and drilling etc.

The theoretical basis for ECM was laid during the late 19th century. The first effort was made by a Soviet Union researcher, W. Gusseff (Владимир Гуссев) (Valenti 2001). However, the concept did not progress much in the following two decades. Interest was resumed during the 1950s when the space development required the shaping of high strength alloys. In 1959, the Anocut Engineering Company in the U.S. produced the first machine of ECM using direct current. From then on, ECM was widely used in various industrial applications.

12.6 Additive Manufacturing

During the 1980s and 1990s, rapid prototyping (RP) and 3D printing were developed. These new manufacturing technologies became critical for the industry to speed up product development.

RP and 3D printing are essentially the same in principle, and are formally called additive manufacturing (AM). Both create a 3D physical model based on virtual CAD models directly without the need for process planning. The data of the 3D CAD models are broken down into a series of 2D cross-sections of a finite thickness. These cross-sections are fed into AM machines so that they can be combined, adding them together in a layer-by-layer sequence to form the physical part. The term AM is formed in contrast to the conventional subtractive manufacturing technologies, such as the various machining technologies (Gibson et al. 2015).

12.6.1 Rapid Prototyping (RP)

The practice of making objects layer by layer is dated back thousands of years in China for making lacquerware and in Egypt for making layered lumbers. In 1892, an Austrian named Joseph Blanther developed a layered method for making a mold for topographical relief maps, and was granted the patent in the U.S. this is widely regarded as the origin of the modern concept of RP. In 1974, Matsubara at Mitsubishi of Japan proposed a topographical process with a photo-hardening photopolymer resin to form thin layers stacked to make a casting mold (Bourell and Beaman 2012).

Some researchers in the U.S. and Japan independently put forward their concepts of RP during the period between the late 1970s and early 1980s. Among these includes Charles Hull, an American researcher, who was granted a patent in the U.

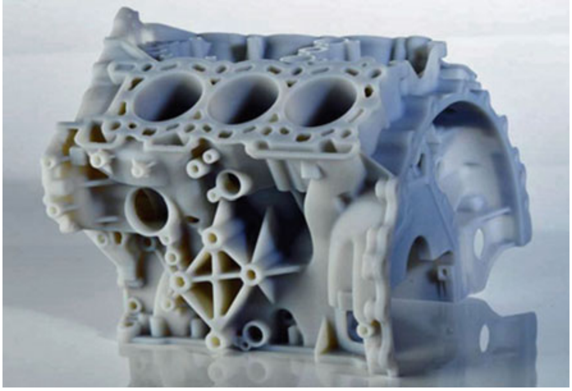


Fig. 12.14 A model of engine block with 3D Print (https://mediacopy.co.uk/3d_printing_.htm)

Fig. 12.15 New teeth with 3D print (https://blog.dentalplans.com/)

S. and started commercialization of RP through founding a company in the U.S. in 1986. Hull coined a term, "stereolithography" (Jacobs 1992), in his patent application; but, this new word was not widely accepted and was soon replaced by RP and 3D printing.

Following this came a booming of RP development. Many concepts were put forward; technologies and systems were developed. The U.S. is a main player in RP development, which made 81.5% of all the RP machines all over the world in 1999.

RP showed great potential in industrial applications. Its advantages can be summarized as below: (1) it can speed up production: design flaws and appearance imperfection could be quickly found and fixed with a physical model; (2) the physical models generated by RP are tangible and real, better than the virtue models in the computer; (3) RP can make models with any shape and geometry.

RP, however, is for making prototype model, not for real production. This is clear in its name.

12.6.2 3D Printing

12.6.2.1 Concept

As we stated in previous section, the working principle behind RP and 3D printing is the same. However, there is a fundamental difference between the two. 3D printing is for real production, not only for making prototype. Now 3D printing has found many applications, such as making dental hardware, artistic objects as well as airplane parts (Figs. 12.14 and 12.15). It should be noted that the list of application is getting longer almost every day.

If we treat “3D printing” as a printing technology, it would be traced back many years. As a manufacturing technology; however, C. Hull was the pioneer.

3D printing has high accuracy and is able to print products of any shape. Items with very complicated geometries, which are difficult to manufacture with traditional technologies, can be easily made with 3D printing. Mechanical assemblies consisting of individual components, such as gears and bearings etc., can be directly printed out without the need of assembling operation. If needed, machining, such as grinding and drilling etc., can be applied to the printed product.

12.6.2.2 Application in Aerospace Engineering

The U.S. Air Force showed great interest in 3D printing. Titanium is widely used in making airplane parts. Its density is only about half of steel. Its strength, however, exceeds almost all steel alloys. If titanium can be melt with laser, then complicated airplane part would be possible to be made through layer by layer addition of the material. Undoubtedly this would have great potential to accelerate the airplane production. In 1985, the Pentagon started to sponsor research projects in manufacturing titanium alloy airplane components with laser melting. The research was conducted secretly, and publicized in 1992.

EADS, the parent company of Airbus, also supported research in additive manufacturing of airplane components. The whole wing of an unmanned airplanes was attempted to be made by 3D printing.

Additive manufacturing shows outstanding advantages in the manufacturing of airplane components. Some are as below: (1) no need for the large presses and the expensive dies required in conventional forging operation; (2) additive manufacturing creates “near net shape” parts; thus, little additional manufacturing operations are needed to obtain the final parts; (3) parts created through additive manufacturing have better mechanical properties than that made from traditional forging operation; (4) lower overall production cost and shorter production cycle.

If implemented successfully in manufacturing of complicated components of high strength, titanium alloy, the additive manufacturing would cause a revolution to the traditional airplane manufacturing industry.

The main industrialized countries in the world all made great effort in advocating additive manufacturing. The U.S., for example, created a national network, Manufacturing USA, in coordinating the investment in emerging advanced manufacturing technologies, among which additive manufacturing is in the center.

12.6.2.3 Future Development of 3D Printing

3D printing is able to make not only prototype models but also real products, showing great advantage in manufacturing of complicated shapes. As a revolutionary technology, it will bring fundamental changes to the manufacturing, business and even society. Some of changes are listed below.

(1) 3D printing's influence goes well beyond traditional factory production. It may find its way to the manufacturing of small items for offices and homes.
(2) 3D greatly shortens the time for production.
(3) 3D also has unique advantages over conventional manufacturing technologies in reduction of cost, reduction of material consumption as well as making parts with complicated geometry which are hard to be produced through traditional methods.

Items that have been made so far through 3D printing include customized cell phones, fiddles, jewellery and ornaments, batteries and automotive parts etc. In fact the list keeps expanding everyday. It is expected that whole machines can be printed in some cases.

In addition, the 3D technology creates new windows for business opportunities. For example, real customized products with very small quantity will become feasible with 3D printing. The potential to integrate it with other new technologies, such as internet, has been a hot topic in not only the academic community, but also in daily conversation (Wright 2001; Rifkin 2011; Schwab 2016).

Although the potential is huge, it is still too earlier to say that it will completely replace traditional manufacturing technologies. Many challenges are still ahead.

12.7 Green Manufacturing

12.7.1 Green Manufacturing: From Awareness to Action

It is hard to mark the exact starting point of green manufacturing. It is generally thought that the concept was first proposed in the 1980s. The publication of the blue book of Society of Manufacturing Engineers (SME), "Green manufacturing", in 1996 defined the concept, scope and contents in a systematic way for the first time.

Kenneth Boulding proposed the concept of circular economy in 1996. It took almost 30 years to move from the circular economy to the green manufacturing of

SME. Why did it go so slow at a time when science and technology were under a fast development after WWII.

As stated in Sect. 9.2.2, the first two Industrial Revolutions brought tremendous changes to the human society. Along with the changes was the inflated desires of our society. To pedal the brake to such a huge “desire inertial”, three decades seems not even long enough.

A severe consequence of the two Industrial Revolutions is the environmental pollution and over consumption of natural resources. It is a critical challenge to mitigate these problems and make the manufacturing industry sustainable (Dornfeld 2013).

Green manufacturing is a new philosophy of manufacturing in addressing the two critical challenges, preventing environmental pollution and saving natural resources. Its goal is to minimize negative effects on the environment and consumption of natural resources for the whole life cycle of a product, covering design, manufacturing, packaging, transportation, use and end of life recycling.

Green manufacturing has caught great attention from both the academia and industry. The main industrialized countries and some international organizations in the world have been establishing regulations, standards and laws to enforce the green criteria on product quality and every life cycle stage. The high green criteria form the so-called “green barriers” in international trade.

Many countries, including Japan, Canada, the U.S., Britain, and Germany, have established national green industry policies attempting to guide the national development of green manufacturing. Ecolabelling systems have been practised in more than 20 countries, including Germany, France, Switzerland, Australia, Singapore, and Malaysia etc. This practice greatly helps promote the product and service of these countries. On the other hand, customers, in the industrialized countries in particular, are becoming more aware of the environmental issues relating to unsustainable production; and tend to buy green products. This in turn pushes the further development of green manufacturing. It is estimated that “green products” make up 5–10% of the total in current market, and green products may become the mainstream in next decade.

Green manufacturing is the focus for many research groups in universities.

12.7.2 Scope of Green Manufacturing

Green manufacturing involves the whole life cycle of a product. Design of course is included. Any green products have to be designed “green”.

The scope of green manufacturing can be summarized as below (CSME 2011).

(1) Green design

Energy saving and less pollution have to be considered in the design stage for any product. In addition, easy maintenance and recycling need to be planned in design stage as well.

(2) Green materials

Use “green materials” if possible, including harmless materials, recyclable materials, remanufacturable materials etc.

(3) Green process

Use production technologies of high energy efficiency and low pollution. For example, net-shaping processes does not need machining; dry machining removes the pollution of cutting fluid.

(4) Green recycling

For mechanical engineering, remanufacturing technology is the most typical, and promising measure of green recycling.

Several other concepts have certain overlapping scope with green manufacturing. These include sustainable manufacturing, environmentally benign manufacturing and lean manufacturing etc. These terms are now widely used interchangeably.

12.7.3 Remanufacturing

Starting from the 1950s, a series of initiatives had been taken in the U.S. to raise public awareness of environmental issues. The National Environment Policy Act (NEPA) was enacted in 1969 and signed into law in 1970 by the President. This is the first major environmental law in the U.S. In the same year the Environmental Protection Agency (EPA) was established. At the same time the Congress passed the Resource Recovery Act with intention to shift the nation’s attention to the practise of recycling, resource recovery and conversion of wastes into energy. Then, the 3 R’s, namely reuse, reduce and recycle, were born.

Similar concepts were developed later for different fields, and in different countries. For instance, in the automotive manufacturing, the “reduce” is replaced by repair and remanufacture; thus, the 3 R’s become 4Rs. In China, 3R’s are used, but the “reduce” is replaced with remanufacture. Figure 12.16 schematically depicts the process of the green manufacturing in which there are three loops, ①, ②, ③. Generally loop ③ is the most expensive, ② is lesser, and ① is the least.

In fact, remanufacturing already existed in the U.S. in the 1930s. During the Great Depression, most people did not have the money to buy a new car. Thus, a business came into existence to fix abandoned vehicles and resell them. In 1942, the U.S. entered WWII, and various resources were prioritized toward the war. Thus,

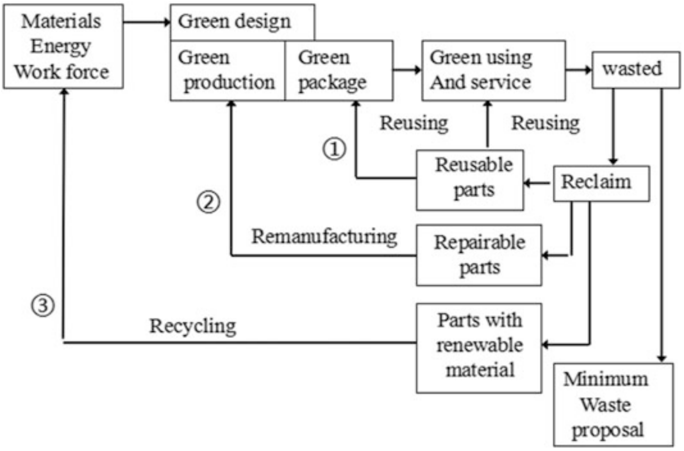


Fig. 12.16 Process of green manufacturing

many cars and trucks had to be operated through remanufacturing. At that time, remanufacturing was only a temporary measure to survive hard times. After entering the 21st century, however, it has become a strategic path to circular economy for many countries.

Remanufacturing has grown fast in the U.S. and Europe. In the U.S., automotive remanufacturing is the largest among many others. Many components, such as engines, transmissions, and brake calipers etc. are put in the market after remanufacturing.

Remanufacturing is also used in the U.S. for military vehicles and weapons, including the Apache attack helicopters, M1A1 tanks, and Minuteman II missiles.

The fundamental mechanism for remanufacturing is that the many individual components in a machine have different life spans, and reach their end of life at different times. For instance, the gearbox housing and frame in a machine tool have very long life time, while the sliding track may have much shorter life due to the many sliding actions.

With adaption of new materials and technologies, it is possible to make the remanufactured products have even better performances than the original ones. For example, nanosurface engineering can remarkably improve the wear-resistance, anti-corrosion and fatigue-resistance of the remanufactured parts.

Xu Binshi, an academician of the Chinese Academy of Engineering, is a pioneer of remanufacturing in China (Xu et al. 2007). The Chinese government has already made a long-term plan of remanufacturing. In the U.S. and Europe, remanufacturing focuses on resuming the original dimension of parts through various technologies or resuming the function of a machine through replacing broken parts. In China, however, a different path is taken. Surface engineering technologies are applied in remanufacturing based on system life evaluation. This not only improves the quality of the remanufactured products, but also significantly increases the remanufactured rate (CSME 2011).

12.8 Some Other Progresses in Manufacturing

Efficiency in direct production processes experienced dramatic increase during the period between 1870 and 1970. However, the progress in management and product design during the same period was not comparable with that in direct production. Thus, management and design became the bottleneck for further advance in productivity. Computer along with the information and communication technologies (ICT) are the real game changer. The first application was in the CAD/CAM. FMS was another application which achieved automation in production equipment. The next step was the automation in all aspects of manufacturing, including direct production and production support systems.

12.8.1 Computer Integrated Manufacturing System

12.8.1.1 Basis: Popularization of Computer

Starting from the 1970s, computers became popularized. Consequently automation has been accomplished in almost every aspect of the manufacturing industry, including:

(1) design automation: this includes computer aided drafting, optimum design, CAD and CAE etc.
(2) automation in manufacturing: this category includes CAPP, CNC, FMS, industrial robots etc.
(3) automation in process control: sensors, signal processing, decision making, control engineering, process monitoring and control, fault diagnosis etc.
(4) automation in management: this includes material requirements planning (MRP), manufacturing resource planning (MRPII), enterprise resource planning (ERP), supply chain and electronic commerce etc.

Application of computers in the above areas undoubtedly played a great role in improving productivity and product quality. However, automation in these separated areas might not necessarily lead to the optimum of the whole production system. Then integration of the automation in the whole production system became a choice.

12.8.1.2 Background of CIMS

Computer Integrated Manufacturing System(CIMS)was first proposed by a American scholar named Joseph Harrington in 1974 (Harrington 1979).

In 1976, a research project, titled as Integrated Computer Aided Manufacturing (ICAM), was started under the sponsorship of the U.S. Air Force. This project was led by Dennis Wisnosky. Harrington helped in designing the ICAM program, and expanded the concept of "CIMS" to include the entire enterprise (Savage 1996).

ICAM identified data as the center of integration and the data had to be shared by different departments within the enterprise. This was then a concept well ahead of time because no manufacturing company realized this necessity and took real action before the 1990s. The project also established the methods to analyze and document the manufacturing activities within an enterprise. Also from ICAM, the standard of modeling and analysis in management and business improvement efforts, namely IDEFs, was created.

Integration requires a network. Wisnosky is among the first to understand the importance of integration, and his work represented a major step toward shifting the focus of manufacturing from a series of sequential operations to parallel processing. ICAM strongly influenced the research activities on computer integrated manufacturing (CIM) and computer aided manufacturing (CAM) in the United States. The ICAM was initially planned to cover all aspects of a manufacturing enterprise. This was then determined to be unmanageable, costly and of high risk (Shumaker 1980). Harrington's concept, hence, was not widely accepted until the 1980s.

Starting from the 1970s, the U.S. economy has experienced a shifting from the secondary industries to the tertiary industries. Manufacturing was thus regarded as "sunset industries". With the decline of the U.S. manufacturing, the traditional industrial areas with heavy manufacturing industries became the "rust belt". This trend was not tuned until the Presidency of Bill Clinton when the U.S. made effort to revitalize its manufacturing with information technology. CIMS then regained attention from both industry and government.

12.8.1.3 Contents of CIMS

In Harrington's concept of CIMS, all the aspects within a business are inter-dependent, and should be considered as a whole. Data collection, communication and processing are the center of the whole process (Harrington 1979).

CIMS, as shown in Fig. 12.17, combines various computer technologies, including advanced manufacturing technology, information technology, automation technology and system engineering technology, to integrate all operations of manufacturing, from logistics to management, with a common data repository. CIMS can achieve the following benefits through integration and optimization: shorter product developing time (T), higher product quality(Q), lower production cost (C), better service (S) and cleaner environment (E).

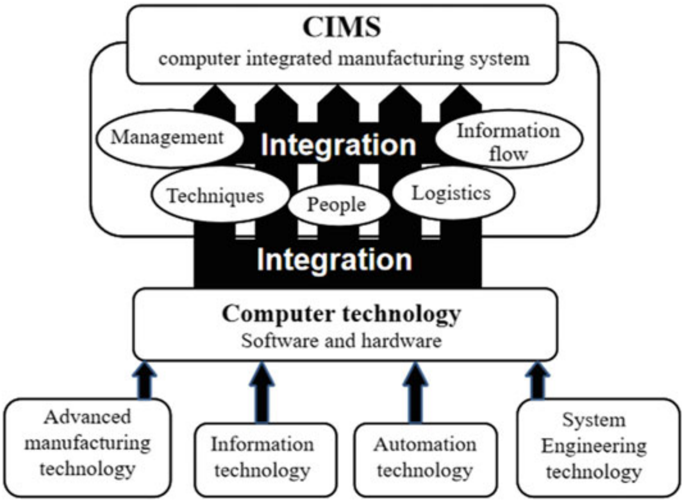


Fig. 12.17 Computer integrated manufacturing system

Since the mid 1980s, CIMS has attracted the attention from many large manufacturing companies, and created significant economic benefit to the relevant companies.

It is a revolutionary step to integrate the individual automations into a whole. CIMS represents the highest level of automation in manufacturing. Now it has been accepted by more and more manufacturing companies, in both developed and developing countries. Application is starting to expand from manufacturing of discrete products to continuous products. However, the majority are still on discrete products.

12.8.1.4 Second Thought on CIMS

One of the initial objectives of CIMS is fully automated, unmanned factories. However, it has gradually become clear that this ideal, fully automated system is not practical, at least presently. With this realization, the current effort is turned to more practical solutions with a certain level of integrated automation in the manufacturing systems (Zhang 2011).

12.8.2 Distributed Manufacturing

Internet was first developed in 1969 in the U.S. In 1991 internet entered a new era through privatization. Then came the internet penetration into manufacturing.

The great potential of internet in manufacturing was realized right after it was invented.

The first attempt was made through a project, named Information Power Grid (IPG), sponsored by NASA and NSF. IPG was initiated with an overall goal to increase the ability of NASA to use distributed computing and data resources to solve problems (Johnston et al. 1999).

A group of business executives in the U.S. compiled a vision-based strategy for the emerging global competitive environment in 1991, and the results were published as “The 21st Century Manufacturing Enterprise Strategy” in 1992 by Lehigh University. Among the main concepts proposed in this report included the agile manufacturing enterprise, factory American net (FAN), and virtual corporations (Yusuf et al. 1999; Sanchez and Nagi 2001).

Virtual corporations mean that multiple firms in different locations can come together to form temporary partnerships through online collaboration. The networked organization helps the individual firms to share skills and resources in the market without interruption of their core business.

Agile manufacturing means that enterprises are enabled to react timely to the fast changing and hard-to-predict market through combining virtual corporations, flexible manufacturing technologies and highly-skilled labor force. At the center is the virtual corporation which is based on network and information technology. In this regard, agile manufacturing bears great similarity with distributed manufacturing.

After the publication of “The 21st Century Manufacturing Enterprise Strategy”, many research projects have been conducted in the U.S. under the sponsorship of the Department of Energy, Department of Defence, NSF and some companies and universities. After 1998, research on distributed manufacturing was also started in Japan, China and some European countries (Gu et al. 2001).

In 2013, the German government launched the Industry 4.0 to promote the competitiveness of German manufacturing. The foundation of this strategy is cyber-physical systems and internet of things (IoT).

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