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CUTTING TOOL ENGINEERING

years of technological development

A CUTTING TOOL ENGINEERING supplement

Tech Timeline: 50 years of manufacturing technology

The past half century has witnessed tremendous advancements in manufacturing technology. Many have been chronicled in the pages of CUTTING TOOL ENGINEERING during our 50-year existence. In this timeline and the articles that follow, we revisit some of the key developments and events.

1950s

- John T. Parsons receives patent for numerical control of machine tools. He conceives idea of a digitally controlled, 3-D servomechanism fitted to a milling machine.
- Massachusetts Institute of Technology and U.S. Air Force demonstrate prototype of an NC milling machine based on John Parsons' idea. (See page 98.)
- IBM ships its first electronic computer.
- Toyota Motor Co. develops manufacturing concepts that eventually become known as JIT (just-in-time) production and TQM (Total Quality Management).
- Monarch Machine Tool introduces an NC lathe at the 1955 Machine Tool Show (predecessor to IMTS).
- Douglas Ross, software researcher at MIT's Servo Lab, creates the APT (Automatically Programmed Tool) system, which allows automatic programming of NCs. Becomes international standard in '78. (See page 102.)
- J.M. Juran and F.M. Gryna publish the *Quality Control Handbook*.
- Wide acceptance and application of throwaway inserts. (See page 148.)
- General Electric introduces Man-Made industrial diamond. (See page 116.)
- Dr. Patrick J. Hanratty develops first commercial CAM software system, an NC programming tool named PRONTO. (See page 119.)
- Development of creep-feed grinding.
- Sinker EDMs debut; wire EDM follows in the '60s.

1960s

- Ruby laser introduced; gas laser debuts shortly after.
- Ivan Sutherland develops Sketchpad, the first commercial CAD software.
- Unimate, the first industrial robot, begins working at General Motors.
- ASCII permits machines from different builders to exchange data.
- Inserts with built-in chipbreakers introduced.
- Aerospace industry begins specifying components made of nickel-base "superalloys," which challenges parts suppliers.
- First CMM (coordinate-measuring machine) built.
- J.F. Kahles and M. Field publish *Machining Data Handbook*. (See page 134.)
- The Cincinnati Milling Machine Co. introduces an NC EDM.
- Cutting tool coatings introduced. (See page 140.)
- First manufacturing cell appears; concept flourishes in '80s.

1970s

- Programmable logic controllers become commercially available. First PLC was manufactured in response to General Motors' request for an electronic device able to replace hard-wired, relay-based control systems.

- Manufactured form of PCD (polycrystalline diamond) emerges.
- Development of waterjet cutting.
- First public demonstration of 3-D CAD/CAM.
- Feasibility of HSM (high-speed machining) in production environments studied. (See page 128.)
- CAT, or V-flange, toolholders developed by Caterpillar engineers and become predominant style in U.S.
- First modular tooling system debuts.
- The Defense Department's ARPANet (Advanced Research Projects Agency Network)—predecessor of the Internet—links 25 computers.
- NC tool presetters introduced.
- Introduction of multilayer tool coatings.

1980s

- Digital control introduced for peripheral equipment and specialty machines.
- 3M introduces Cubitron (sol-gel) abrasive grains.
- Introduction of StereoLithography Apparatus, which incorporates a laser that transforms liquid plastic into a solid 3-D object, jump-starts rapid-prototyping industry.
- PCs used to track machining parameters and develop in-house machinability databases.
- Shrink-fit toolholders developed.
- Indirect tool-monitoring technologies and development of adaptive controls for machine tools facilitate untended machining.
- High-pressure coolant-delivery systems used to break chips.

1990s

- James P. Womack, Daniel T. Jones and Daniel Roos publish *The Machine that Changed the World*, the book that gave rise to the phrase "lean manufacturing."
- Thin-film-diamond tools appear.
- Hard turning eliminates grinding in the production of certain types of parts.
- U.S. auto manufacturers jointly implement a new quality standard—QS 9000—for their Tier 1 suppliers.
- DIN, the German standards organization, publishes a standard for HSK toolholder shanks; HSK holders gain a toehold in U.S. (See page 154.)
- Top U.S. manufacturing executives predict (in 1997) that China will become America's biggest global competitor.
- Tighter environmental laws governing metalworking-fluid disposal and improved tool coatings spur interest in dry machining.
- Open-architecture CNCs developed.

2000s

- Demand spikes for multitask machine tools that can turn and mill. (See page 110.)
- Machine tools equipped with linear motors debut at IMTS 2000; a prototype on display boasts feed rates of 2,400 ipm and rapid-traverse rates of 4,000 ipm.
- 9/11 terrorist attacks depress an already weakening manufacturing economy; recovery begins in early 2003.
- Use of Swiss-style machine tools grows, a result of demand from the medical community and industries requiring small precision parts.
- Growing use of FEA (finite element analysis) to optimize the designs of machine tools, tooling and fixturing.

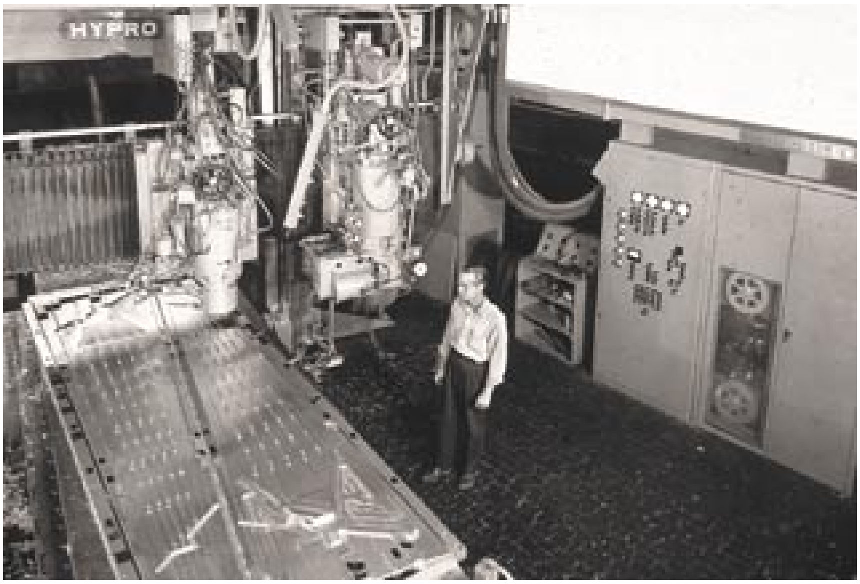
Numbers Take Control: NC machines

BY WILLIAM MAKELY

It's not exactly clear which numerically controlled machine tool entered the market first. Many companies claim to be among the first, but most records were destroyed or lost due to subsequent company closings and acquisitions, and many of the people involved at the dawn of the NC age have left the industry. In the final analysis, though, when NC appeared it altered forever the way machine tools operate.

Sources agree that in 1949, the U.S. Air Force commissioned the Massachusetts Institute of Technology ServoMechanism Laboratory to begin research on NC machine tools. Such machines would enable the Air Force to more effectively produce complex spares and other parts for military aircraft on a repeatable basis. MIT began its research in 1950.

In 1952, MIT demonstrated a prototype of an NC machine tool. The demonstration impressed Giddings & Lewis Machine Tools, and a subsequent order for 40'×20' dies for a press being built for the Air Force reinforced the benefit of building an NC mill. The size of the dies and the tolerances of 0.0010" to 0.0015" required by the Air Force would compound the chance for machining errors if performed manually.



Giddings & Lewis

Numericord, in the '50s, controls milling of a mold for skin panels for an Air Force jet.

In April 1953, G&L joined with MIT and General Electric Co. to build a digital control system named Numericord, using a magnetic-tape playback system GE was developing. The control developed by MIT produced key-punched paper tape whose signals were transferred to magnetic tape, which drove a machine tool's servos. Because the control was offline, the taped signals could drive any number of similar machine tools.

Commercially available NC machine tools debuted in 1955, at the Chicago Machine Tool Show (predecessor to IMTS). The event showcased several NC machines, driven either by punched cards or punched paper tapes. Monarch Machine Tool Inc., Cortland, N.Y., which had been developing NC since 1952, introduced its first NC lathe. G&L had completed its NC 5-axis skin mill and was demonstrating it at its Fond du Lac, Wis., plant after deciding not to exhibit it at the show.

Father of the NC machine

The NC machine tool was born in northwest Michigan during the late 1940s. The father was John T. Parsons.

In 1947, Parsons was running a company in Traverse City, Mich., that produced helicopter blades. He devised a technique for producing airfoil templates on a precision jig mill, writes M. Eugene Merchant in a monograph titled "An Interpretive Review of 20th Century U.S. Machining and Grinding Research."

The operator of the mill relied on numerical data, produced by an IBM punched-card machine, to manually position the milling machine's lead screws in two axes. The templates were machined to a tolerance of 0.0015".

Based on his success, continues Merchant, Parsons conceived the idea of automating a drive mechanism actuated by digital information that would directly operate the lead screws of the milling machine in three dimensions.

Parsons demonstrated the concept for the Air Force in 1948, machining a scale-model wing section on a Swiss boring mill fitted with a universal table. Shortly after, Parsons reached an agreement with the Massachusetts Institute of Technology ServoMechanism Laboratory, wherein the lab would design and build a digitally controlled, 3-D servosystem.

The MIT prototype, demonstrated in 1952, differed from Parson's invention. But, as Merchant writes, it validated the idea that computers could effectively control machine tools.

Initially, both the aircraft industry and machine tool builders feeding that industry were reluctant to consider changing to NC machines. But 1958 data on the economics of NC, based on real applications, won over many doubters. The Boeing Co., for instance, stated in a report that "numerical control has proved it can reduce costs, reduce lead times, improve quality, reduce tooling and increase productivity."

Acceptance led to evolution. In 1957, G&L introduced its first 5-axis Variax NC profilers, and, in 1958, Kearney & Trecker Corp., Milwaukee, introduced its Milwaukee-Matic II, the first commercial NC machining center with an automatic toolchanger and automatic work positioning.

Once proven effective, NC technology expanded steadily to boring machines, sinker electrical discharge machines and other machines. Improved control led, in turn, to new machine designs and new manufacturing techniques.

Kearney & Trecker

Kearney & Trecker's 1958 Milwaukee-Matic II NC machining center featured an automatic toolchanger.

But true maturity in NC development, according to Paul Warndorf, vice president of technology at AMT—the Association for Manufacturing Technology, didn't come until the development of integrated circuits replaced vacuum tubes with more efficient, more reliable electronics.

NC machines were born to meet a need for quality control, repeatability and cost-effectiveness. Out of the birth struggles of the 1950s arose a new way of controlling machinery that has become indispensable.

About the Author

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Upping Input Speed: automating NC

In the early 1950s, the U.S. Air Force, Army and Navy initiated a program to purchase machine tools to be put in reserve for future mobilization. Final decisions on what machines would be purchased and how they would be allocated were the responsibility of the Air Force. William M. Webster and Max A. Guenther, engineers for the Air Force's Manufacturing Technology Div., were members of the group that handled the planning.

MIT

The first NC machine tool, which was demonstrated at the Massachusetts Institute of Technology in 1952.

The program presented an opportunity to create a market incentive strong enough for the machine tool industry to develop and produce commercially available models of numerically controlled machine tools. Webster and Guenther used their recognition and understanding of the potential of NC technology to direct the division not only to include NC machines in this bulk buy, but also to put them into immediate use in the production of military aircraft rather than storing them until needed. Of the 500 machine tools finally authorized for purchase at the end of 1955, 105 were NC skin mills and profile millers.

As such, the Air Force created the initial market for the commercialization of NC technology. This would have taken longer without investment from the government—perhaps 5 to 10 years longer.

U.S. industry benefited greatly. As the manufacturing industry began to put NC to work, though, one impediment to utilization of the technology remained: The length of time required for each program to be input into the machine controller on punched cards or tape, which contained minute incremental motions that the machine tool needed to make, in sequence, to move the cutting tool along the toolpath during the machining of a part. The time required to manually prepare such a program could, depending on the part's complexity, be more than 50 times the time needed to machine that part.

The Massachusetts Institute of Technology's ServoMechanism Laboratory, working in conjunction with the Air Force's Manufacturing Technology Div., recognized this problem and, even before the prototype NC system had been put into operation, began taking steps to automate the programming process. It was evident that the only technology that could do this effectively was the then-evolving digital computer. At the time, MIT had developed and was operating its Whirlwind computer. The ServoMechanism Laboratory, therefore, began its research on this computer.

In 1956, software researcher Douglas Ross was commissioned to find a workable approach to automatic programming of NC machining. Ross had been a mathematics major at MIT and had come to the ServoMechanism Laboratory to work in the realm of human-computer systems for high-speed data processing. His research led to the development of the Automatically Programmed Tool (APT) system.

Ross started with the premise that persons doing part programming should be able to express their machining instructions in a simple, English-like language, which, though simple, should constitute a rational system, one that was open-ended. It would, therefore, need to be readily expandable and capable of growing with use-based experience.

Ross envisioned the language as a system enabling interaction between a


The Mitre Corp.

Wide shot of the Whirlwind computer room in 1951.

human and a computer in such a way that the human could work with the computer in a conversation-like mode, interchanging ideas with it to arrive at an overall program. "The language must bridge the gap between the fundamentally incompatible characteristics of the two parties," Ross said. "The human is quick-witted but slow, while the computer is slow-witted but extremely fast."

'The human is quick-witted but slow, while the computer is slow-witted but extremely fast.'

The language system Ross developed reconciled these two characteristics. "[It permitted] a person with no programming skill to give instructions for machine tool motions in easy-to-learn, English-like terms, and to relegate to a general-purpose digital computer the job of translating these instructions into a language that would be understood by the computer," said MIT professor Francis Reintjes.

Thus, Ross had removed the last significant technological impediment to utilization of NC by the manufacturing industry on a broad scale. "The development of APT was a major turning point in the evolution of NC, because it settled once and for all the issue of whether or not NC could be made economically viable in the light of programming costs," Reintjes said. Justifiably then, the APT language became the U.S. standard for programming NC machine tools in 1974, and became the international standard in 1978.

Reference: "An Interpretive Review of 20th Century U.S. Machining and Grinding Research: An e-Monograph on a Notable Chapter in the Lore of Machining Process Technology," by M. Eugene Merchant, senior consultant, in association with Susan M. Moehring, manager of program development, TechSolve Inc., Cincinnati.

Minimizing Movement: multitasking

As soon as the phrase "secondary operation" appeared in the metalworking dictionary, shops set out to erase it. Moving a part from one machine to another and setting it up again takes time and effort, and can compromise accuracy. As a result, manufacturers have continually sought ways to make one machine tool perform multiple tasks that otherwise would require multiple machines and setups.

Various forms of "multitasking" have existed for decades, including custom machines and arrangements such as multiple-spindle screw machines with side-working and end-working tools. Those approaches, however, generally mean dedication to long runs of specific parts and lengthy setup procedures—not a good fit in the current small-lot, just-in-time manufacturing environment.

Today's multitasking machine—typically a turning and milling center—permits quick changeovers, in addition to performing multiple operations in one chucking.

Kirk Mills

Multitask machines minimize moving parts from machine to machine.

The advent of NC and CNC programming was the first step toward this kind of flexibility. Lathes were designed to turn round parts, and, until relatively recently, a turning center was limited to functioning only in this manner. To implement live tooling—a first step toward multitasking—the rotating tool's speed must be a programmable function. For nonturning operations, there must be a way to lock and index the lathe spindle or move it with a C-axis.

Tom Jackson, presently manager of technical services at Emco Maier Corp., Columbus, Ohio, and an employee of Monarch Machine Tool Inc., Cortland, N.Y., during the early days of modern multitasking, said: "I don't think, right up front, there was a full C-axis. There was basically a 3° to 5° braking system or pinning system, where you could lock in and drill holes, like bolt patterns, around the OD of the part. Full C- and Y-axis capability grew through the years with the technology of the controllers."

Ernie Hollenbacher, who worked nearly 30 years at Monarch in programming, sales and manufacturing, said early attempts at multitasking "went on for years" and described how drill heads were mounted on automatic chuckers. "It was slow and it was crude, but it worked." He added, "You're not getting anything done when you are making setups, whether you're in a little woodworking shop or a big-time user of machine tools." The trend is to "take a part off the machine, pack it up and ship it."

In his "High Production Turning" presentation at IMTS 1988's Fourth Biennial International Manufacturing Technology Conference, James E. Buckley, executive vice president of Saginaw (Mich.) Machine Systems Inc., said that in the late 1970s and early 1980s, cam and tracer controls were replaced by multi-axis NC and CNC systems. Those provided "more flexibility, less changeover time and cost, as well as inherent abilities to do more complex operations with standard tooling arrangements," he said. Buckley added that such systems would allow manufacturers "to evaluate techniques more viably possible than ever before to eliminate or combine what were previously separate costly processes."

Jim Cordier, a veteran of 48 years in engineering and customer service at Hardinge Inc., Elmira, N.Y., said multitasking evolved "because you wanted to do more and more with one setup. If you do a part complete in one setup, you made a more accurate part and did it quicker."

Multitasking capability has advanced in sync with CNC computing power and machine technology. Steve Ambrosia, vice president of Emco Maier, said that today's machines represent the continuing evolution of the multitasking concept, capable of multiple operations, quick changeovers and even multiple machine configurations. Emco Maier machines, for example, are modular in construction, and "customers can get two turrets or one turret, two spindles or one spindle, and automation can be very easily added to the mix as well," he said.

Perhaps the metalworking dictionary needs a new phrase to describe the continually multiplying capabilities of multitasking machine tools.

Hard-Pressed Technology: manufacturing synthetic diamonds

From the time in 1796 when chemist Smithson Tennant showed that diamond was carbon, experimenters attempted to synthesize diamond from graphite using intense heat and pressure.

Reportedly, a team led by Count Baltazar von Platen, at the Allmanna Svenska Elektriska Aktiebolaget Laboratory in Stockholm, Sweden, succeeded at the task in 1953. However, this initial triumph was not publicized or published.

Engineers regulate the machine used to produce Man-Made industrial diamonds at General Electric's Metallurgical Products Dept.

Shortly after, on Feb. 15, 1955, the General Electric Co. team of Francis Bundy, Tracy Hall, Herbert Strong and Robert Wentorf Jr. claimed credit for the first reproducible transformation of graphite to diamond. According to CARBIDE ENGINEERING (the former name of CUTTING TOOL ENGINEERING), Wentorf, a physical chemist who reportedly once made diamond in GE's high-pressure diamond-making apparatus using peanut butter as the source of carbon, reported: "Finally, after more than 4 years of experimentation, a diamond was produced at the General Electric Research Laboratory when a carbonaceous material was subjected for many hours to super pressures, up to 1½ million psi. The crystal's longest dimension was about 1⁄16"."

According to a book by Kurt Nassau titled *Gems Made by Man*, upon succeeding, Hall said: "I attempted many hundreds of indirect approaches but to no avail, and I was becoming discouraged. Then, one wintry morning, I broke open the sample cell after removing it from the belt. It cleaved near a tantalum disk used to bring in current for resistance heating. My hands began to tremble; my heart beat rapidly; my knees weakened and no longer gave support. My eyes had caught the flashing light from dozens of tiny triangular faces of octahedral crystals that were stuck in the tantalum and I knew that diamonds had finally been made by man. After I had regained my composure, I examined the crystals under a microscope. The largest, about 150 microns across, contained triangular etch and growth pits such as I had observed on natural diamonds. The crystals scratched sapphire and other hard substances, burned in oxygen to give carbon dioxide and had the density and refractive index of natural diamond. A few days later, an X-ray diffraction pattern unequivocally identified the crystals as diamond."

GE used a "belt device" to synthesize diamond. Tungsten-carbide rams were driven into a cavity contained by a double-tapered carbide cylinder, contained, in turn, by a steel jacket—a belt. Between the rams was a graphite cylinder—a furnace—containing the material to be put under high heat and pressure.

In 1957, GE commercially introduced its Man-Made industrial diamond. The November edition of CARBIDE ENGINEERING stated that more than 100,000 carats of synthetic diamonds had been produced at GE's Metallurgical Products Dept. in Detroit for use in grinding wheels, lapping compounds and similar applications. The grit sizes ranged from 60 mesh down through 600 mesh, large enough for most industrial abrasive requirements.

During that year, U.S. industry imported an estimated 7 million carats of fragmented bort, which is the class of natural material against which manufactured diamonds compete. At that time, a carat of ungraded manufactured diamond sold for $4.25, slightly higher than the cost of ungraded natural diamond.

Today, similar methods are employed to manufacture synthetic diamond. A mixture of graphite and a catalyst, typically nickel, is subjected to a pressure of about 1 million psi and a temperature of 1,800° C for approximately 1 hour. During this time, diamond crystals nucleate at many sites in the mixture. The mixture is then cooled and the pressure is reduced to atmosphere. The diamond crystals are then separated from the remaining graphite and nickel using an acid wash.

Synthetic diamond is generally considered superior to its natural diamond counterpart for industrial purposes because it can be produced in unlimited quantities and, in many cases, its properties can be tailored for specific applications. Consequently, manufactured diamond accounts for more than 90 percent of the industrial diamond used in the U.S.

In addition, a layer of diamond crystals can be placed on a carbide substrate by subjecting them to high temperature and pressure. This yields polycrystalline diamond compacts, which emerged in the early 1970s and are used for milling and drilling tools. This manufactured PCD is a synthetic analog of a natural PCD, which, in spite of its toughness, saw limited use because it was both rare and difficult to shape.

Tom Wright

Diamond, the hardest material, has a knoop

1957 was also the year that Wentorf produced cubic boron nitride, which the company trademarked as Borazon. The manmade crystal is created by heating equal quantities of boron and nitrogen at temperatures exceeding 3,300° F and pressures above 1 million psi.

Although an article in the March 1957 issue of CARBIDE ENGINEERING stated that CBN is as hard as diamond, possibly because it can scratch a diamond, diamond has a Knoop hardness of 8,000 to 8,500 compared to 4,500 to 4,600 for CBN. However, CBN can withstand temperatures higher than 3,500° F, whereas diamonds burn up at 1,600° F. The density of the two materials is about the same, with CBN having a specific gravity of 3.45 compared to 3.50 to 3.56 for diamond.

The article concluded: "Evidently in the cubic crystal of boron nitride, each nitrogen atom donates one of its rarely used electrons to a boron atom. This boron atom uses this extra electron to form another chemical bond with a nitrogen atom, and in this way the sheets of atoms are tied together to form a strong crystal, after the manner of diamond."

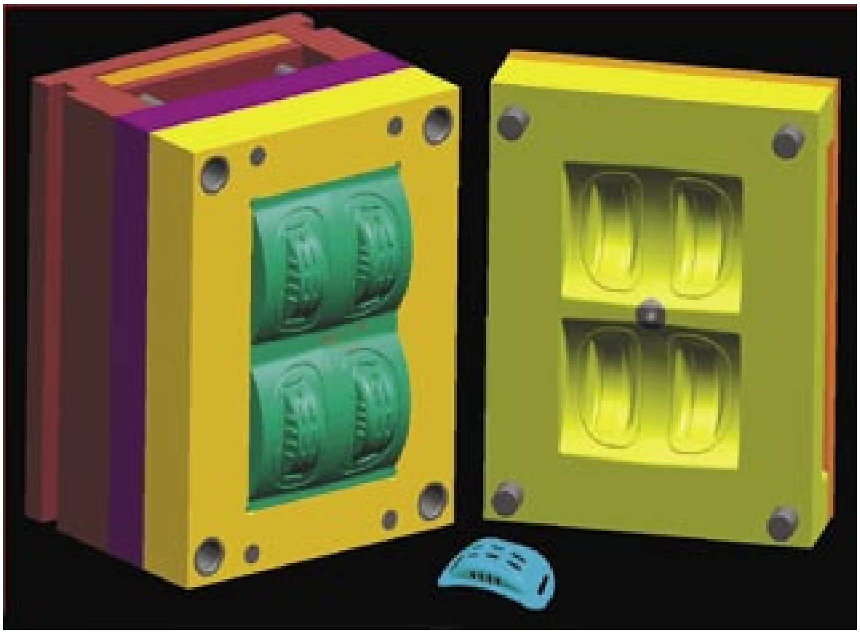
Reference: American Museum of Natural History.

Father Figures: developers of CAD/CAM

BY GREGORY FARNUM

Creating complex geometrical shapes on the computer (computer-aided design, or CAD) and using digitized data to guide machines (computer-aided manufacturing, or CAM) are as integral to the modern factory as electricity. Few of us, however, have much idea how this technology originated, so let's take a look back.

Though the Greek geometer Euclid doesn't get any royalties, some people point to him as the father of CAD/CAM because his fourth century B.C. work, *The Elements*, established the geometrical principles that form the basis of CAD/CAM software. Let's call him one of several fathers.


Accelerated Mold Technologies

A mold for a police helmet chin guard designed with Unigraphic software.

Another is John T. Parsons, president of Parsons Works, Traverse City, Mich. In the late 1940s, prompted by the U.S. Air Force's need for templates more precise than could be obtained by the manual techniques of the time, Parsons proposed placing machine tools under servocontrol, guided with positional data generated by a computer, which could generate a great deal more data than would be practical by manual calculations. His concept was to machine to set points as guides for subsequent manual finishing, which would both speed the process and make it more accurate.

Parson's idea was picked up by the ServoMechanisms Laboratory at the Massachusetts Institute of Technology, an institutional father that figures large in our story. The MIT researchers refined Parson's idea into a system whereby the cutting tool would traverse a series of straight lines between defined points at a prescribed rate of travel. This way, the cutting tool would be almost constantly on the programmed contour, spending little time making noncutting moves. The MIT researchers demonstrated the fruits of their labor—the first numerical control (later broadened to computer numerical control) machine tool—to a select group from the military, aerospace and machine tool industry in September 1952.

Then there's the guy who is often called the father of CAD/CAM, Dr. Patrick Hanratty. Among other contributions to the field, Hanratty, in 1957, developed the first commercial CAM software system, an NC programming tool named PRONTO. Of course, if one can digitally create patterns in space to guide a machine tool, one can do the same thing for other machinery as well, a fact that wasn't lost on the fledgling robotics industry and builders of other types of industrial equipment. Thus, the direct link between CNC and CAM.

Of course, PRONTO and the other programming tools that quickly followed created geometrical information by first having that info entered on a keyboard—a time-consuming way to create a shape. That's where Ivan Sutherland came in. Sutherland, then a grad student at MIT, kicked things up a notch in 1963 with his Sketchpad software, developed as part of his Ph.D. thesis. Called the first "true" CAD software, Sketchpad allowed the designer to graphically interact with a computer via a light pen, which was used to draw directly on the computer's monitor. Sutherland can, therefore, be considered the father of the graphical user interface (GUI) as well. Though modern CAD systems dwarf Sketchpad in their power and complexity, few—if any—can match it for ease and directness of input.

During this period, CAD research was also being conducted in the U.K., at Cambridge University's Computing Laboratory, and in France, where the car companies Citroën and Renault were funding research in complex 3-D curve and surface geometry computation, work which laid the foundations for the 3-D CAD software to come.

All this activity wasn't lost on the industrial giants, specifically the automotive and aerospace companies. They began adopting and adapting the technology. Before the '60s had ended, GM, Ford, McDonnell-Douglas and Lock heed, among others, were operating their own proprietary CAD systems.

As the ’70s progressed, the increasing power of computers, and the introduction of lower-cost minicomputers, made CAD accessible to a wider array of users. A host of CAD companies, many of them still in existence today, arose to meet the growing demand. This trend was furthered by the emergence of powerful UNIX workstations and PCs in the early 1980s, along with the growing power of the CAD systems themselves.

Today, it’s hard to imagine a manufacturing firm without a CAD/CAM system or the ability to transfer digital data to CNC machine tools.

Some people point to Euclid of Alexandria as the father of CAD/CAM because his book *The Elements* established the geometrical principles that form the basis of the software.

And what can we expect from tomorrow’s CAD/CAM offspring? Look for greater emphasis on linking CAD/CAM technology with PLM (product life-cycle management) and other systems in an effort to rapidly track and control every aspect of the manufacturing process.

About the Author

Gregory Farnum is a Detroit-based journalist and a regular contributor.

Quickening Pace: high-speed machining

It is difficult to define "high-speed machining," because the spindle speed a tool can be run at depends on the workpiece material and other factors. Therefore, HSM could be 8,000 rpm or 100,000 rpm—or somewhere in between.

Whatever definition is used, though, the benefits of HSM are the same: increased productivity, reduced costs and improved surface finishes.

The origins of HSM can be traced back to the 1920s, to German inventor Dr. Carl Salomon. He theorized that at a certain spindle speed on a given material, the heat generated at the tool/workpiece interface would peak. This peak, the "critical speed," is different for each material. On either side of the peak lies a bounded area—a range of speeds—in which a tool cannot perform.

Salomon also theorized that once speed was pushed above the upper speed range, the temperature would decrease enough that heat-induced tool wear would be negligible. However, this part of the theory has never been verified. In fact, research conducted during the late 1950s found that temperature increases monotonically.

A systematic investigation of HSM was conducted by R.L. Vaughn at Lockheed Aircraft Corp. in 1958. He determined that the rate at which metal can be removed depended on the size and type of machine, available horsepower, cutting tool selection, workpiece material properties and cutting parameters.

During the early 1970s, a series of studies was initiated by the U.S. Navy and Lockheed Missiles & Space Co. The objective was to determine the feasibility of HSM in production environments. Their reports on machining aluminum alloys and nickel-aluminum-bronze demonstrated that it was economically feasible to introduce HSM into production environments.

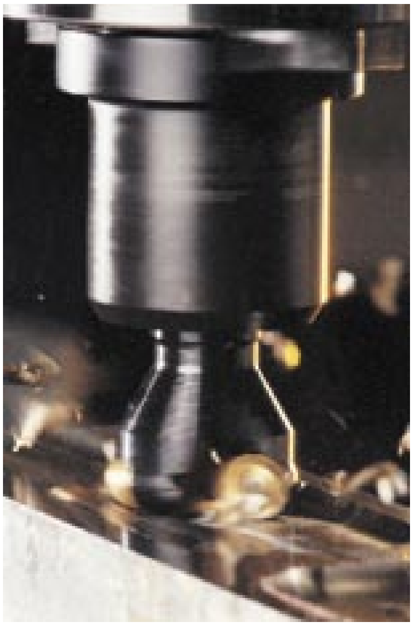
In the late 1970s and early 1980s, the U.S. Air Force awarded a contract to the General Electric Co. to provide a database for machining aluminum, titanium, nickel-base superalloys and steels.

Starting in the 1990s and continuing through today, major advances in all aspects of HSM—machine design, motion control, spindle design, tooling and chip formation—have broadened the application of HSM among manufacturers.

TaeguTec

A button cutter is used for HSM.

HSM requires machine components to have high rigidity, thermal stability and damping capacity. Chip formations is essential, too. Two types have been observed: continuous and shear-localized. Aluminum is more prone to produce continuous chips because of its high thermal diffusivity and relative softness. Shear localization occurs with harder materials such as titanium and nickel-base superalloys. However, cutting parameters should be chosen to favor the creation of shear-localized chips because they permit easier handling and, possibly, reduce tool wear.



Carboloy Inc.

The benefits of HSM are increased productivity, reduced costs and improved surface finishes.

Toolholders must be highly balanced. Unbalanced holders decrease tool life and can lead to chatter, which degrades surface finish. Furthermore, an unbalanced condition can damage the spindle, resulting in repair costs and lost revenue because of the associated downtime.

The aerospace industry was the first to apply HSM. Today, the technology is also being used in the automotive, medical, and mold and die industries.

References: "High Speed Machining of Aluminum for Use in Aerospace Applications," by Kevin Luer, Center for Manufacturing Systems Engineering, Lehigh University, Bethlehem, Pa.; *Metals Handbook, Ninth Edition, Volume 16, Machining,* ASM International, 1989.

'Bible' Story: *Machining Data Handbook*

Conducting research and collecting data about the machinability of materials was critical to advancing metalcutting technology during the early and middle decades of the last century. Just as crucial was compiling that data into a usable form. Metcut Research Associates Inc., Cincinnati, spearheaded such an effort. The end product of its work was the 1966 publication of the *Machining Data Handbook*, heralded as the "bible" of the industry.

The story of the book's publication begins with Dr. Michael Field. He, along with his colleague at The Cincinnati Milling Machine Co., Norman Zlatin, set out in 1948 to establish a company devoted to conducting research and development aimed at helping American manufacturing companies solve their immediate machining problems and deploy existing and new machining technology. Joining them was Dr. John F. Kahles, who, at the time, was professor of metallurgy at the University of Cincinnati.

Metcut's John F. Kahles directed the research effort that led to the publication of the *Machining Data Handbook*.

Industry's initial response to contracting Metcut to conduct research was lukewarm. The trio struggled. Eventually, though, a few larger companies bought into the idea, and the tiny enterprise grew.

A major boost for Metcut occurred in the late 1940s, when it was subcontracted to conduct R&D for the Manufacturing Technology Division of the U.S. Air Force Materials Laboratory. Metcut performed subcontract work for ManTech four times between 1949 and 1960.

Then, in 1964, the Air Force contracted Metcut to establish and operate, within Metcut, the U.S. Air Force Machinability Data Center. The center's prime function was to collect, evaluate, store and disseminate machining data and information. In 1972, the U.S. Army's Materials and Mechanics Research Center assumed the center's sponsorship, under a Department of Defense contract from the Defense Logistics Agency, and it became the Metcut Machinability Data Center.

By that time, the center had become the core of Metcut's program for the deployment of data, knowledge and understanding of metalcutting and grinding technology throughout the U.S. The center developed a library devoted to machining technology. It also developed and offered a continuing program of seminars on state-of-the-art machining and undertook the development of a handbook containing starting recommendations for speeds and feeds.

Kahles, working closely with Field, masterminded the program, which was devoted to producing a compendium of best-practice machining data and recommending machining practices for turning, milling, drilling, grinding and nonconventional material-removal processes performed with cutting tools on common work materials.

The research involved collecting both published and unpublished machining data generated by universities, research laboratories and manufacturing companies. This data was combined with machining data that Metcut had already generated, and continued to generate, from its own machining research and testing.

The data was then analyzed, interpolated and evaluated for consistency and accuracy by additional in-house machining tests. The immense research effort resulted in Metcut's publication of the first edition of the *Machining Data Handbook*.

The research effort continues at Metcut. The handbook, which is currently in its third edition, now comprises two volumes and lists data for 61 classes of work materials and 58 types of conventional operations.

Reference: "An Interpretive Review of 20th Century U.S. Machining and Grinding Research: An e-Monograph on a Notable Chapter in the Lore of Machining Process Technology," by M. Eugene Merchant, senior consultant, in association with Susan M. Moehring, manager of program development, TechSolve Inc., Cincinnati.

A Better Edge: tool coatings

Coated cutting tools are so ubiquitous today, with about 80 to 85 percent being coated, it's hard to imagine a time when none were. But that was the case until the late 1960s, when the first chemical vapor deposition coating appeared.

Initially, the major toolmakers developed CVD coatings in-house and introduced their respective coated grades around the same time. The first coating was titanium carbide, an extremely hard compound that's similar to tungsten carbide. It was initially applied as a single layer about 5µm thick.

By 1975, tools were also being coated with titanium nitride and titanium carbonitride. Gold-colored TiN is an all-purpose coating that provides good lubricity and resists abrasive and adhesive wear. The coating increases tool life and productivity by keeping the cutting edge sharper longer, and works well when machining ferrous materials.

Compared to TiN, TiCN has a higher hardness, better wear resistance and is tougher. This coating is recommended when higher feeds and speeds are needed, and for cutting difficult-to-machine metals and aerospace-grade materials. It is also appropriate for abrasive materials, like cast iron and high-silicon aluminum.

The appearance of other coatings soon followed, including aluminum oxide. Also known as alumina, Al_2O_3 has excellent thermal-insulation properties and its chemical stability and hardness retention at high temperatures make it appropriate for use with tools operated at higher cutting speeds.


Richter Precision Inc.

Pipe taps and assorted components being CVD-coated.

During the mid-'70s to early '80s, tools were introduced with multiple layers of CVD coatings. Coatings such as TiN, TiC, TiCN and Al_2O_3 are combined in numerous ways to suit specific applications. Almost all multilayer coatings feature a base layer of either TiCN or titanium oxycarbonitride for wear resistance and interfacial microstructural control. These special layers eliminate the brittle eta phase that used to result from carbon depletion at the coating/substrate interface.

Because the coating layers and substrate have differing levels of thermal expansion, cracks form in traditional CVD coatings when the tools cool after deposition (at about 1,850° F). To overcome this, coating companies developed medium-temperature CVD coatings in 1985, which, as the name implies, are deposited at lower temperatures (about 1,700° F) than CVD coatings. The lower temperatures eliminate cracks in the coating. As a result, MTCVD coatings offer the advantage of increased toughness and smoothness without sacrificing wear or crater resistance.

The next big development was physical vapor deposition coatings. Pioneered by Latrobe, Pa.-based Kennametal Inc., these coatings were deposited at even lower temperatures (below 950° F). In 1985, Kennametal introduced the KC710, the first widely available PVD TiN-coated carbide insert.

TiCN, titanium aluminum nitride and a variety of other PVD coatings appeared around 1990. Eventually, multilayer PVD coatings were also introduced. Unlike CVD coating development, which was motivated by manufacturers of cutting tools, PVD coating development was driven by providers of PVD coating services and an active scientific community.

PVD coatings have two distinct advantages over CVD coatings. First, their 3µm thickness works well on sharp-edge tools, where a thicker coating might have trouble adhering and create a dull edge. Second, tools are PVD-coated at relatively low temperatures; therefore, PVD coatings can be used on HSS without adversely altering the substrate's underlying properties. Also, PVD coatings have no pre-existing cracks, which result from the energetic ion bombardment that occurs during the deposition process and induces a state of compressive stress.

PVD TiAlN offers higher hardness than TiCN and excellent oxidation resistance, permitting high-speed and dry or near-dry machining. It's more stable at higher temperatures than TiN or TiCN.

In the mid-'90s, AlTiN began being deposited on tools, initially in Europe. An AlTiN coating is comprised of more than 50 percent aluminum and has a microhardness of 3,500 HV, compared to 2,600 HV for TiAlN.

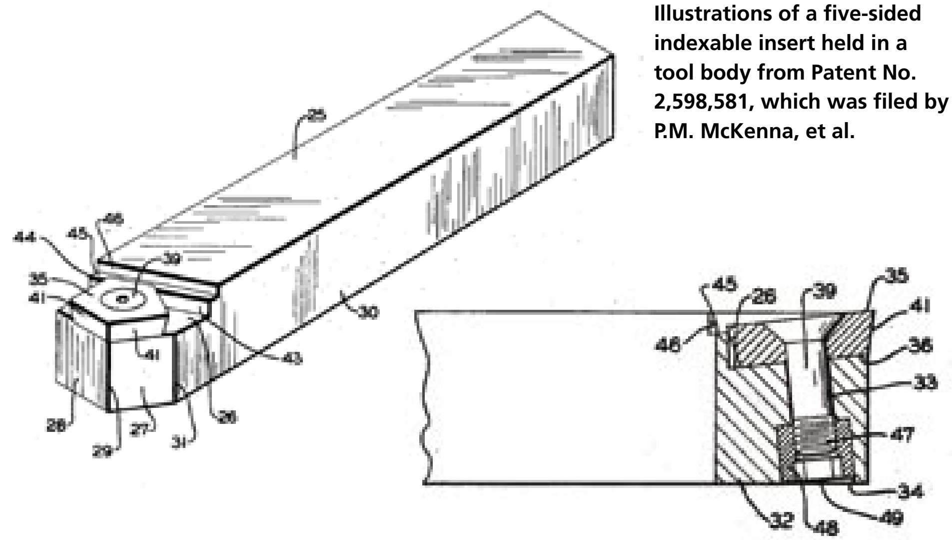
Although CVD Al_2O_3 coatings are common, research into developing a cost-effective, 100 percent PVD Al_2O_3 continues.


Guhring
Drillscoated with TiN.

To up the hardness level even more, carbide tools are also coated with diamond. Although engineers in the former Soviet Union began researching diamond coatings in 1977, followed by the work of Japanese scientists in the '80s, it wasn't until the early '90s when tools coated with diamond, applied via the CVD process, became commercially available. Diamond-coated tools are recommended for machining high-silicon aluminum and other nonferrous materials, graphite, composites and green ceramics.

Reference: Dr. Dennis Quinto, Balzers Inc., Elgin, Ill.

Short Changes: indexable inserts



Illustrations of a five-sided indexable insert held in a tool body from Patent No. 2,598,581, which was filed by P.M. McKenna, et al.

Kennametal

The development of tungsten-carbide metalcutting tools in the first third of the 20th century represented a major manufacturing breakthrough in terms of increased metal-removal rates and tool life. Hard, long-lasting carbide cutting edges were brazed into steel holders and resharpened when worn.

Resharpening, however, required removing the entire tool from the machine followed by handwork on a grinder, both of which took a fair amount of time. In addition, reground cutting edges were often dimensionally inconsistent, and overly aggressive or misapplied grinding could damage the edge and reduce its effectiveness or turn the tool into scrap.

In the 1940s, toolmakers began to investigate alternatives to brazed tools. In a recent interview, Wilbur "Bill" Kennicott, former vice president of product engineering at Kennametal Inc., Latrobe, Pa., recalled presenting a paper titled "Mechanically Mounted Cutting Inserts of Cemented Carbide" in the late '40s at a Society of Manufacturing Engineers meeting in New York. "I was pretty much laughed off the podium," he said.

Obviously, the derision was undeserved. Kennicott's colleague, Bob Cline, a draftsman during the early days of Kennametal, recalled that company founder Philip M. McKenna "always used to say, 'Once the tool is in the cut, you don't need any braze material to hold it in place.' "

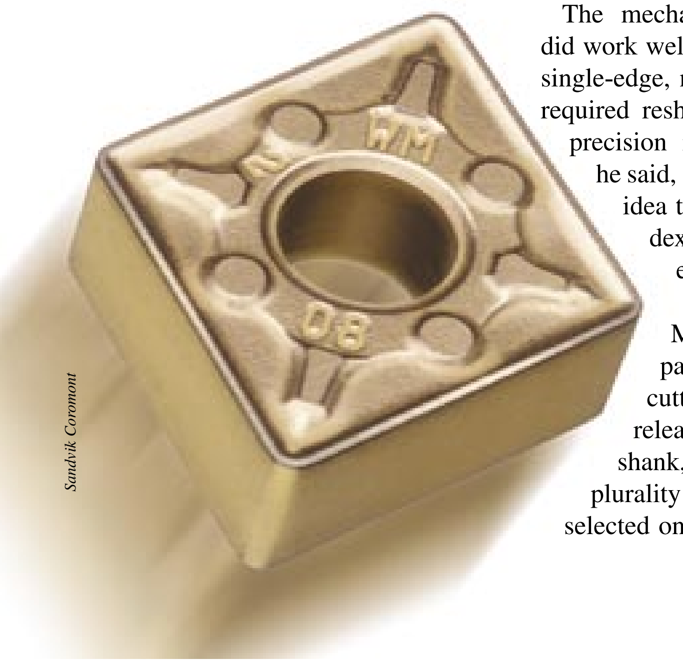
The mechanical clamping system did work well, Kennicott said, but the single-edge, nonindexable inserts still required resharpening. The time and precision required for regrinding, he said, "brought us around to the idea that we could provide indexable, factory-prepared edges."

In 1952, Kennicott and McKenna were awarded a patent for a "multi-edged cutting element that may be releasably (sic) secured to the shank, in any selected one of a plurality of positions, to bring a selected one of the cutting edges to cutting position."

The five-sided cutting insert and screw-on holding method was a pioneering example of indexable-insert technology. The pentagon shape required a complicated holder, Kennicott said, so the next version was four-sided. Later, triangular inserts were developed for machining a square shoulder.

The first indexable inserts mimicked brazed tools in that they featured positive-rake geometries (a side view of the cutting edge recalls the prow of a barge), limiting indexing to the edges on one side of the insert. The next developmental step was made possible by advances in the metallurgical properties of the inserts, specifically in the area of resistance to crater wear caused by heat and pressure. The improved performance permitted the use of negative-rake geometries, which had stronger square edges that could handle a more aggressive—but higher pressure—cut than a positive-rake geometry. The square edges also enabled negative-rake inserts to be turned over as well as indexed on each side, providing eight cutting edges.

CUTTING TOOL ENGINEERING



Sandvik Coromont

documented the rapid acceptance of indexable inserts, reporting the results of a 1956 survey by Detroit toolmaker Wesson Co., which found that "throwaway" tools would "shortly reach the startling total of 40 percent of all single-point tools used in metalworking," up from the then-present total of 15 percent. Some shops sought to use throwaway tooling exclusively.

The survey listed "several indirect cost reductions" as reasons for the wide acceptance, including reduced maintenance of costly tool grinders and to lessen dependence on hard-to-find, high-wage tool-grinding personnel. In addition, the indexable inserts of those days repeated within 0.003"—the tolerance of most turning operations at that time—producing reductions in setup time with concurrent decreases in downtime. Estimated time to change an inserted tool was 1.3 minutes, as opposed to 10 minutes or more for a brazed tool.

The "throwaway" title that quickly became attached to indexable inserts rankled carbide engineers, who considered their precision tools undeserving of such a commodity-like description. Kennicott mused that throwaway was somewhat of a misnomer, pointing out that "80 percent of the materials in the inserts could be recycled metallurgically." He recalled the superintendent of a Niagara Falls-area manufacturer who encouraged other local shops to save their used inserts, enabling a local boys club to be financed exclusively on the money gained by recycling the worn-out tools.

Hollow Holding: HSK toolholders

HSK toolholders were developed in the early 1990s. HSK stands for Hohl Shaft Kegel. Translated from German, this means hollow shank taper.

The HSK design was developed as a nonproprietary standard. The working group that produced the HSK standard consisted of representatives from academia, the Association of German Tool Manufacturing and a group of international companies and end users. The results were the German DIN standards 69063 for the spindle and 69893 for the shank.

The HSK working group did not adopt a specific product design, but rather a set of standards that defined HSK toolholders for different applications. The group defined a total of six HSK shanks. These shank styles are designated by the letters A through F. Each style is also identified by the diameter of the shank's flange in millimeters. Styles A, B, C and D are for low-speed applications. Styles E and F are for high speeds. The main differences between the styles are the positions of the drive slots, gripper-locating slots, coolant holes and the area of the flange.

The shank itself is made as a hollow taper with a ratio of 1:10. The surface inside the shank is cut with a 30° chamfer, making it possible to clamp the toolholder from the inside. The wall of the shank is designed to be thin enough to flex slightly. On the outer surface of the shank flange is a traditional toolchanger V-groove and slots for locating and orienting an automatic toolchanger's (ATC) gripper.

The principal difference between styles A and B is the size of the taper. The B-style shank has a taper one size smaller than an A-style shank with a flange of the same size. D and F shanks have tapers one size smaller than C and E shanks with the same flange diameter as well. Styles C and D were designed exclusively for manual use, with the elimination of features to accommodate ATCs.

To handle extremely high speeds and machining of light materials, styles E and F are totally symmetrical. Their symmetry minimizes unbalance, which can be a significant problem at high speeds.

An HSK connection depends on a combination of axial clamping forces and taper-shank interference. All these forces are generated and controlled by the mating components' design parameters. The shank and spindle both must have precisely mating tapers and faces that are square to the taper's axis. There are several HSK clamping methods. All use some mechanism to amplify the clamping action of equally spaced collet segments.

When the toolholder is clamped into the spindle, the drawbar force produces a firm metal-to-metal contact between the shank and the ID of the clamping unit. An additional application of drawbar force positively locks the two elements together into a joint with a high level of radial and axial rigidity.

As the collet segments rotate, the clamping mechanism gains centrifugal force. The HSK design actually harnesses centrifugal force to increase joint strength.

Centrifugal force also causes the thin walls of the shank to deflect radially at a faster rate than the walls of the spindle. This contributes to a secure connection by guaranteeing strong contact between the shank and the spindle.

The automotive and aerospace industries are the largest users of HSK toolholders. Another industry that is seeing increasing use is the mold and die industry.

Diebold Goldring

"There are two ends to it," said Dan Springhorn, president of Diebold Goldring Tooling U.S.A., Sharon, Wis., which makes HSK toolholders. "High-speed machining is usually what people think of when they think of HSK, but a large number of people are also using it for low-speed, high-stock removal where a high stiffness it necessary."

Whatever the application, HSK toolholder use is definitely on the rise. "In 1996, when we opened, we estimated that 3 percent of the market in the U.S. was HSK," said Springhorn. "I would estimate today that it is somewhere around 15 percent. I think eventually people will look at the HSK standard the way that people look at the CAT standard now."

Reference: "The Secrets of HSK," by Dr. Eugene Kocherovsky and Bruce Travis, CUTTING TOOL ENGINEERING, September 1998.