Evolution of Today's 5-Axis Machining in the Die Mold Market

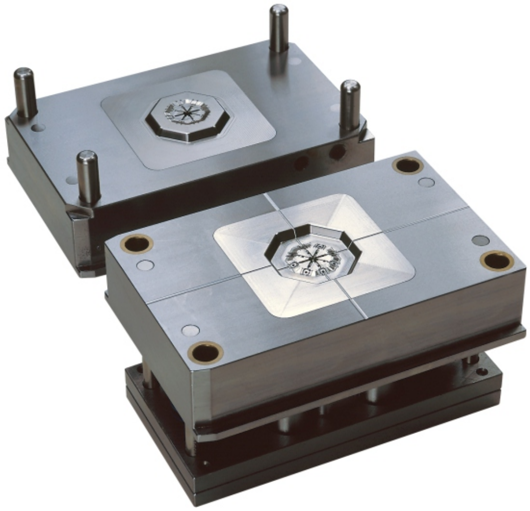
MAKINO

5X Continuous Chronology

What Are Dies and Molds?

Dies and molds are some of the tools necessary for modern manufacturing industries to run mass-production. Consumer industries for dies and molds range broadly over transportation machinery, industrial machinery, electric machinery and equipment, household goods, office goods, optical devices and equipment, glass containers, packaging, construction materials and equipment, medical, toys and sundries.

Since these products and equipment consist mostly of parts, units (subassemblies) and components which are used in volume, dies and molds are utilized by virtually every company manufacturing such equipment, products, parts and components. In terms of industrial applications, dies and molds are classified into a wide variety of applications; stamping and press dies, plastic molds, die casting dies, forging dies, casting dies and molds, extrusion, powder metallurgy dies, rubber dies, medical, blow molding, thermoforming and ceramics dies—just to name a few. Dies and molds would be rarely noticed outside industrial plants. In fact, as with most final products, consumers would struggle to recognize or even discern the function and value of dies and molds. While these molds do not catch the eye of consumers, without them, high-volume production of many industrial goods, components and parts would be impossible.



Some of the important components of a typical die and mold assembly and their functions include the following:

- Core
- Cavity
- Inserts
- Cams
- Slides
- Trim Die
- Forging Die
- Ejector Plate
- Die Shoe
- Mold Base
- Die Plates
- Die Sets
- Guides, Guide Pins and Bushings
- Heel Blocks and Heel Plates
- Dowels and Keys
- Pads
- Stripper Pads / Plates
- Pressure Pads
- Draw pads
- Spools
- Keepers
- Retainers

Virtually all these die/mold component parts are manufactured on a machine tool. The final form, shape, finish and function for all these parts—and the proper functioning of the mold—is dependent upon the machine and manufacturing process. The quality of the parts produced is determined by the quality of the mold.

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A Look Back

In 1937, Mr. Tsunezo Makino the founder and namesake of Makino started his machine tool business in the Meguro district of Tokyo, Japan. At the time, his business was strategically located in the center of the die mold manufacturing area. In fact, the original Makino site was adjacent to Meiki—a large die mold producer. The location provided the opportunity to work closely with expert craftsman in the area to understand what was required in a milling machine to produce high quality dies/molds. As a result, Makino started manufacturing the No. 1 Knee-type Vertical Milling Machine. Makino was intimately involved with the die and mold business as a key supplier and partner providing a technology base, background, experience, and product—all directly linked to die and mold business. Makino became well known (especially among die and mold manufacturers) for their Vertical Mills and Tool and Cutter Grinder.

In 1958, Makino developed Japan's first magnetic-tape NC Vertical Milling Machine—the first generation of today's CNC machines. By the early 1970s, the die and mold business was building larger and heavier dies and molds requiring bigger machines. In addition, there was an evolution from high-speed steel (HSS) to carbide cutters necessitating heavy-duty spindles with higher torque and greater stiffness and rigidity. Basic machine design required a highly rigid bed and column structure, large guideways and meticulous assembly to ensure the tightest geometries and highest precision. Makino introduced wide, integral, hardened ground guideways with matching hand-scraped, turcite-lined surfaces to handle the heavy cutting forces while maintaining fine surface finishes required by the die and mold industry.

During this timeframe, many die and mold manufacturers were creating, storing and maintaining elaborate, expensive wooden models of their cores and cavities used in the manufacturing process. Recognizing the need, Makino developed the Automatic Copy Milling Machine (Tracer Mill or Copy Mill) which could be used to trace (or copy) the wooden model and translate it directly into spindle motion for replicating the core or cavity into metal. Following shortly afterward, Makino developed the first programming device for automatic NC tape generation with 3D capability named "Makino My-Programmer." This device would facilitate translating the wooden model surfaces geometry directly into NC tape. With this advancement, core and cavity data could be stored on NC tape eliminating the need for maintaining and storing wooden models.

In the early 1980s, drawing upon its die and mold experience, Makino recognized the advantages that "graphite" electrodes would ultimately bring to the Die Mold industry and began production of the first Graphite Milling machines (SNC series) the world had ever seen. In addition, these key high-speed machining technologies were developed for the die and mold marketplace:

High-Speed Spindles

Recognizing that high-speed spindles were critical to both graphite machining and core and cavity finishing, Makino introduced a number of spindle design innovations that lead to today's patented core-cooling, under-race lubrication, jacket design.

NC High-Speed Adapter

High-speed spindles are only productive if they can be fed at high machining speeds and maintain precision tool paths. In 1984, Makino developed the NC High-Speed Adapter to improve the high-speed feed capability of early machine tool controls. That was the birth of Makino's proprietary, Super Geometric Intelligence (Generation 5) motion control software used today.

Makino was not only developing the technologies and machines but, was heavily committed to supporting the die and mold market with the tools to productively apply the machines.

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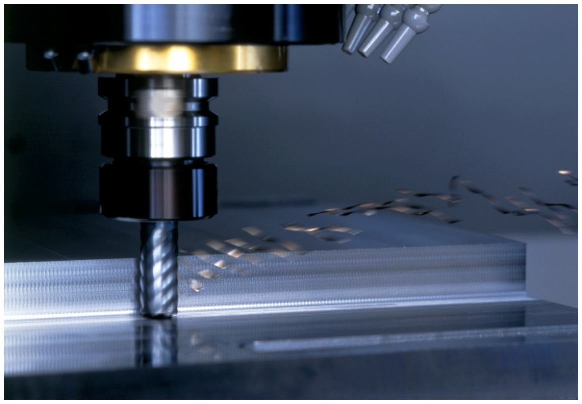
In 1985, Makino development was focused upon high-speed machining (HSM) targeting 50% reductions in both cutting and non-cutting time to decrease machining time and reduce costs.

In 1992, Makino combined high-speed spindle technology, HSM, cutter path, chip load, feedrates, pick feed, cusp height, coolant pressure, tool deflection and surface finish into Flush Fine (FF) cutting concept to speed and assist in these machining applications:

- Cutter path (scan pass)
- Part approach
  - Ramp-in
  - Helical

Furthermore, Makino provided leadership to the die and mold Industry. Recognizing that die and mold makers—although quite profitable—typically were smaller businesses with few assets or little capital, banks in the early 1960s were reluctant to loan money for equipment to small- and medium-sized die and mold operations. To assist, Makino started selling machines to the die and mold industry on an installment basis. In addition, Makino leveraged the relationship with their bank to assist small- and medium-sized die and mold operations with their capital investments. As a result, Makino's relationship with the die and mold industry grew and there was significant investment by die and mold makers in production facilities—with Makino at the center of this growth.



For years, the typical die and mold part (cores, cavities and mold working parts) were produced on traditional 3-Axis machines. This approach required multiple setups and handlings and utilized long tools that limited spindle speeds and feeds. The 3D features were created using a technique of stepping the cutting tool down in Z-level increments to produce the final profile. Obviously, this is a long, labor intensive method of manufacturing. Compounding that issue, there were certain minute features that were not able to be machined due to the reach into the part limitations and the limits of tool length to diameter ratios—requiring an additional EDM process to complete the part. Traditionally, there was also a significant amount of "hand finishing" to complete the manufacturing of the cores and cavities.

During the 1960s various manufacturers started to produce rotary tables for the machine tool industry. The initial products were typically limited to a single axis, indexing only and were slow and relatively inaccurate. In addition, full 5-Axis capability was limited by the control technology of the day. Over time, those rotary workhead tables advanced in accuracy, speed and number of axes available. However, even with the progression of table technology, the commercial tables still were not accurate enough to meet the demands of the die and mold market. The typical demands (for plastic molds) are approximately 0.0005 inch (about 12 micron) for appropriate part release from the mold, tight geometry in pocketing where there is no room for movement and for part surface quality and proper mold shut off accuracy. By contrast, commercial tables provide about 22.5 arc. seconds positioning—which translates to about 0.0009 inch (24 micron). That is two times the typical demands of the die and mold market. Another limitation of the tilting/trunnion tables is the speed of both the tilting and rotational axes. With speeds ranging from 25 rpm to 30 rpm, the speed of the rotary axes is not capable of matching-up with the feedrates achievable on the linear axes.

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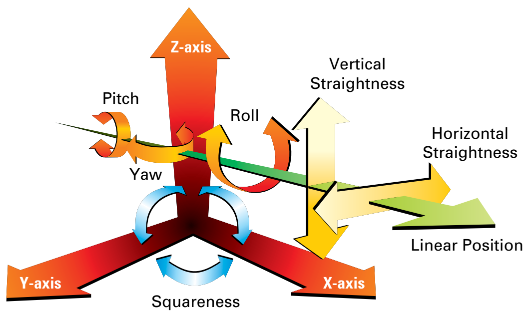
Recognizing the potential of a 5-Axis approach for the die mold industry, Makino developed and introduced the V33-5XB machine incorporating a Makino designed and built tilt/trunnion table with 3 arc seconds positioning translating to 0.0002 inch (5.25 micron). The next generation machine, the Makino V33i-5XB utilized a Direct-Drive (DD) motor type table that attacked the speed issue increasing it from 30 rpm to 150 rpm—a five-fold increase in positioning rates.

Seeking to provide the highest level of precision and surface finish to the Die and Mold industry, Makino's manufacturing philosophy is centered around 2 + 3 Machining. The 2 + 3 Machining is a practical approach based upon the following key principles:

- Position the least accurate axes (i.e.; the tilt and rotary secondary axes) to produce the highest accuracy
- Machine with the highest accuracy axes—the standard three axes of the machine utilizing the precision built into the basic machine:
  - Straightness
  - Flatness
  - Squareness
  - Positioning accuracy
  - Repeatability
  - Motion characteristics:
    - Roll
    - Pitch
    - Yaw



2 + 3 Machining provides the following benefits – when compared to the more traditional 3-Axis machining approach for die and mold parts:

- Tilt (or rotate) the part to gain access for machining
  - Multi side machining access
  - The ability to position the part for angled surface cuts
  - Assures short tool reach to support high-speed machining
  - Affords optimum tool position for highest precision cutting and extended tool life
  - Produces tight geometry in pocketing and key details where there is minimal room for movement
  - Ability to do core / cavity work as well as cooling holes, workings, details, etc. in a single holding
  - Positions part for angled surfaces, draft, tapers, etc.
  - Tighter relationships to all surfaces milled in a single set-up
- Part set-up and handling reduction
  - Reduces lead-time, set-up, WIP, costs
  - Faster "through-put" and shorter lead-times
- Shortening of tool and tool holders
  - Higher stiffness, rigidity and spindle speeds
  - Minimizes cutting cycle times utilizing higher spindle rpms and higher feedrates
  - Maximizes tool life while improving quality and reducing costs
- Tilt milling to get bench and polish-free surface finish on draft surfaces
  - Ultimate in surface finish
- Easier programming
- Highest accuracy
- Provides access to multiple sides in a single set-up
- Minimizes or eliminates hand fitting

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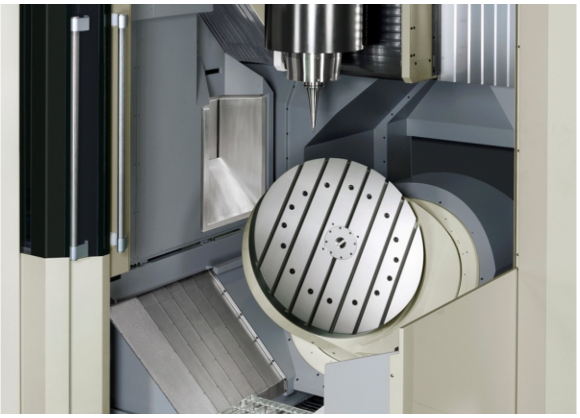
Over time, machine tool builders have experimented with various configurations, geometries and approaches for a 5-Axis machine tool platform. More than 216 different designs have been constructed, introduced and tested—each with its own challenges. In addition to the basic alignments, geometries and motion characteristics of a 3-Axis machine, 5-Axis designs add two more axes of potential errors. In addition, cutting forces, workpiece weight and moment, speed and motion all impact the overall precision of the machine.

Today, Makino offers a variety of full 5-Axis vertical machining center machine tool products for the die/mold industry. The D300, DA300 and D500 machines utilize traditional, tilt/rotary table designs with tilting and rotary axes under the workpiece to position the work relative to the spindle.

In addition, Makino has introduced a new, unique "truncated knuckle" or Z-type design used on the D200Z and D800Z machines. The Z-type design shortens the critical distance between the center of rotation of the tilting and rotating axes to provide a more rigid, stiffer design capable of greater speeds and tighter precision. The design guarantees that the center of mass for the workpiece never extends beyond the bearing diameter of the table ensuring quick, smooth motion and unmatched volumetric accuracy.

The methodology behind both the tilt / rotary table design machine and the new, unique, "truncated knuckle" or Z-type design is to position and move the work relative to the fixed spindle.



Additionally, the DA300—as well as other members of the D-Series machine family— while being full 5-Axis machines, can also be utilized as a highly-productive, five-face machine targeting multi-faceted parts in the production market. Tilting and rotating the part provides unparalleled access to all five sides of the work. This approach minimizes setup and work handling, facilitates using shorter, more rigid tooling, combines operations to improve quality relationships between part features and supports compound angle features. In addition, the advanced kinematics of the machine slashes non-cut time, reduces cycle time, cuts cost and increases productivity.

Most recently, Makino introduced the V80S and V90S machines—large, high-speed 5-Axis machines designed specifically for the die and mold industry. Obviously as mold core and cavity parts become larger, they also increase in weight and resulting mass and inertia as the part is moved. This especially is the case in high-speed machining and finishing. To attack this design issue and provide the machines high-speed, extraordinary precision and large die and mold part capability, the V80S and V90S machines position the spindle and tool relative to the part.

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General Technology Behind the Machines

Advancements in technology of the components utilized in the construction of machine tools lead to the capabilities exhibited by today's machines. Those technologies include the following:

- Advanced, digital servo designs that have improved feed axis smoothness by more than 3 times, provides tighter servo tuning and amplified responsiveness. In addition, digital servo feedback has been increased from 1 million to 3 million pulses per revolution. These advances both reduce cycle times and improve accuracy.

- During machine run-off, Makino takes this technology even further by strategically "tuning" the servo feedback / gain to provide the most accurate contouring capability.

- Direct Drive (DD) motor technology has quickly benefitted both tilt and rotation axes designs—whether they be under the parts (i.e.: tilt/rotating table designs) or on the spindle (i.e.: articulating spindle designs). DD motor design eliminated the prior slower, wear-prone rack and pinion type designs. Today's DD motor technology provides high-speed rotational motion (i.e.: 100 to 150 rpm), devoid of mechanical wear elements that generate lost motion and are extremely accurate. Now it is possible to feed, utilize the tilt and rotary axes of the machine with the same types of speed and precision typically only associated with the traditional basic 3-Axis machine tool.

  While DD motors provide the speed and precision necessary for 5-Axis machines, Makino surrounds the DD motors with a temperature controlling, cooling jacket to eliminate any negative thermal impacts upon the machine accuracy.

- Core-cooled ballscrews provide the opportunity to thermally control the heat generated by positioning the axes of the machine, using temperature-controlled fluid through the core of the ballscrew. This eliminates thermal impact upon the machine positioning components ensuring that it will maintain extreme accuracies over the entire manufacturing process time of long cores and cavities —typical of the die and mold industry.

  Unlike many competitors, Makino not only utilizes core-cooled ballscrews but, also expands the thermal control area to include the ballscrew support bearing and servo mounting area. This guarantees that the kinematic motion of the machine will not impact the machine's positioning accuracy and repeatability. For long cycle time die and mold components, the machine will remain thermally constant during the machining operations.

  Core-cooled ballscrews offer several key advantages:

  - Shorter "warm-up" cycle
  - Lower stabilization temperature
  - Less thermal growth and tighter accuracies
  - Reduced operation temperature
  - Longer component life

- High precision, optical glass, non-contacting scale feedback developments provide the positioning accuracy and repeatability required to guarantee that the die and mold components manufactured on the machine will meet the highest quality and performance standards. Housed in an air pressurized, sealed box, this critical compost is protected from chip and coolant contamination and its non-contacting optical provides long-term precision.

Unlike many competitors, Makino utilizes these super, high precision scales on virtually all the 5-Axis machines as a standard feature. In fact, the D200Z machine incorporates 0.0125-micron scales.

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Commercial Control Developments

All automated motion control manufacturing machines, from bare-bones concepts of the early days to highly advanced systems today, still require 3 primary components:

- A command or control function
- A drive or motion system
- A feedback system

Early automated motion machines utilized mechanical cam-based automation applied to a stylus that "traced" a template and transformed that input into motion using hydraulics to move the individual machine axes. In the 1950s, initial numerically controlled (NC) machines employed vacuum tubes and mechanical relays as their primary controlling mechanisms. At the time, the controllers were "point A to point B" type positioning that functioned along a single axis of motion. By the mid to late 1950s, NC progressed to become 3-Axis capable—moving a single axis at a time.

In 1958, Fanuc shipped the first commercial Fanuc NC to Makino Milling Machine Company, Ltd. Makino developed Japan's first magnetic-tape NC Vertical Milling Machine which was the earliest generation of today's CNC machines. Additional quick developments lead to the introduction of a "continuous-path" NC (more capable than the initial point-to-point version) and the electro-hydraulic pulse motor was developed. In 1960, Fanuc introduced its open-loop, continuous-path, NC Control—named the Fanuc 220. By 1964, over 35,000 NC Controls were in use nationwide. High-density, integrated circuits (IC) technology hit the scene in 1966, transforming the NC Control market to an all IC platform.

One of the challenges during this timeframe was the torque amplification required to take the small output of an NC Control to drive very large motors and mechanical drive systems associated with moving the physical components of the machine. Additionally, to enhance accuracy, a closed-loop feedback system was needed to provide real-time positional location.

A key development was the introduction of the servomechanisms, which produced powerful, controlled movement with highly accurate measurement information. Using a variety of mechanical or electrical elements, the output of the servomechanisms could be used to ensure that proper movement occurred, providing a "closed-loop" control system.

During the 1960s, the capability, power and availability of computers increased dramatically. In addition, the price of computers fell drastically with the widespread introduction of mini-computers. By 1972, the industry was moving to Computer Numerical Control (CNC) as the basis for controlling a machine tool.

The introduction of the microprocessor in the 1970s further reduced the cost of implementation, and today almost all CNC machines use some form of microprocessor to handle all operations. The microprocessor led to a subdivision or distribution of tasks providing enhanced capabilities and speed of the CNC Control. Multiple axis motion, G-Code programming, tool data files and data, work coordinate systems, canned cycles, sub-programming, user macros, etc. and distributed control of various machine tool elements are all an outgrowth of this technology.

AC servo motors came on the scene in 1999 to support higher speeds, quicker acceleration/deceleration and tailoring of motion characteristics to minimize kinematic impact upon the machine structure and motion. Bell shaped acceleration/deceleration curves, minimization of jerk and high-gain servo designs provide peak performance capability while retaining precise motion characteristics.

The introduction of lower cost CNC machines radically changed the manufacturing industry. Considerable improvements in consistency and quality of high-volume repetitive parts can been achieved with reduced frequency of errors. Non-linear features, curves and even three-dimensional structures can be readily produced and repeated.

Commercial Control Developments

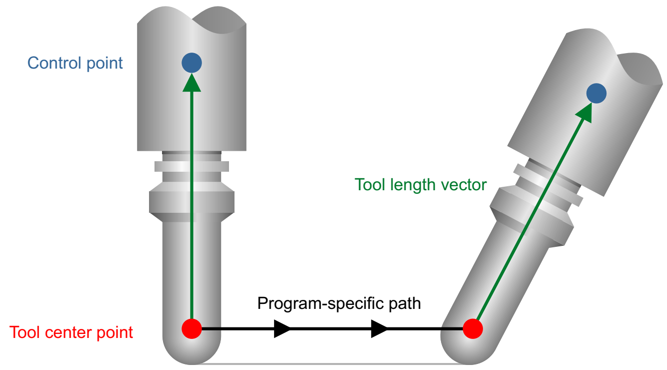
While these developments were revolutionary, equally important were the essential software advancements critical to addressing more complex, multi-axis parts. Several major software developments include the following:

- **Dynamic Fixture Offset (DFO)**
  DFO is a multi-axis control technique that can be utilized on parts that require work on multiple locations, positions and sides—employing a single work offset. As the part is rotated and tipped to each static position during the program, the machine tracks the part position so that the program runs correctly. This methodology does not require the part to be on center, which reduces fixture complexity and lowers costs due to the dynamic fixture offset. Programming is relatively easy and part setup and exchange is quick. DFO is also capable of running canned cycle routines, such as drilling and tapping.

- **Tilted Work Plane (TWP)**
  TWP is used when a part requires work to be done at positions other than normal to the Z-Axis. It provides the ability to machine a feature on a plane tilted relative to the basic reference surface of the workpiece using a secondary coordinate system referred to as a "feature coordinate system." The function can be realized with many different machine designs (ie: tilt/rotary, articulating spindle type and mixed machine types of designs).

- **Tool Center Point Control (TCP)**
  TCP is a function that constantly compensates the tool by changing the attitude of the tool. It enables the tool center point to move along a specified pathway—even if the tool's direction changes with respect to the workpiece. Like TWP, this function utilizes the same center of rotation parameters and can be applied to many different machine designs (ie: tilt/rotary, articulating spindle type and mixed machine types of designs). TCP makes programming simpler, maintains the programmed feedrate during all simultaneous moves, and can reduce the complexity and cost of fixtures. Since the workpiece does not need to be located on the center of rotation—due to the utilization of a work offset—setup and part handling times can be greatly reduced as well.

- **3D Cutter Compensation (3DCC)**
  3DCC performs 3-dimensional compensation in a plane (compensation plane) perpendicular to the tool vector. For machines having multiple rotary axes for freely controlling the orientation of a tool axis, this function calculates a tool vector from the positions of these rotary axes. The function then calculates a compensation vector in a plane (compensation plane) perpendicular to the tool vector and performs 3-dimensional cutter compensation. 3DCC works in conjunction with TCP.



Tool Center Point Control (TCP)

Further Makino Enhancements and Proprietary Developments

From its founding, Makino has been closely tied and highly focused on the die and mold industry and the unique demands on machine tools in that market segment. Therefore, over the decades, Makino has initiated many enrichments to technology, products and processes directly related to the key demands of that industry:

- **Volumetric Accuracy**
  With the typical demands (for plastic molds) in the 0.0005" (about 12 micron) range for appropriate part release from the mold, tight geometry requirements for pocketing, surface blends, matches and the critical need for controlling product shape and contours (via the mold)—volumetric accuracy was paramount. Makino designs eliminated overhangs and unsupported areas that would negatively impact precision. A unique axis configuration was introduced that placed the X-Axis and Z-Axis on the column and the Y-Axis under the table to insure fully supported travels, minimal reaches, no stack-up of components and exceptional cutting conditions. Using large, strategically designed Finite Element Analysis (FEA) optimized castings for structural rigidity and torsional stiffness and meticulous assembly techniques targeted delivering half (or less) of the industry specified standard tolerance, Makino products provided the volumetric accuracies required to meet the demanding die and mold industry.

- **Thermal Control**
  Since many die and mold components could have very long cycle times, it was imperative that the machines be thermally stable. Precision and volumetric accuracy needed to be constant over the long machining cycle times—or the thermal changes would be reflected in the final die and mold parts. Makino utilizes large, symmetrically designed castings to provide a long thermal time constant (i.e.: rate of change of the casting temperatures). The symmetrical design ensures that the machine will maintain the critical geometries. An insulation layer and machine sheet-metal provide additional protection from temperature to the castings.

  Recognizing the need to be proactive, Makino introduced a number of "intelligent" (or "i") machine design features to minimize, eliminate or control machine thermal growth:

  - Makino not only utilizes core-cooled ballscrews, but also expands the thermal control area to include the ballscrew support bearing and servo mounting area. This guarantees that the kinematic motion of the machine will not impact the machine's positioning accuracy and repeatability. For long cycle time die and mold components, the machine will remain thermally constant during the machining operations.

    Core-cooled ballscrews offer several key advantages:
    - Shorter "warm-up" cycle
    - Lower stabilization temperature
    - Less thermal growth and tighter accuracies
    - Reduced operation temperature
    - Longer component life

  - Direct Drive (DD) motor technology provides the speed and precision necessary for 5-Axis machines. But to ensure constant temperature control, Makino surrounds the DD motors with a cooling jacket to eliminate any negative thermal impacts upon the machine accuracy.

  - Makino utilizes a closed-loop, thermal compensation system that encompasses all the machine elements. A thermal sensor, located in the bed casting, measures the temperature of the casting and an oilmatic unit (i.e.: freon chiller) using temperature-controlled fluid and maintains the core-cooled ballscrews, DD motors with a cooling jacket and spindle all to the same temperature. In effect, this system creates

Further Makino Enhancements and Proprietary Developments

an "ambient manufacturing zone" that minimizes (or eliminates) the thermal impact upon the accuracy and precision of the machine. This can be especially beneficial for long cycle time parts typical of the die and mold industry.

- **High-Speed Spindles**

Initially developed for high-speed surface finishing of dies and molds, high-speed spindles have long been a core competency of Makino. Intimately familiar with the die and mold industry, Makino spindle development has, for decades, been driven by these strategic requirements of a die and mold spindle:

- Outstanding stiffness and rigidity for ideal cutting conditions
- Minimal run-out for accuracy and surface finish
- Negligible vibration for chatter free cutting and fine surface finishes
- Thermal stability providing precision from start to finish
- High RPM capability for small tools and surface finishing

Today, Makino's high-speed spindle design represents more than thirty years of proprietary development, multiple patents, hundreds of technological advances and tens-of-thousands of machines in the field. Critical elements of the design include the following patented features:

- Core cooling
- Under race lubrication
- Closed loop oilmatic

- **Motion Control**

Directly related to high-speed spindle development was that of motion control. Early on, Makino recognized the motion control limitations of control technology and in 1984 patented and introduced the NC High-Speed Adaptor which bypassed the control and drove NC data directly to the axes providing a 200% to 300% surge in feedrates—dramatically increasing productivity. Working with Fanuc to "package" this proprietary feature in the Fanuc control of the day, Makino gained limited, exclusive usage of what was the beginning of Fanuc High Precision Contour Control (HPCC) utilized today.

Recognizing the need for continued higher feeds in the complex, contoured, high-definition 3D surface applications typical of the die and mold industry and the coming commercialization of HPCC (by Fanuc), Makino continued its development of motion control software. In 1991, Makino introduced two proprietary motion control software developments:

- Geometric Intelligence Control (GI)
- Super Intelligence Control (SGI)

GI.5 and SGI.5 represent the latest generation of those initial Makino developments involving more than thirty-years of painstaking, proprietary progression.

SGI.5 is especially useful when machining complex, three-dimensional, freeform core/cavity surfaces, and high-definition surfaces representative of the die and mold industry. These features typically are defined using many continuous small blocks (1 mm or shorter) in the program. SGI.5 analyzes and corrects the feedrate based upon the program geometry. Machining errors that occur with standard CNC machine tools are eliminated.

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Further Makino Enhancements and Proprietary Developments

This system can virtually eliminate part gouging caused when a cutter overshoots the programmed path due to servo error. Even at higher feed speeds, SGI.5 can correct servo "droop." A combination of highly refined AC digital servos and proprietary software make it possible to feed at rates faster than standard CNC systems while maintaining high accuracy.

SGI.5 software:

- Excels in the data intensive environment of complex die and mold parts
- Maintains highly accurate motion—even when the axes are fed at high speeds
- Makes high-speed AND high-accuracy machining possible
- Provides advanced acceleration and deceleration control technology
- Enables efficient axis motion
- Achieves much higher accuracy than conventional approaches
- Significantly reduces part processing time
- Creates remarkably smooth machining surfaces
- Dramatically reduces cycle time for complex, three-dimensional, freeform core/cavity surfaces
- Improves productivity
- Reduces costs

With the growth and introduction of 5-Axis machines—especially in the die and mold industry—new developments and technologies were introduced to attack the issues created when the part is tilted and rotated to position it relative to the spindle.

Inertia Active Control (IAC)

As the workpiece and fixture are rotated and tilted for access—especially on a tilt /trunnion style design machine—the resulting change in position of the mass center can have a negative impact upon the accuracy of the 4th and 5th axes thus degrading the volumetric accuracy of the machine. This phenomenon is directly related to the part and fixture weight. In addition, the actual speed used to tilt and rotate the part can change the error due to the inertia generated during the motion. Makino developed IAC as a methodology for minimizing this error by correcting the inertia impact upon positioning.

Various Posture (VP)

Even with the extensive manufacturing processes and assembly techniques implemented by Makino to build an extremely, volumetrically accurate machine—the addition of a 4th and 5th axis either under the part or on the spindle increases the potential error sources and their impact upon machine precision. In addition to using DD motors for the tilt and rotary axes, Makino developed and introduced VP control to recognize, measure, map and compensate for the minuscule errors associated with multi-axis machines.

Collision Safeguard (CSG)

One additional concern with multi-axis machines is that of collisions. The relationship between the part and elements of the machine change as the part is tilted and rotated relative to the basic axes of the machine. Therefore, it is imperative to protect the workpiece, fixture, tooling and machine from unexpected crashes.

Further Makino Enhancements and Proprietary Developments

Makino's CSG utilizes a solid model, running "real-time" machine control data to protect the machine from doing damage to itself. Importing of geometries associated with the part, fixture and tooling can also be used to safeguard the part, fixture and tooling from collisions during complex, multi-axis machining.

Professional 6 Control (Pro 6)

While traditionally utilizing a Fanuc control, Makino has provided a proprietary graphical user interface (GUI) aimed at creating a user-friendly machine-to-human interface. The objective of the Professional Series Control was to harness the power of the Fanuc control while making data entry and operation simple using menu- and graphical-driven input screens.

The Pro6 is the latest version of Makino's proprietary GUI interface control. It facilitates moving quickly from parts to profits with elegant functionality by creating a seamless transition where the operator meets machine. A large color touchscreen provides streamlined screen layouts, operator assistance, "On-Board" Manuals, G-Code and M-Code "look-up" and expanded datacenter memory for large die and mold programs.

5X Continuous (5XC)

5XC represents the "next-generation" of 5-Axis Machining. Several technologies are converging to take 5-Axis machining to the next level. Mold and die makers will benefit from more capable machining centers, milling tools and CAD/CAM systems that are rendering 5-Axis machining remarkably more productive. 5-Axis machining technology has increasingly grown more capable over the years, but there still have been drawbacks that made some shops think it was out of their reach. In fact, there have been inherent limitations that kept 5-Axis technology from achieving its potential from a pure machining productivity perspective.

That is changing rapidly with advancements in machine tool technology, as well as with enabling technologies such as cutting tools and CAD/CAM software. Combined, these advancements render 5-Axis machining processes astonishingly more productive than that of a few years ago. Though perhaps counterintuitive to some, a more expensive machine and cutting tool will result in the lowest cost per part—oftentimes by a significant amount.

The combination of these technologies enables faster generation of smooth and accurate 3D surfaces in difficult materials as well as increased tool life. Mold and die makers will likely be the first to recognize these benefits, but these process improvements also serve a wide range of 3D applications such as orthopedics, medical, optics and aerospace.

Just as critical is upgraded control technology that does much more than process program blocks faster. It also can automatically smooth 3D tool paths, "know" the true position of the entire cutting tool and workpiece to provide real-time collision avoidance, and even dynamically map and compensate automatically for small tool position errors caused by workpiece inertia.

5-Axis control opens up new opportunities to better utilize cutting tools. Conversely, new cutter geometries are emerging that better utilize 5-Axis mills. Even with a common ball nose end mill, you'll get much better utilization of the cutting edges and higher material removal by tilting the tool and cutting with the outer radius of the ball. 5-Axis machining makes that possible.

Tooling & Software Developments

Some recent tooling developments that can deliver even greater gains in productivity include:

Multi-Flute End Mills

This one is simple math. Having more flutes on a cutting tool lets you maintain higher speeds and feeds simply because you have more edges in play. Makino has proven this out in tests with six-flute end mills. Moreover, the extra flutes provide more cutting surface on a given tool, which results in longer tool life. Altogether, these advantages result in much higher metal removal rates, better surface finish and lower overall cost.

Barrel-Shaped Tools

Barrel-shaped cutters can provide great benefits on a 5-Axis machine. These cutters have contoured profiles that enable wider cutting contact with a contoured workpiece surface, almost like a super-large ball nose end mill. Coming in several configurations, perhaps the most common is a large radius tool that curves down to a small radius at the tip. The biggest advantage of this tool is that it provides an equivalent or better surface finish with larger stepovers, resulting in fewer passes required to machine a 3D surface. Then, the small radius tip of the tool can get into tight corners. Not only can manufacturers do more with a single tool, it results in continuous machined surfaces with significant reductions in blending issues. Barrel-shaped milling tools also come in multi-flute configurations. Add it all up, and the result is fewer tool passes with better surface quality, faster feed rates, less tool changes and a more productive cutting process.

CAD/CAM

In addition to tooling technology evolution, advancements in CAD/CAM software systems were critical to support 5-Axis machining and the emerging tooling. CNC programming has historically caused bottlenecks in 5-Axis machining because of the complexities of the surface geometry and the many tool vectors. However, as CAD/CAM vendors continue to add features, programming is becoming more adept at creating efficient tool paths in less time. As an example, some systems layer 5-Axis features on top of a more familiar 3-Axis functionality. Users can also start by generating a 3-Axis program as normal, and then add in the 5-Axis moves where the tool is tilted away from adjacent surfaces to reach features and avoid collisions.

CAD/CAM systems have also evolved to support multi-flute cutters and barrel-shaped tools. Tool shape and geometry can be defined so that the system can automatically generate tool paths with larger stepovers while maintaining or improving the machining tolerance to the surface model. The result is less need for blending, matching and stitching.

Traditionally, one of the big challenges of 5-Axis machining was avoiding collisions. Today's powerful validation software goes a long way to reduce that risk by simulating the entire cutting process and identify any inadvertent cutter or toolholder collisions with adjacent workpiece surfaces. To this end, Makino utilizes its CSG (Collision Safeguard) which keeps the part, fixture, and tooling safe from collisions during complex, multi-axis machining.

These enhanced CAD/CAM features substantially reduce the time it takes to go from a CAD/CAM file to a proven 5-Axis part program. When lead time is critical—such as in die/mold work—that's a huge competitive advantage.

Further Makino Enhancements and Proprietary Developments

With today's 5-Axis machine, control capability, new tooling technology and CAD/CAM system developments, 5XC facilitates orienting the cutting tool, and its edges, in an optimum position relative to the workpiece. This can be accomplished by either positioning the part relative to the tool (i.e.: tilt/trunnion table designs) or the tool relative to the part (i.e.: articulating spindle style designs). By targeting machining with the ideal contact point of the tool and part, the best cutting conditions are achieved. Rather than cutting with the tip (or null point) of the tool, tilting or tipping of the tool affords using a larger, more productive, efficient cutting point on the tool.

- Using the optimum cutting interface point results in more efficient metal removal, can lead to high-speed machining and produces a much better surface finish. This can lead to lower cycle times and less hand-finishing and secondary operations.

- Tilting the tool can provide access into smaller, features, blends and matches much deeper in the core or cavity. Positioning the tool (or part) can provide access using shorter and more rigid tools, with less run-out to efficiently machine these small features. This process can reduce the numbers of tools, decrease the number of programs and eliminate much of the blending and matching required with prior processes.

  In addition, small form-shaped tools can produce tiny, detailed, critical features and surface finishes deep within a die and mold component. These geometries and surfaces can be readily achieved on a milling machine—eliminating the need for secondary operations (i.e.: sinker EDM which also requires the production of an electrode) and final hand-finishing of the component.

- Shorter, more rigid tooling with less runout can also enhance optimization of the machining process. Shorter tooling can provide significant advantages in the tool length to tool diameter ratio (L/D), can dramatically impact radial and axial depths of cut as well as enable cutting feedrates to drastically enhance metal removal rates (i.e. MRR).

- Various tooling developments and progressions have provided a diversity of advanced shape design and capabilities that can be utilized on a 5-Axis machine. Expansions in tooling geometry, coatings, grades, tool profiles, radii and hybrid variations have introduced many new tools to the market:
  - Ball nose endmills
  - Bull nose endmills
  - Multiple cutting surfaces or flutes
  - Oval form cutters
  - Taper form cutters
  - Lens form cutters

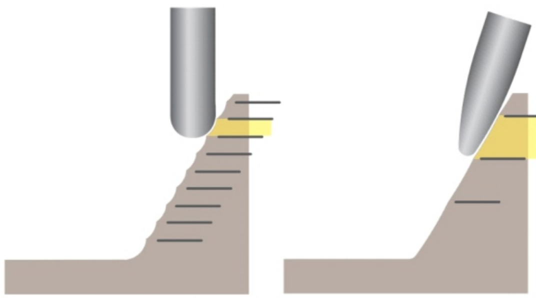
  These instruments can dramatically reduce the number of tools required to complete a project, enhance machining of small, detailed features and significantly reduce cutting time and improve productivity.

As an example, a barrel-shaped tool can be used to produce a complex, 3D die/mold part profile using one, long feeding tool path and this unique shaped tool. The multiple diameters of the tool and tool shape are used—with the capability of a 5-Axis machine—to produce the finished surface. Traditionally, this surface would have taken many tool paths and multiple passes and tools to produce the finished surface.

Further Makino Enhancements and Proprietary Developments

In a mold lifter application, a barrel cutter was used to cut the profile and lifter surface on a 5-Axis machine. In this application, the cycle time was reduced from 59 minutes (with a traditional 3-Axis machining approach) to 13 minutes, resulting in a 46 minute (78% reduction in cycle time with improved surface finishes).

A final example looks at the finishing of a sloped surface in a mold cavity. Traditionally, on a 3-Axis machine, this surface would have been developed using a Z-Axis stepping technique and a ball nosed end mill. However, using a ball nosed end mill on a 5-Axis machine, the final, finished surface can be generated in a single machining pass. Obviously, this saves time, extends tool life, requires fewer tools and toolpaths and generates a better surface finish.



Conclusion

Add it all up, and today's 5XC machining technology can deliver:

- Reduced preparation times
  - Reduced programming time
  - Less programs
  - A reduction of tool paths
  - Decreased need for blending, matching and stitching of surfaces
  - 5-Axis to reduce set-ups and handlings
  - A decrease in the number of tools using barrel-shaped tools
- Improved access to part geometry
  - More uniform surface finish/quality
  - Better blending/matching, etc.
- Significantly reduced cycle times
- Increased throughput/shortened lead-times
- Higher productivity
- Smoother, more accurate machined surfaces
- Better surface finishes—extending mold life
- A decreased or eliminated need for secondary processes, EDM and benching or hand-finishing
- Lower tooling costs
  - Shorter, stiffer, more rigid tools extend tool life
  - Reduced run-out
  - Multiple inserts prolong tool life
  - Longer tool life
  - Fewer tools required for a project
- Increased profitability
- Lower machining costs
- Decreased cost per component
- Diminished lead-time