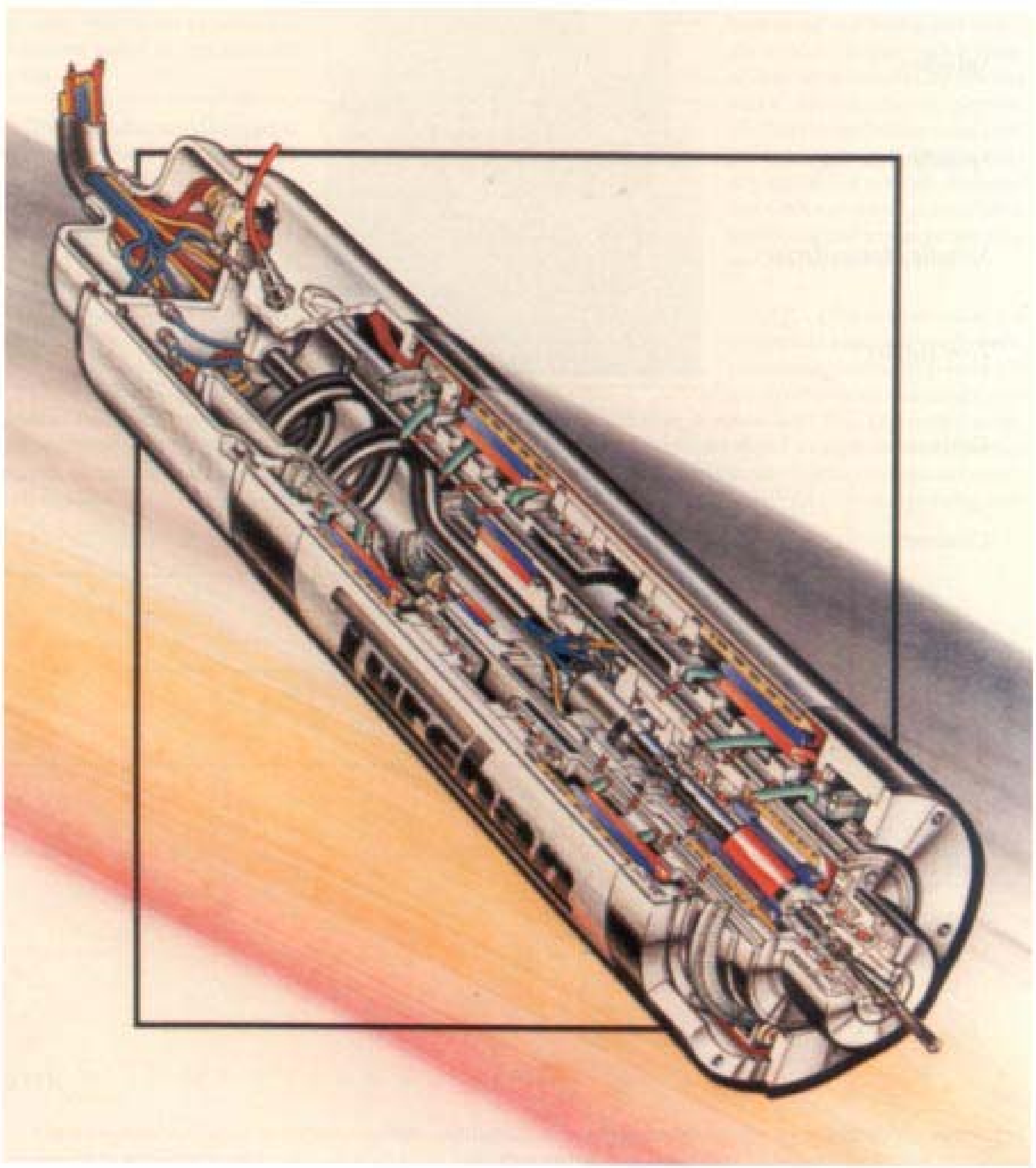
HIGH SPEED MACHINING



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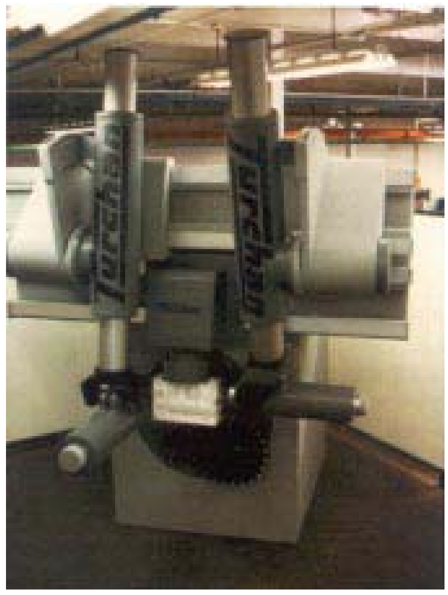
A special spindle with integral3 axis CNC motion capability, the spindle has a motorized 60,000 RPM inner spindle, cradled in an eccentric quill, which allows Thrilling of aluminum alloys in less than ½ a second.

These spindles could be applied to flexible transfer lines and result in a substantial reduction of stations. Ultimately, they may be applied to new machine architectures.

Two of these spindles are carried by this machine dubbed ARMED FORCES.

The system was specifically designed as a minimum module for both prototype and high volume production of prismatic aluminum powertrain components, completely machining an integral head and block in 60 seconds.



ABOUT THE AUTHOR

Manuel C. Turchan, CEO of the Turchan Technologies Group, has relentlessly pursued the development and production application of high speed machining and its enabling technologies, such as magnetic bearing spindles, air bearing ways, linear motor servos, Thriller® combination tools, composite machine structures, totally dry machining systems, diamond and CBN tool coatings, innovative processing and advanced machine and control architectures.

A Turchan affiliate, has developed a radical, breakthrough process supplanting PVD and CVD for synthesizing materials and coatings including diamond and CBN. This materials sciences group has also developed a unique method of joining materials called Cold Fusion. and a revolutionary coating process called Photo·cote. for corrosion proofing metals that uses no wet chemistry.

NOTE

The contents of this paper concern the background, benchmarks and status of high speed machining. The author has endeavored to be concisely comprehensive, accurate and informative. Any suggestions, additions, omissions or corrections regarding this material for future editions are sincerely appreciated.

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Machines

Spindles comprise the heart of high speed machining capability. The CNC machining center is its body. High speed spindles dictate higher performance slide/servo requirements. A two (2) inch diameter, four (4) insert mill running at 20,000 RPM needs an effective feedrate of 800 IPM.

High performance machine tools feature rapid traverse rates of 1,200 inches per minute. Linear motor servos and low inertia designs can double or triple those feedrates.

Perhaps more important than high federate capability, is high acceleration and deceleration. Conventional machining centers achieve 0.2 g's. High performance systems start around 1 g and go as high as 4.0 g's. At that rate, the forces of acceleration exceed cutting forces. Therefore, design optimization becomes critical. The goal is to achieve maximum stiffness with minimum inertia.

One approach to decreasing inertia is through the application of light-weight materials such as aluminum, composites and structures such as honeycomb and isogrids.

To eliminate the stick-slip phenomenon, ball and roller bearing guide ways provide a satisfactory, yet economical solution. In some cases, air bearing ways are used. Although dynamic stiffness is more difficult to achieve with these bearings, workpiece material may dictate their use as in the space shuttle tile machining system shown in Fig-

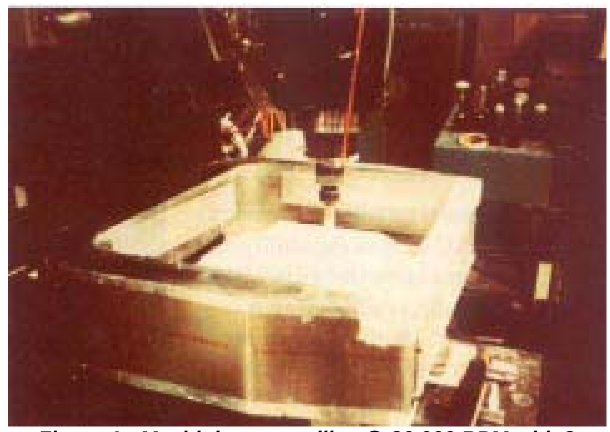

Figure 1 - Machining pure silica @ 20,000 RPM with 2. diameter diamond tool (Turchan 1978)

Air bearing ways eliminated lubrication which trapped silica dust that would quickly destroy conventional guide ways.

Elimination of spindle lubrication effluents by using permanently lubricated (grease-packed) bearings circumvented contamination of the silica tiles prior to glazing.

Machine design is often dictated by workpiece peculiarities such as this high speed turning and milling system for cruise missile fuselage machining. (Figure 2) The 2219 T-6 aluminum is machined from the inside with 20,000 - 40,000 RPM spindles reaching 52" into a 16" I.D.

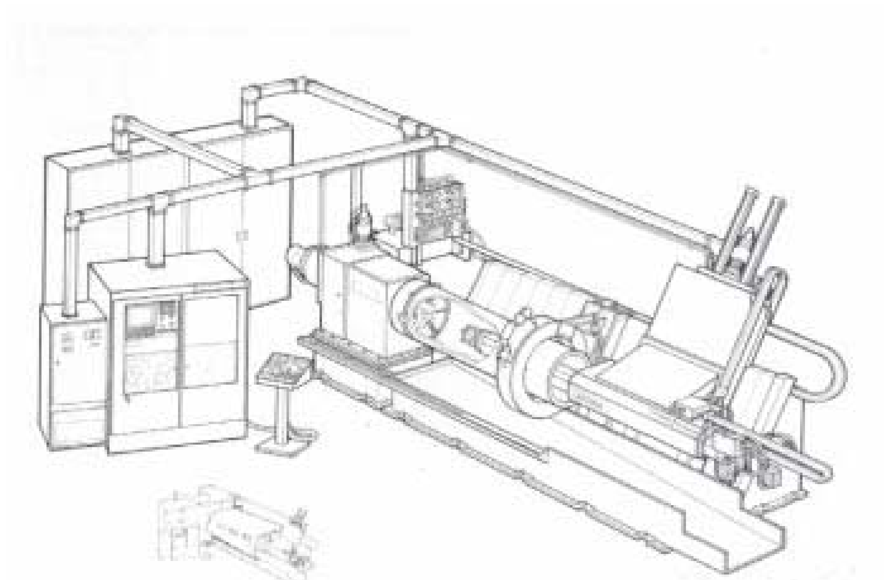

Figure 2 - Cruise Machining (Turchan 1977)

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In some cases, fascination with a design, even without a production application, can lead to exciting developments. One such machine design is the Hexapod, derived form the Stewart Platform used for flight simulators and test platforms.

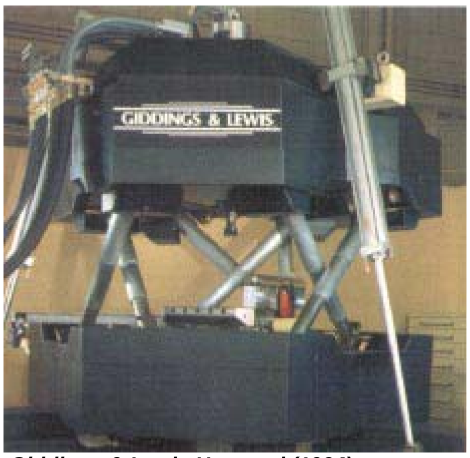

Figure 3 - Giddings & Lewis Hexapod (1994)

Giddings and Lewis, Ingersoll and a number of other companies, tried to apply the concept in one version or another to machining.

Some advantages are; a self-reacting structure requiring little or no foundation, relatively less expensive to manufacture (in volume), capable of extreme accuracy and high speeds.

G&L first exhibited their Variax at IMTS .94 with a high speed spindle. It's a bit too early to predict the degree of success that G&L and Ingersoll will have with their fascinating machines, but every government lab should have one. Designs to accommodate high speed spindle speeds go back to the fifties. Probably the grand-daddy of all high speed machining was Molins. Under the invention and direction of Dr. Theo Williamson, Molins simultaneously developed high speed machining and the flexible manufacturing system. Their System 24 - nearly 50 years later, is still unrivaled in innovation and comprehensive execution.

Figure 4 - Molins System 24 (1995)

Systems were installed at Hewlett-Packard and IBM. The System 24.s name was derived from 24 hours per day that the system would run unmanned. That was 1953!

Figure 5 - The Streaker (1973))

In the late .60.s and early .70.s with the advent of computer numerical control, machines became capable of higher speeds such as the Streaker, an all aluminum-cast, super-structure that featured 2,000 IPM and a 5 horsepower, 60,000 RPM Oberg spindle. Later versions with 5 axis capability were used for routing fiberglass and composites.

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About that time, high speed, high powered systems were beginning to penetrate the automotive industries. Forty (40) horsepower spindles, running at 12,000 RPM, with carbide insert-style tooling, generating in excess of 10,000 SFM, were precursors to today's special purpose high speed machines.

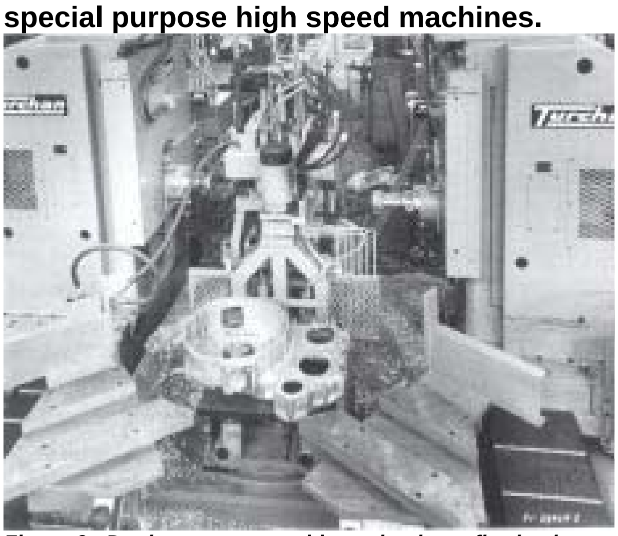

Figure 6 - Duplex system machines aluminum flywheel housings @ 10,000 SFM (1975)

As controls and their interfaces evolved, and spindles became more powerful at higher speeds, earlier high volume concepts evolved into complex centers capable of completely machining automotive cylinder heads and blocks in one place. Specialized combination tools eliminated tool change time and linear motors shuttle workpiece fixtures in practically zero time.

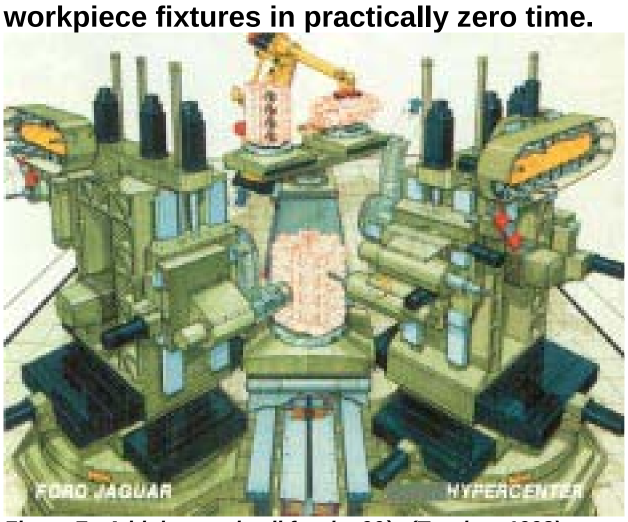

Figure 7 - A high-speed cell for the 90`s (Turchan 1993)

Aircraft and Aerospace really spurred further investigation of high speed machining. Through the efforts of R. L. Vaughn, and later R. King at Lockheed, Molins' systems at Hewlett- Packard were called upon to demonstrate high speed machining to kindle enough interest to fund more development. Lockheed worked with Ex-Cello's Bryant Spindle Division to retrofit several machines, such as Omnimill's and Bullards, with 20,000 RPM spindles to develop tooling and investigate high speed machining's advantages.

Figure 8 - This ubliquitous cruciform became a symbol of Lockheed.s high speed machining efforts

Figure 9 - High speed 5-axis profiler USAF (Turchan/Intertec 1981)

Aircraft and Aerospace gantry mills and routers were equipped with 20,000 RPM spindles capable of 20 horsepower cuts.

In the meantime, General Motors, under the auspices of Alex Maier, Executive Vice President and "corporate scientist", undertook a project to develop the high speed machining system of the future for prismatic aluminum parts.

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The first step in this plan was to develop high speed drilling in 390 aluminum alloy. They used the EXTREMON system shown here (see Figure 10), routinely drilling holes at 40,000 RPM, in a fraction of a second. Ultimately, the project, which was initiated for the Saturn and then the Manhattan Powertrain, met its demise in the face of an austerity program.

Figure 10 - High speed drilling development at the GM Tech Center (Turchan 1982)

Interestingly enough, the survivors of that program have forged a mandate for General Motors to decry dedicated transfer line systems in favor of machining centers with somewhat higher spindle speeds (< 15,000 RPM) and faster feedrates (< 900 IPM). The premise is that investigations show that extremely high spindle speeds > 15,000 RPM, feedrates in excess of 1,200 IPM, and acceleration rates > 0.5 g.s are not useful and, in fact, are past the point of diminishing returns from both reliability and increased productivity perspectives.

Figure 11 - Construction for high speed machining

(Turchan 1985)

New materials were considered for high speed machining systems, including polymer concrete. The first was Granitan S-100, developed by Ciba Geigy for Studer grinders. Granitan exhibited superior damping and thermal characteristics. Precision machine surfaces could be cast-in inserts or replicated using these techniques. Probably the biggest advantage was cost in producing multiples of the molded bases.

The system shown in Figure 11 utilized a polymer concrete base with air bearing ways, aluminum honeycomb construction and three (3) point machine leveling to carry a pair of 30,000 RPM spindles. Directdriven rotary axes index 360º in less than one second.

The need for high speed, rotary axes is evidenced by this special purpose, scroll compressor machining system by Ex-Cello GMbH. With spindle speeds of 40,000 RPM, the R-theta movement cannot be accomplished with the customary 10-11 RPM machining center rotary axis. .

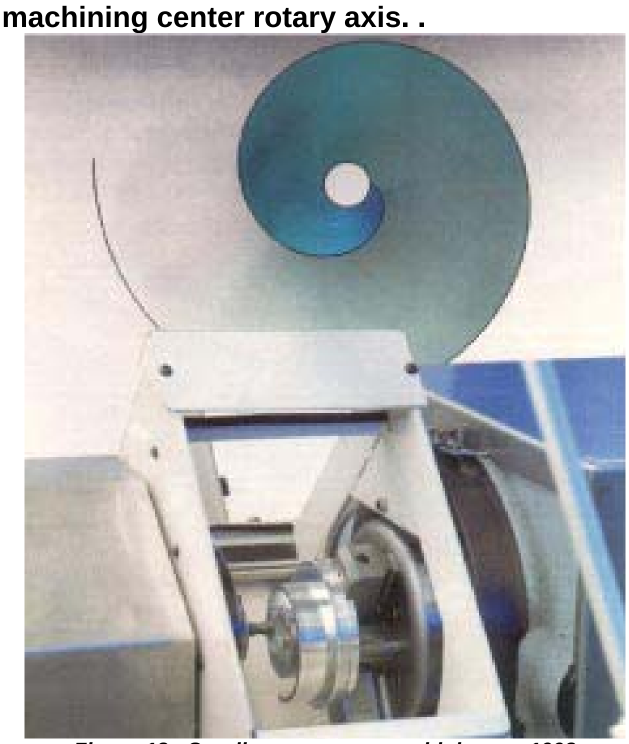

Figure 12 - Scroll compressor machining ca. 1992

<u>Spindles</u>

A poor man.s high speed machining center can be achieved with the addition of a speed increaser. These utilize the machining center.s main spindle to drive planetary gears or traction-driven tool holders. (See Figure 13.)

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Figure 13 - Traction-driven speed accelerator (SHOWA 1993)

These devices are fine for light duty applications, but lack the stiffness required for high-power, high speed machining.

An intermediate and flexible step to a high speed machining center is a high speed spindle with taper adapter and services for quick change manifold attachments. The theory is that a high speed spindle can be waiting in your tool carousel for the appropriate specialized moment of use. (See Figure 14.)

Figure 14 - Quick change spindle IBAG (1993)

Another method is a revolver of high speed spindles. In the application shown (figure 15), six high speed spindles are ready with dedicated tooling (all that.s needed) to machine Thomson Industries. Aluminum pillow blocks.

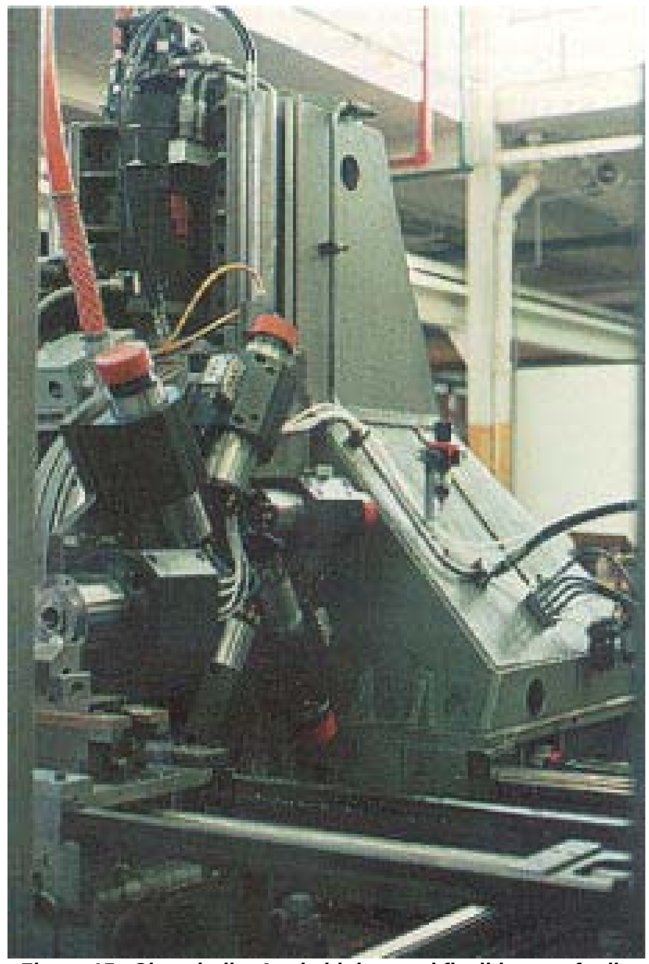

Figure 15 - Six spindle, 4 axis high speed flexible transfer line (Turchan 1986)

In this scenario, the spindles run continuously, indexing from one to another in less than a second. No run-up/run-down or warm-up is necessary. Parasitic tool change time is eliminated with less than one second revolver indexing.

For the most part, today’s modern high speed machining centers feature 20-30,000 RPM, 10-20 horsepower fixed center line spindles.

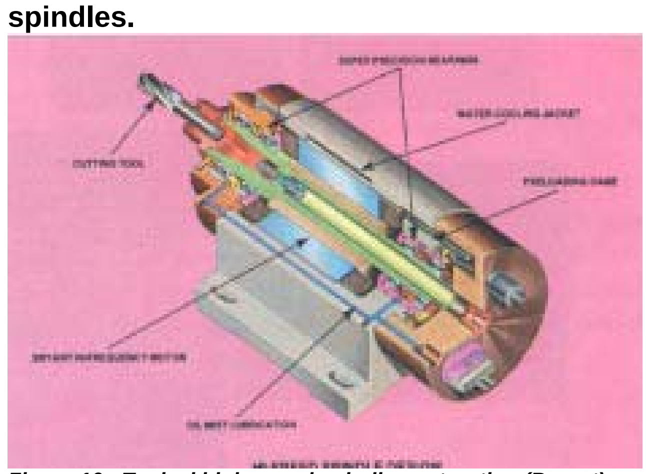

Figure 16 - Typical high speed spindle contruction (Bryant)

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They are mostly integrally motorized, AC induction motors running off frequency converters.

Higher performance, high speed, high power, motorized spindles utilize angular contact ball bearings. The bearings are usually Silicon Nitride (Si_3N_4) balls running in 52100 bearing steel races. (See Figure 17.)

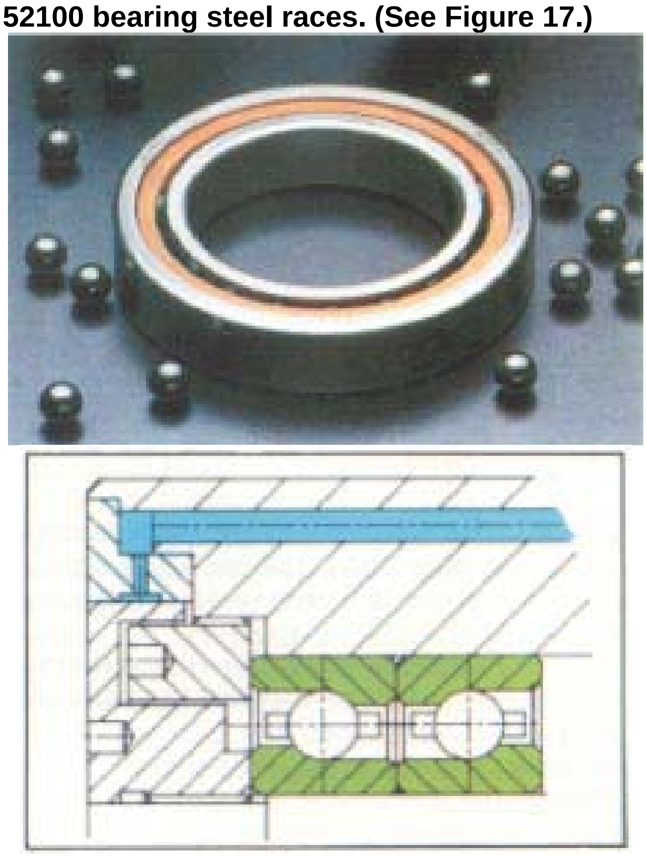

Figure 17 - Hybrid ceramic bearings

The ceramic balls reduce centrifugal forces, operate at lower temperatures, and provide a greater modulus of elasticity. The class 7-9 bearings usually have a 15º contact angle and race curvature radius of about ½ of the ball diameter. Increasing the contact angle for higher axial stiffness, e.g., 25º, lowers speed capability because of the increased spin-roll ratio. DN ratios of 2.2 million are achievable with minimal lubrication.

Magnetic bearing spindles have been around since the late .70.s. Active magnetic bearings were first developed for inertial navigation systems by Helmut Habermann, one of the original Peenemunde scientists. His company, S2M, built 60,000 RPM, 20 HP spindles to Turchan specifications, and were first shown on a high speed machining center at IMTS in 1980. (See Figure 18.)

Some inherent advantages of the magnetic bearings are automatic tool balancing, and direct radial and axial force sensing. Additionally, there are virtually no frictional losses and no lubrication requirements. The magnetic bearing promises theoretically infinite life.

There are, however, offsetting drawbacks to current magnetic bearing milling spindles. These detriments include; extremely high cost, relatively low force, expensive repair, and the risk of catastrophic failure resulting from minor faults.

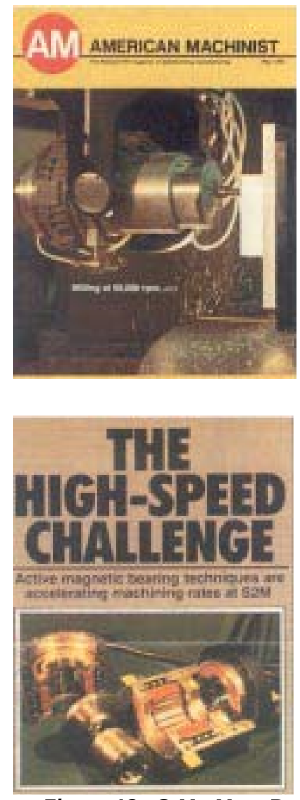

Figure 18 - S_2M - Mag. Bearing spindle components

Magnetic bearing spindles are also currently available from IBAG, who have, in conjunction with Mecos-Traxler and the University of Zurich, developed a digitally based system. The digital system has advantages in controllability and stiffness with a SERCOS interface.

Alternative bearing systems include hydrostatic bearings. These bearings, however, are limited in speed due to losses generated by oil shear. The hydrostatic bearing spindle is capable of highly damped operation, high stiffness and nearly perfect runout. (See Figure 19.)

Figure 19 - Hydrostatic spindle from Whitnon

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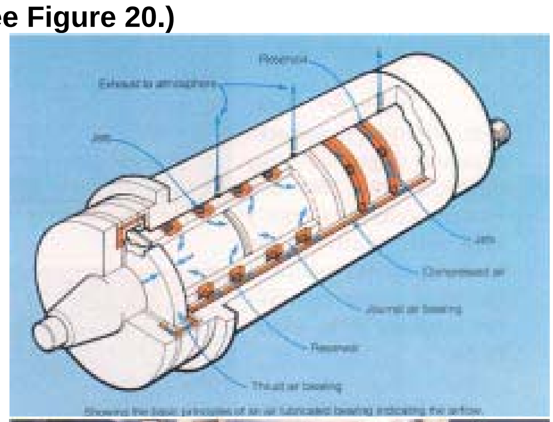
Aerostatic spindles are useful for grinding and high speed milling where relatively low cutting forces are required. Very long-life and smooth running are the principal advantages of air bearing spindles. They are often used in the range of 30- 90,000 RPM for circuit board drilling and routing, as well as some light machining of aluminum alloys.
(See Figure 20.)



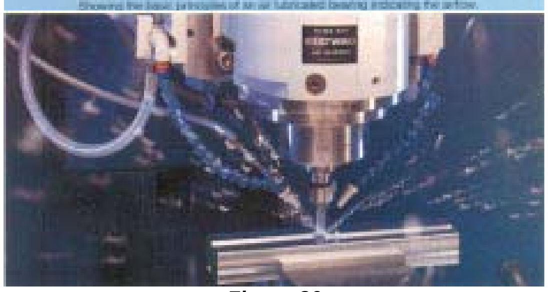


Figure 20
Figure 21 - Westwind air bearing spindle

Another form of air bearings is the foil bearing. This hybrid of air bearings, with the addition of thin foil strips to support the air columns, has achieved operational speeds of 130,000 RPM and loads of 100 lbs. The foil bearing holds great promise for an inexpensive, high speed, high load bearing.

Hollow roller bearings provide high load capacity, while utilizing minimal inertia rolling elements. The rollers have about 70% hollowness ratios. A 50 mm bearing, as shown, can manage 180 lb. axial load. It is extremely forgiving with a high modulus of elasticity. Diamond-coated versions of this bearing are currently in test at 45,000 RPM. (See Figure 22.)

Figure 22 - Hollow roller bearing (Turchan 1993)

Motors – Drives

Indirect drives are not practically feasible for use in high speed machining. Their use is generally limited to applications below 20,000 RPM and fractional horsepower.

Even for slower spindle speeds that yield high surface speeds, e.g., 3,000 RPM, 17,00 SFM, belts and pulleys may induce enough disturbance to adversely affect tool life. A better motor application would be a direct drive. (See Figure 23.) Cutting speeds of 15,000 SFM are realized at the periphery of the 22" diameter cutter.

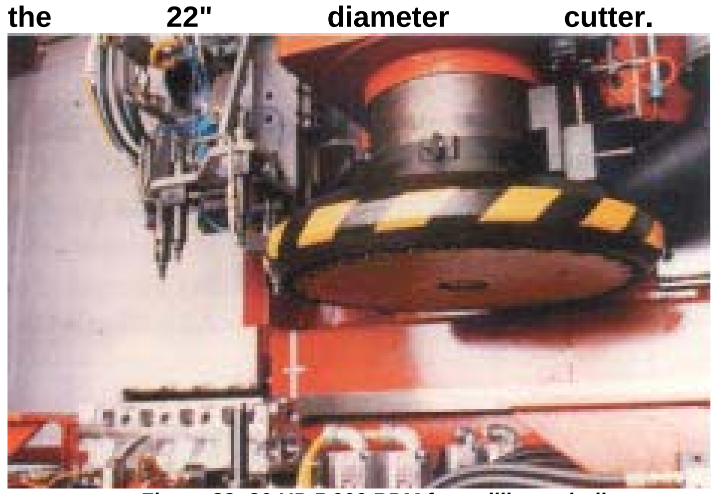


Figure 23 -30 HP 5,000 RPM facemilling spindle (Turchan1991)

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Integrally motorized spindles are best suited for operation in the > 10,000 RPM range. Evolving from grinding spindles, the common source of power for high speed milling spindles has been high frequency AC squirrel cage induction motors coupled with frequency converters.

The evolution has been toward permanent magnet DC motors, which develop higher torque at lower speeds. This benefits larger tooling and shorter change cycles. Even though these motors are more expensive compared to AC motors, use of rare earth magnets can produce higher power densities and lower rotor temperatures.

Vector controlled AC motors are currently taking over the high speed spindle drive arena. These vector-controlled motors are capable of full torque at zero speed. Vector drives can take a digital velocity command from the CNC, as well as derive position and velocity feedback from the motor, and thus provide spindle orientation.

Other drives include gas turbines, which have virtually no speed limitation, and have been used in the range of 50,000 RPM and 15 HP. Noise and speed control under changing loads are the primary drawbacks.

Some of the first and best, high speed spindle drives were hydraulic turbine (pelton wheel) designs found in the Molins System 24 Machines. These featured speeds of 20,000 RPM and 20 horsepower. (See Figure 24.)

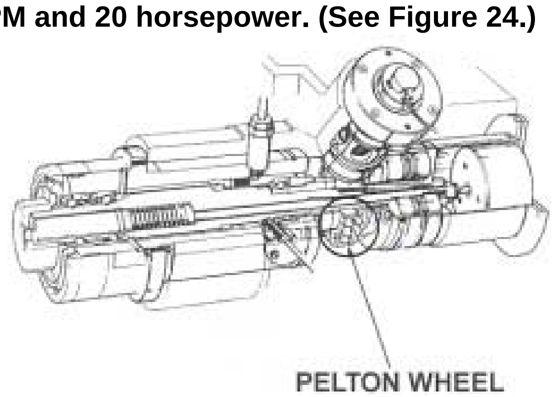

Figure 24 - Molins Pelton wheel drive spindle (1953)

A new motor system, known as a multiphase, bipolar, brushless DC motor, is a candidate for high speed spindles. This motor utilizes field weakening methods to deliver maximum power at high speeds (where DC motors usually exhibit back EMF causing high speed, power limitations) producing a nearly hyperbolic torque curve, as compared to a straight line for conventional, brushless DC motors. Extremely low torque ripple practically eliminates motor-induced vibration.

This new motor design is currently being investigated for application to next generation, high speed spindles.

Tool Holders

Currently, variations of the .HSK. (DIN 69892/3) are popular on high speed spindles because the hollow taper allows centrifugal force to work for the tool retention mechanism, as well as a more precise standard, locating on both the face and the short, shallow taper of the holder. (See Figure 25.) On the other hand, some limitations have been observed in excess of 30,000 RPM, even with the .E. type HSK design which eliminates tool holder keyways and internal spindle nosekeys. Application of any tool holder at such speeds requires careful consideration.

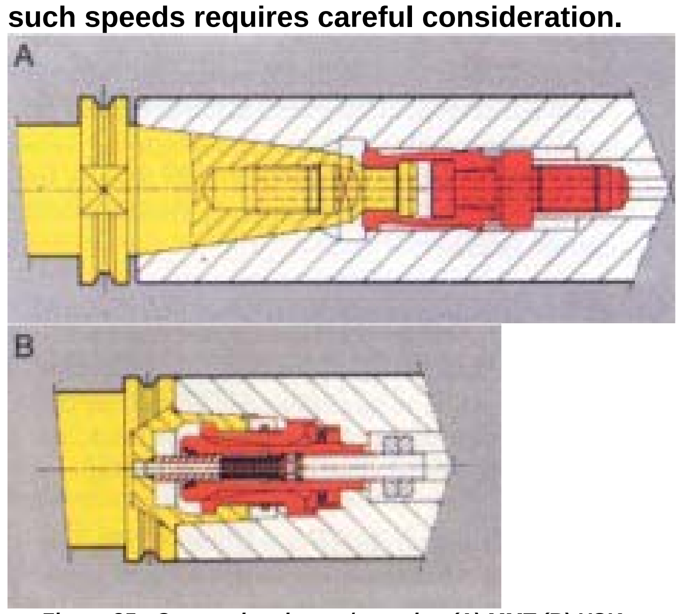

Figure 25 - Conventional taper/retention (A) MMT (B) HSK

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Figure 26 - Cutaway of hydraulic chuck (Schunk)

On the other end of the tool holder, hydraulic chucks, or shrink fit holders, provide the most concentric and dynamically rigid interface for the tool shank. Experience shows that the tool holder, interface of tool and spindle, is normally the number one challenge in high speed machining. (See Figure 26.)

Tools

The preferred material tool for high speed machining is cemented tungsten carbide. Various gades are available, providing more or less toughness versus stiffness. The problem with carbide is its affinity for aluminum, which results in build-up edge and potentially premature failure.

Coatings are readily available for carbide tools to minimize cobalt leaching and aluminum affinity. Some coatings, such as titanium nitride, actually exhibit a greater affinity for aluminum than carbide does. This is sometimes due to the columnar growth of the coating. Even though it may be only microns thick, the surface "roughness" may cause aluminum build-up.

A better choice of coating for high speed machining of aluminum would be titanium carbo-nitride, zirconium nitride or titanium aluminum nitride. These CVD coatings have shown some promise in high speed machining of aluminum, as well as ferrous materials. There is much left to learn about these coatings. applications.

DiamondBLACK®.s Amorphatec® coating has also shown improvement over uncoated carbide grades. The ultimate coating for solid carbide tools is diamond. As diamond inserts are suited for high speed machining of aluminum by large diameter face mills, they are, alas, not readily adaptable to small, < 12 mm (½.) diameter round tools, such as drills and end mills. Precorp has been providing diamond-veined drills and end mills for some time. These tools start out as cylinders of cemented tungsten carbide with high pressure, high temperature, polycrystalline diamond sintered, helical grooves. The PCD is ground to the cutting edge, while the carbide is ground into flutes. This is a relatively expensive fabrication process. By its very nature, tool geometry is limited. The barrier to successful diamond coating of round tools has been virtually insurmountable. The main problems are:

1. Poor adhesion, CVD diamond coating processes are poisoned by cobalt present in cemented carbide grades. Impurities in the diamond coating arise, and bonding is inhibited.

2. CVD methods do not lend themselves easily to even coating of curved surfaces.

3. The CVD process is expensive from the perspective of time and equipment required to coat round tools.

4. Surface textures are rough and crystalline in character, tending to pick up aluminum, similar to built-up edge (BUE). (See Figure 27.)

5. Only thin films < 20 microns will avoid rounding, sharp-cutting edges, and subsequently, increasing cutting force. No thin film diamond (< 20μ) to date has been able to withstand an interrupted cut in aluminum.

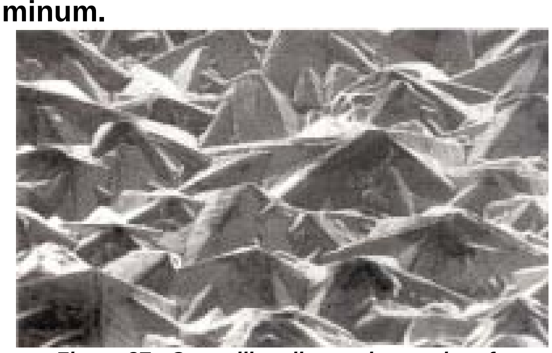

Figure 27 - Crystalline diamond coated surface

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There have been Advanced Technology Programs (ATP) directed at diamond coating round tools. The partners in this cooperative effort included, Kennametal, Norton, Boeing, GM and Cummins. The success of diamond coated round tools is one of the “holy grails” of high speed machining of aluminum.

A recently developed, radical diamond synthesis method has been demonstrated to produce coatings which are superior, even compared to PCD, in cutting of 390 aluminum allow (> 16% silicon).

This method is different from all other CVD methods in that it is carried out in atmosphere as opposed to a vacuum chamber, it achieves a true metallurgical bond, synthesizes 1,000 times faster than any CVD method, and it is essentially insensitive to any carbide substrate chemistry.

This method, know as QQC, has been used to coat bearings, cutting tool inserts, and is currently in test, high speed drilling in the Big Three’s automotive plants.

The ultimate promise of a suitable diamond coating on tungsten carbide is key to economical, high speed machining, especially without coolants.

As much as 1/3 of productive time on machining centers is consumed by tool change. For a high volume production job, saving a few seconds lost to tool change could ultimately save the capital cost of several machining centers.

One way to achieve such a savings is through the use of combination tooling, such as sub-land drills or a dreamer (drill ream, chamfer) or Thriller® tools (drill, chamfer, thread mill).

Figure 28 - Thriller ®Tool

The chart depicted in Figure 29 illustrates the time savings that can be realized from high speed Thrilling, as compared to conventional tooling required to produce a precision threaded, chamfered hole.

Other advantages of combination tools, such as the Thriller®, include reduced duty cycle on the high speed spindle by elimination of starting and stopping, and reduced power requirements. The Thriller® is a proven and effective tool used world-wide by automotive industries. (See Figure 28.)

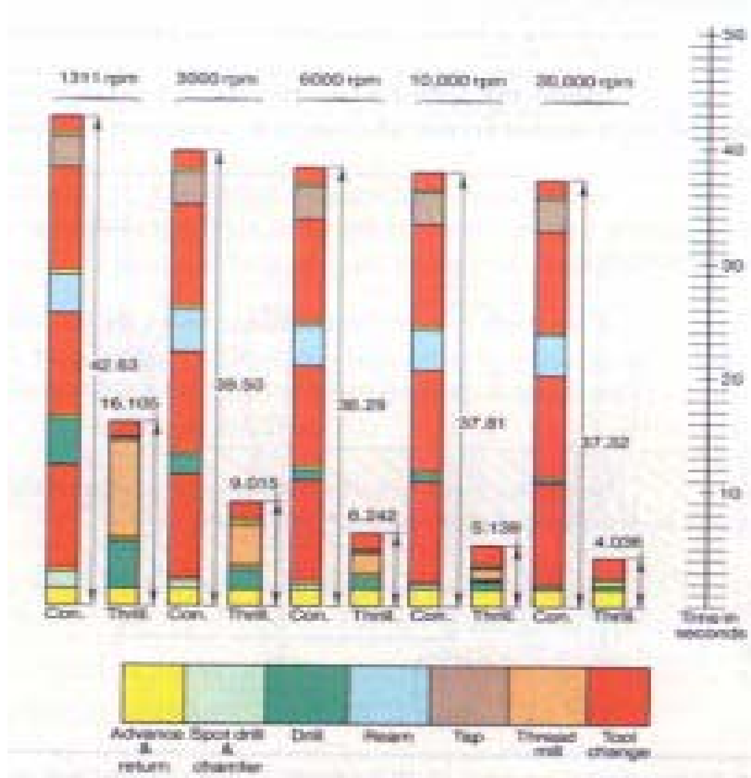

Figure 29

Thriller spark plug tools, NPT and various hydraulic port feature combinations, may do more than five (5) operations simultaneously. Some combinations are capable of producing several unique holes. The significance is reduced tool change time and reduced tool inventory.

Even though these tools may be substantially more expensive than their single operation counterparts, the time saved, usually, easily justifies the expense.

Tool life in high speed machining should equal or exceed conventional speed machining. One must take into account the metal removal rate (MRR) since the amount of time will be substantially greater at high speed.

Coated tools, especially diamond coated tools when available, should outlast multiples of uncoated tools. In fact, it is expected that a diamond coated tool will last 50 to 100 times longer.

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Coolants

Various coolants are useful in high speed machining of aluminum from oil-based to synthetic grades.

Most improvements in productivity and tool life result from the method of coolant delivery as opposed to its composition.

Through tool coolant improves the ability of coolant to interact with the tool/workpiece interface. It can also flush chips from a drilled hole better than externally applied coolants.

Suppliers of carbide can now provide carbide blanks with helically extruded pairs of holes.

High pressure makes a big difference in cutting conditions because it further improves the coolant's ability to interact in the cut.

High speed spindles are limited in the amount of pressure they are capable of handling. Some special Deublin couplings are pretty much topped out at 1,800 PSI and 15,000 RPM. The pressure is high enough, but speed is less than required for most high speed aluminum machining with small diameter tools.

High pressure, through tool coolant, could be far more effective if the coolant exit holes were more strategically placed. By directing the coolant at the cutting edge from an exit hole in the flute or gullet face of the tool, the uncut chip can be made to hydroplane and quite significantly reduce cutting forces.

This approach has been proven effective in cutting titanium, inconel and monel in excess of 2,000 SFM with at 0.010" feed per tooth and 2,000 PSI coolant pressure through the tool.

Much attention has been given to the deleterious effects of metalcutting coolants and lubricants in the automotive industry lately. A study conducted by Harvard for GM and the UAW, confirms the carcinogenic effects of long term exposure.

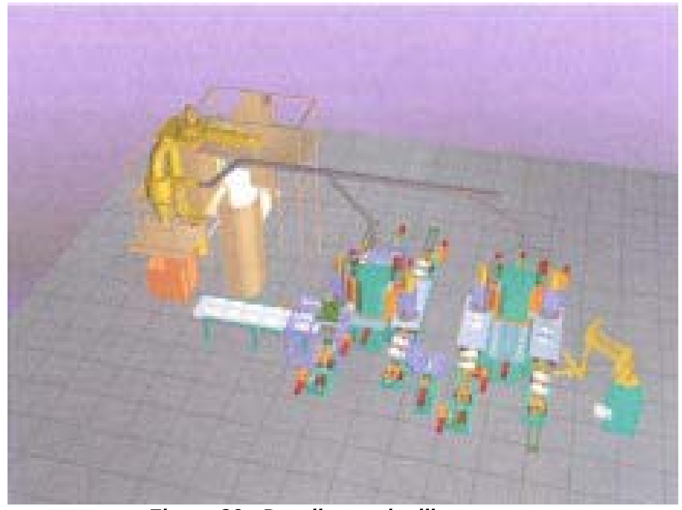

Figure 30 - Dry diamond mill system

The Big Three are anxious to totally eliminate coolants from their factories. Since 1991, completely dry, high speed machining of aluminum has been successfully installed in Big Three plants. Here are some typical specifications:

- Spindle speed - 2,600 RPM
- Cutter Diameter 22"
- Insert - PCD Tipped/Coated
- Surface speed - 15,000 SFM
- Feed per insert - 0.008"
- Parts per hour - 600
- Operations - Rough and Finish Mill opposite surfaces of cast aluminum (380) automatic transmission components
- Feed rate 600 IPM
- Cut time - 1 second per pass, per part

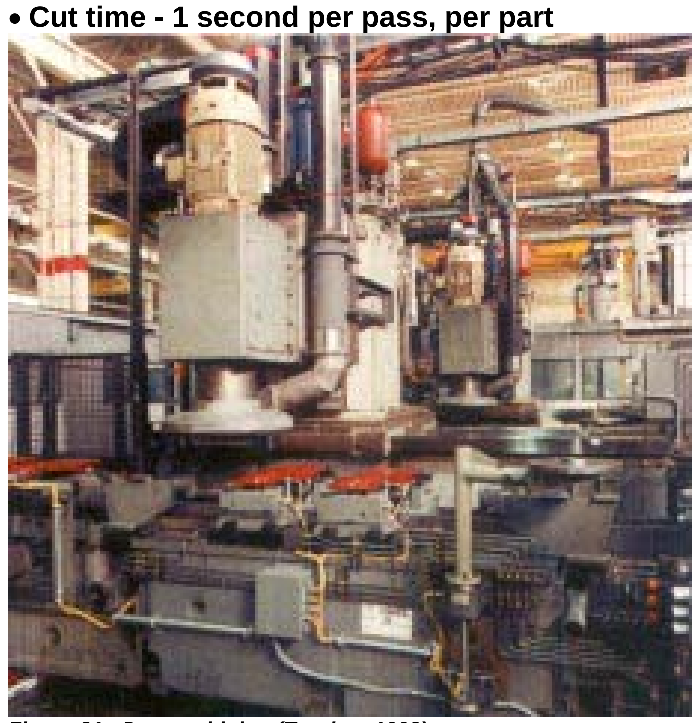

Figure 31 - Dry machining (Turchan 1993)

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The tremendous success of these installations has whet the appetite of automotive manufacturing engineering staff. There is now a groundswell of activity in pursuit of dry machining for all applications, (drilling, boring, thrilling, end milling).

The primary enablers for success are:

- High Speed Spindles
- New Tool Geometries
- An Effective Diamond Coating on Carbide Round Tools

Some nearly dry machining is being demonstrated where a small amount of Boelube is induced through the tool precisely before impact with the work. Although the amount of fine spray is minuscule, the coolant could be more of a health hazard in this insidious form.

The first machines are just now being installed at Big Three plants with completely dry aluminum drilling capability. Although still in the validation stages, this work could be a significant breakthrough for personnel safety and environmentally conscious manufacturing.

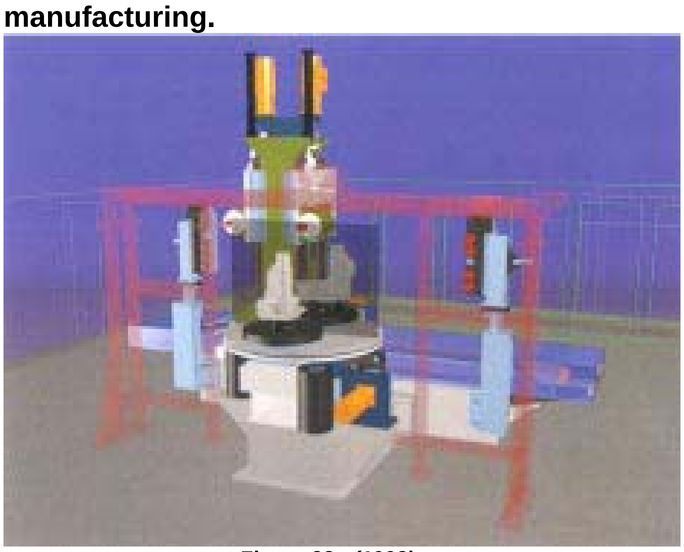

Figure 32 - (1993)

The system shown in Figure 32 has two (2) 30,000 RPM spindles. Diamond tools mill 3 lugs and drill, ream and chamfer 2 manufacturing holes. The 2 second pallet swap and 1,200 IPM federates enable the system to qualify 220 aluminum transmission cases per hour without coolant.

Cast iron and steel are already cut dry with little difficulty, in fact, in some cases, coolant is detrimental to the process.

Using silicon nitride (Si_3N_4) inserts, cast iron can be roughed at 5,000 SFM. In fact, Greenleaf indicates that they don’t really know what the maximum speed is for their Si_3N_4 (whisker reinforced) grades.

CBN can machine cast iron at up to 7,000 SFM, but CBN inserts (PCBN) are just as expensive, if not more so than PCD. It is expected that CBN coated carbide tools will be commercially available within two years. Perhaps then, high speed machining of cast iron can be become commonplace.

By the time high pressure, through tool, coolant systems are available for high speed spindles, they might not be needed (or desirable).

Speeds and Feeds

Generally, suggested feeds and speeds are determined by the cutting tool.s material and/or coating and the workpiece material, e.g., aluminum can be cut by high speed steel at 10,000 SFM and faster. Carbide is more desirable and with diamond, speed is limited only by other system components.

Assuming there is no limit set by the machining center or tooling, spindles should be run flat out at maximum RPM.

Although probably not nearly attainable with small diameter tooling, aluminum should be cut at > 10,000 SFM. Concomitantly, the feedrate should be from 0.003 to 0.010" per tooth or insert, provided there is sufficient horsepower. It is desirable to maintain a good chip load because the chip needs to extract all the energy (heat) of the cut to achieve an adiabatic process.

Spindle horsepower is also an important consideration because at high speed it is easy to run out of power.

So, speeds and feeds are really dependent on your application and should basically follow these general guidelines:

Aluminum - try to achieve at least 10,000 SFM to realize adiabatic conditions. Less than 0.001" chip thickness can cause brinelling of the material in front of the cut, and ultimately premature BUE, leading to catastrophic failure.

Cast iron - with silicon nitride (Si_3N_4) up to 3,500 SFM, with cubic boron nitride (CBN), 7,000 SFM if you can stand the noise and heat.

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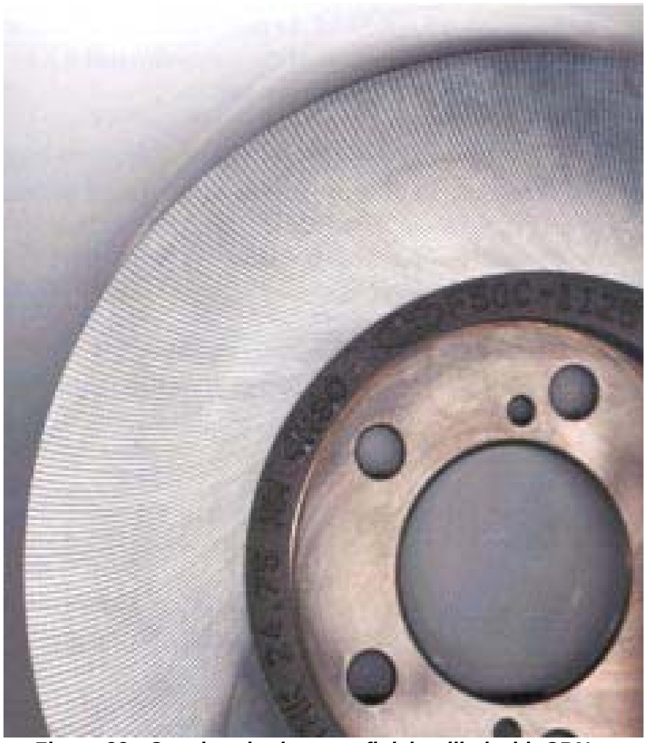

Figure 33 - Cast iron brake rotor finish milled with CBN at 7,000 SFM

Steels

Finishing with light cuts (to minimize benching of dies) using coated carbide or CBN, use spindle's maximum RPM. Some finishing machines use 90,000 RPM spindles.

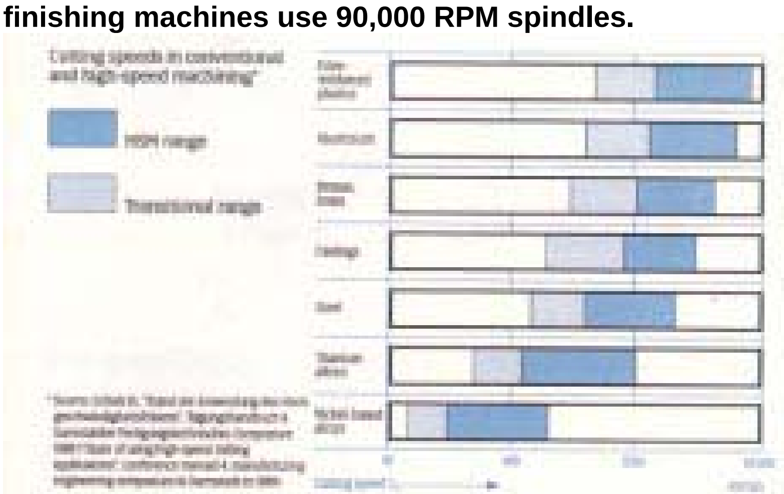

Figure 34

Conclusion

High speed machining applications date back to the early fifties. Spindles, toolholders and cutting tools are developing to meet the demanding requirements. Systems are now benchmarked world-wide in the automotive, aircraft, electronics and other sectors. High speed machining is a key enabler for dry machining of aluminum which is gaining momentum in automotive and aircraft applications due largely to safety, health and environmental issues. Diamond tools will be in the forefront of this rapidly developing market. Where PCD is limited in its application to small diameter, round tools, diamond coatings will bridge the gap to enable widespread application of high speed machining.

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