Developing The
“Sweet Spot”
In
Grinding

By
Steven Kendjelic
CNC Grinding
cncgrind@earthlink.net

Preface

Various methods have been employed in the effort to grind difficult to machine materials. The milling and broaching process's generated high tooling costs and required secondary operations to remove burrs. Surface grinding while an accurate process, was slow and did not always provide a feasible cycle time. With the small incremental infeed and limited part cooling, thermal damage resulted when material removal rates were increased.

In Electro Chemical Grinding (ECG), the electric current passing from the wheel (cathode) to the work piece (anode) removes material 80% by electrolytic action and the other 20% through mechanical action using an abrasive wheel. While the material removal rates are as much as 60% faster than surface grinding the economic costs of electrolyte and disposal usually make this the non-preferred method. Similarly, Electro Chemical Discharge Grinding (ECDG) follows the same basic principles, however, the abrasive grinding wheel is replaced by a graphite wheel. Both processes permit low machining temperatures and forces used on hard materials with minimal burrs. This process is limited, however, to tolerances of $^{+}/-$ .002 in. or more while the edge of the work piece features edge degradation. Recently the author has used a steel core, direct plated uncoated Cubic Boron Nitride grain in the ECG process, which eliminated the form-dressing requirements. Nonetheless, closer part tolerances will require true grinding operations. Electro Chemical Machining has also been experimented with for dressing metal bond grinding wheels. In a conventional production grinding application the dressing of the wheel requires a dedicated off line electro chemical machining station due to the process requirements and electrolyte solution.

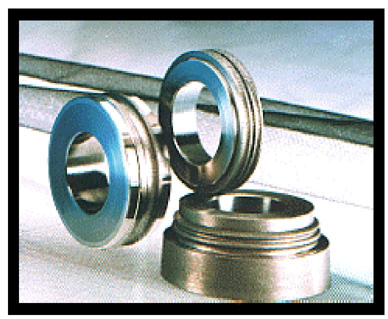
With the effort to improve processes and reduce costs, engineers must decide to "shoot the right horse" on outdated technology when it's no longer economically feasible for modern production. When technical improvements no longer appear possible new system technologies set off a new curve of technological evolution driving the old one to eventual extinction. There have been many collaborative efforts by machine tool builders, university professors, and applications engineers that have shaped our industry's past and pushed our industry toward the future. The visions of individuals like Gerhard Lang, Juergan Richter, Dr. Werner Redeker, and Dr. Stewart Salmon helped developed processes in the 1970's that have been constantly evolving to the present. Although these luminaries each had visions of grinding's future, they still required the abrasive tools necessary to implement their visions.

When the author was in the machine tool industry an abrasives expert named Ron Birmingham once said to me, "Machine tool builders know how to make machines but I can show you how to optimize for performance" "It's as simple as razors and razorblades." The following Abrasive Engineers that have dedicated themselves to designing abrasives for machines to perform optimally. Hans Noichl, John Besse, Paul Gibree, and Dan Jackson also deserve the recognition for furnishing the tools to make their visions a reality. This article is dedicated to each of these individuals that the author as an Applications Engineer has had the opportunity to work with and try and develop the "sweet spot" in grinding.

Profiling devices

Although there are many types of profiling devices, this paper will focus on diamond rolls and the processes used in their manufacture. Rotary dressing devices commonly referred to as diamond rolls are manufactured using a variety of processes. Each process is able to address a specific objective, meeting numerous criteria from the end user such as cost, product life and dimensional accuracy.

The sintered rotary diamond roll is produced by manufacturing the desired form in a graphite ring. The diamonds are then glued into this ring surface and metal powder is then place into the cavity. The assembled mold is then placed in a kiln and heated to approximately 2,000 degrees Fahrenheit. Unfortunately, this heating of the diamond roll is often sufficient to result in distortion of the desired form. Next, the diamond roll is placed on a cylindrical grinder mounted between centers. The form is then dressed into a conventional grinding wheel and a coupon is then generated from the grinding wheel. If any deviation from the mean is found, the diamond roll is then ground with a diamond-grinding wheel to correct the size or contour. An additional problem is that this grinding or lapping performed on the diamond roll produces wear or flat topped diamonds. A significant number of forms such as, thread forms and flat rolls do not lend themselves well to the sintered process. However, sintered diamond rolls do fit the criteria for bearing grinding, where less metal removal is required and fine finishes are part of the manufacturing process. Single layer direct plated rollers are often used to quickly prove process capabilities prior to full production at a fraction of the cost.



Reverse-plated rotary diamond rolls provide superior accuracy in comparison to the sintered roll. In this process, the form is CNC machined into the mold providing the precision of the geometry for the form roller. The diamonds are then handset or random sets into the mold using the appropriate types of diamonds required for corner radiuses or other form intricacies. Small oblong or needle diamonds which are typically three times as long as is wide, can be used in areas to reinforce small radii where form degradation would first occur during grinding use.

The mold is then submersed in a nickel bath and a low voltage charge is applied. This electroplating process applies nickel in multiple layers to the diamonds placed in the mold. After the electroplated diamond is bonded together in a metal matrix providing maximum protrusion of the diamond particles, then the metal core is inserted into the mold.

This type of process requires a longer manufacturing cycle than the sintered process but produces a superior product. After completion the mold is split like in a similar manner to the sintered process. The reverse plated product provides longer tool life at higher accuracy than the sintered or single layer direct plated product.

When using any type of rotary diamond dressing device, the diamond quality and size or mesh type directly influences roll life and surface finish to the end user. A typical 30/40-mesh size would produce a theoretical median particle diameter 0.021 of an inch. Optimal grinding makes use of the largest mesh size possible producing an aggressive grinding wheel that will allow the surface finish required to be achieved. Often, handset diamond rolls are the rolls of choice. When a fine mesh size dressing device is used a vitrified wheel will exhibit a closed or less free cutting nature.

A process known as crushing can be used when it is not possible to purchase diamond rolls due to the lot size, cost effectiveness etc. Crushing is also the method of choice when radius size cannot be manufactured in a diamond roll. So as to not to flat spot the roll when it starts to infeed into the wheel a small "jump start" or "mini-crash" is sometimes needed. The contact area between the wheel and roll, as well as the contour must determine if this is necessary. A typical "jump start" would be negative 0.002 at a speed of 15.0 inches until contact is made, then a normal infeed with a wheel speed of 350 SFM. The downside of this method is that this profiling process is slow and requires refurbishment frequently.

Abrasive types

A discussion of abrasive machining would be incomplete without including wheel technology. Extensive developmental work has taken place in the past decade with both conventional and superabrasive wheels. Superabrasive is the nomenclature applied to diamond and Cubic Boron Nitride (C.B.N.) abrasives. Diamond is the hardest known abrasive (7000-9000 Knoop hardness) followed by Cubic Boron Nitride (4700 Knoop hardness) the conventional fused aluminum oxide (Al_2O_3) is 2100 Knoop hardness. In comparison, high carbon steel is rated at approximately 800 Knoop. Due to the process used in manufacturing plated and vitrified grinding wheels, increased wheel speed is possible before reaching a burst or separation of bond layer. The grinding process provides a superior surface finish to conventional machined surfaces. While initial inspection for surface finish or Ra (average of the height of peaks and depth of valleys from the mean line) might meet the print requirements, inspection is also needed for work hardening or micro cracks at the subsurface processed. Better understanding and control of process parameters serves to eliminate micro cracks and poor surface finishes. The two major world suppliers of C.B.N. and diamond are GE Superabrasives and the DeBeers Company. Washington Mills, Norton and European suppliers such as General Abrasive / Treibacher are sources for conventional abrasives. The 3M company supplies ceramic grain under the trade name 321 Cubitron™.

Adding air

Conventional abrasives utilize various types of friable fused alumina oxide grains as well as blends of grains and grain treatments in creep feed grinding (2100-2500 Knoop hardness). The abrasive structure used in creep feed grinding differs from the surface grinding application in that the wheel density is changed by artificial inducement with pore forming agents. The use of aluminum oxide bubbles or hollow spheres for inducing porosity provide thermal insulating properties. The distribution of the pore formers is an important issue in direct relation to pore former volume. The bonds used in the manufacturing of grinding wheels, when fired, control the wheel hardness. Grinding wheel bonds are engineered to the application of their use. Materials below 38 Rc require increased bond volume and grain volume for use.

Abrasive use and understanding the specification

Typical creep feed wheels are 40% abrasive grain 10 to 20% bond, and 40 to 60% induced porosity. Conventional abrasive wheel grains can be, Regular, Friable, Modified Friable, Microcrystalline, and Macrocrystalline. The cutting action of the grain is broken down into two basic grades, grains that are very tough and grains that are friable. White aluminum oxide is considered a cool cutting friable grain. When a small (.5%) amount of chromium oxide is added the grain becomes pink and is used for its form holding characteristics. Sulpher is added by some manufactures to aid in lubricity. Other manufactures use cobalt and titanium treatments.

Tough grains, such as ruby with approximately 3% chromium oxide are used for rough grinding and high material removal rates (MRR). Ruby is manufactured by fusing pure alumina and chromium oxide. Ruby is also known for being tougher than white aluminum oxide for its form and corner holding abilities.

The friable grains provide a self-sharpening action by grain fracture thus exposing new cutting edges. This self-sharpening of the abrasives is accomplished by the macrofracturing process of the grain. If the grain did not fracture, wear flats would develop and draw higher power from the spindle drive, most likely causing thermal damage to the work piece.

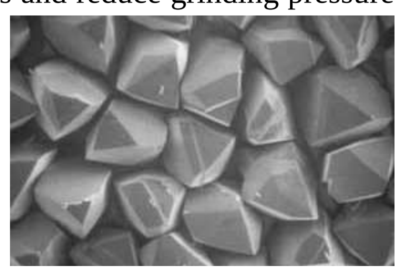
Grinding wheel markings are often a mystery, as markings tend to differ greatly between manufactures. In an effort to shed some light on this mystery, the following examples(s) illustrate and define the general markings of a typical creepfeed-grinding wheel.

87A	**601**	**H**	**9**	**A**	**V237**	**P23**
↑	Grit size	↑	↑	↑	↑	↑
↑	Nominal	Grade	↑	↑	↑	Induced pore former size 30/54
↑			↑	↑	↑	grit size equivalent
Pink / White abrasive			Structure	↑	Vitrified bond and hardness	
88A & 89A				↑		
				Creep Feed		

32A	**80**	**F**	**16**	**VCF2**
↑	Grit size	Grade	↑	Vitrified Creep Feed 2nd Generation
Sulfur treated white aluminum oxide			↑	
			Structure	

Bridging the gap

Ceramic grains bridge the gap between regular aluminum oxide and superabrasive C.B.N. grains. Ceramic grain is a microcrystalline aluminum oxide that when sufficient grinding pressure is obtained, the grain becomes dull and fractures along microcrystalline structure exposing multiple new cutting edges. With material removal rates above standard Al_2O_3 but below the superabrasive grain, they do lend themselves to specific operations. This type of grain is commonly mixed with standard abrasives to reduce costs and reduce grinding pressure in surface, profile, cylindrical and creepfeed applications. The use of ceramic grains in profile surface grinding offers significant improvement in wheel wear as the single grain forces are high and permit the fracture of the fine grain microstructure of the ceramic grains. In creepfeed the use of ceramic is typically 20 to 30% of the wheel content due to the lower single grain force. Increased ceramic content would not permit the grain to achieve the desired effect of self-sharpening.



The desired effect of any grinding process is achieving dimensional accuracy, part geometry, and surface quality all at an economical cost. These process characteristics must be anticipated prior to grinding to obtain process reliability. To optimize an existing process the engineer must use empirical methodology to define and evaluate existing operating characteristics, determine known wheel operating characteristics and unique part grinding requirements to optimize grinding variables. These building blocks are the necessary data collection for interpretation of the various phases.

Since most creep feed grinding applications are one-pass operations and we have discussed material removal rates for this process, the following formula can be used to determine the specific material removal for this process.

Material Removal Rate (MRR) = Depth of cut multiplied by grinding federate equals cubic inches of material per minute.

This example is the European calculation for material removal rate using the DIN 8589 classification:

$$\mathbf{Q_w = a_e * a_p * v_f \div 60}$$

$\mathbf{a_e}$= depth of cut

$\mathbf{a_p}$= width of cut

$\mathbf{v_f}$= X axis table speed

Below is a typical conventional abrasive creep feed cycle time estimate based on the cubic metal removal already calculated.

Length of grind including the arc of contact	200 mm (7.87 inch)
Grinding feedrate	300 mm/min. (11.81 inch)
Time in minutes	0.6666667
Time in seconds	40

Length of grind divided by the feedrate equals time in minutes and seconds.

The next group of variables must also be known or calculated.

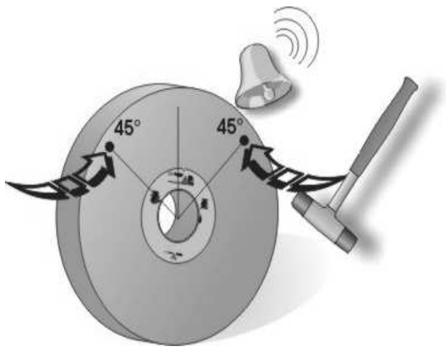
Close door/Cycle start/Approach grind		5 seconds
Grind time (from above calculation)		40 seconds
Dress & Park axes		15 seconds
Load/Unload parts		30 seconds
	Total	90 seconds
	Cycle time minutes	1.5
	10% Safety	1.6
	Cycles per Hr.	37.5
	Number of parts per cycle	2
	Parts per hr.	75
Parts per year required		25,000
	Total Hours	333.3333
Hours per year needed at 80% efficiency		416.66667

For high production yields the use of one grinding machine tool with two work areas can be utilized. This permits the operator to load or unload components in a safe and isolated work area while the machine tool is under operation. A lights out application of a machine tool of this type simply requires a robot to pick and place pre and post ground components and eliminate the operator for part loading. Some grinding cells also have multiple work areas with automated wheel changers when used with in process gauging eliminate the operator intervention.

Traveling table cycle			*Traveling Column with rotary index table cycle*	
Close door/Cycle start in seconds Cycle	*5*		Cycle Start in seconds	*5*
Grind head down in seconds	2		Grind head down in seconds	2
Wheel approach in seconds Arc of contact Turn on coolant	2 1		Wheel approach in seconds Arc of contact Turn on coolant in seconds	2 1
Grind time in seconds	36		Grind time in seconds	36
Turn off coolant in seconds	1		Turn off coolant in seconds	0
Wheel run out in seconds	2		Wheel run out in seconds	2
Grind head retract in seconds	2		Grind head retract in seconds	2
Return to home position in seconds	3		Return to home position in seconds	0
Dress cycle in seconds	10		Dress cycle in seconds	10
Load / unload in seconds	30		Index rotary table	5
			Grind head down in seconds	2
Total in seconds	94		Wheel approach in seconds Arc of contact	2
Cycle time in minutes	1.57		Turn on coolant in seconds	0
Plus 10% safety in minutes	1.73		Grind time in seconds table 2	36
Cycles per. hour	35		Turn off coolant in seconds	1
Number of parts per load	2		Wheel run out in seconds	2
Parts per hour	69		Grind head retract in seconds	2
Parts per year required	40,0		Dress cycle in seconds	10
Total hours	576		Index rotary table	5
Hours per year needed at 80% efficiency	721		Total in seconds	126
			Cycle time in minutes	2.09
			Plus 10% safety in minutes	2.30
			Cycles per. hour	26
			Number of parts per load	2
			Parts per hour	104
			Parts per year required	40,0
			Total hours	384
			Hours per year needed at 80% efficiency	480

The above chart illustrates the cycle times when comparing a machine tool with and without a rotary table

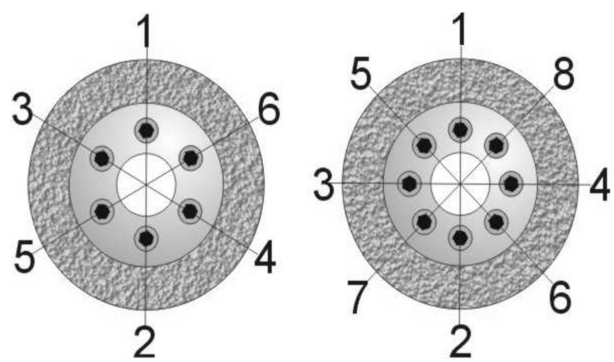
Proper wheel safety



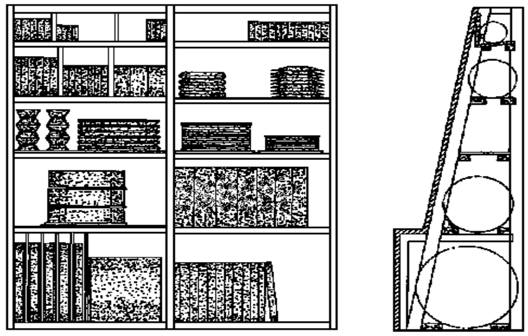
When using a conventional vitrified grinding wheel, it is necessary to check for cracks prior to mounting the grinding wheel to the flange. Cracks can occur due to improper storage and/or handling of the brittle structure of the wheel. The preferred method of testing for cracks is to perform a ring test, paying careful attention to the sound the wheel generates when struck.

When performing a ring test a metallic device must not be used to strike the wheel. Instead, a plastic or wooden implement should be used to strike the wheel at various points two inches from the outside diameter. If a ring at one portion of the wheel does not sound the same as the sounds generated at other points along the wheel, discard the wheel. One shortcoming of the ring test is that it is difficult to achieve a good ring test on wheels above the wheel width of two inches. Reference the America National Standard (ANSI) section 6.1.1.2 for further information.

Proper mounting of the grinding wheel is necessary in accordance to ANSI torque specification. Plastic or paper blotters must always be used in mounting the wheel on the flange. Consult ANSI specifications section 6.10.2 for torque requirements when mounting grinding wheels. Over tightening of the wheel can crack the wheel possibly causing to the wheel to burst and cause injuries to operators. Take care to mount wheels with the mount up arrow up as the manufacture has pre-balanced the wheel prior to shipment.



Wheel storage



As illustrated above proper storage of grinding wheels prevents damage due to handling errors. Treat all grinding wheels with caution and use plastic or paper blotters. A cracked grinding wheel can explode and cause serious injury or fatality. Prior to storage, vitrified bond wheels should be spun dry after shutdown of coolant. If the wheel is removed from the wheel flange inspect the area of the wheel bore prior to the next use.

Superabrasives

The diamonds used in today's superabrasive grinding operations conduct heat faster than any metal. C.B.N. exceeds diamond in thermal stability remaining stable at temperatures up to 2000ºC. Diamond reverts to graphite at much lower temperatures. Careful coolant application is necessary to reduce and control the heat buildup during the cutting operation in the deep arc of contact. The high heat promotes the grain to pullout of the bond. Diamond being carbon based does not provide the cutting action in tool steels of C.B.N.   The metal bonded and resin bonded grinding applications with C.B.N. and diamond wheels conduct heat faster to the cutting area. Resin bonds maintain grit protrusion by using a bond that erodes in proportion with the crystals. Direct plated C.B.N. used as a replacement to the resin bonded C.B.N. application can increase the run time significantly, wheel life can be weeks with no downtime for re-profiling.

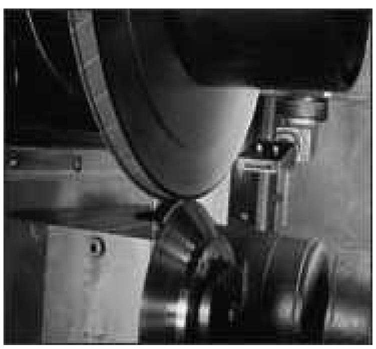
Typical materials ground with C.B.N. are tool steels (D2, T15), hardened alloy steels, bearing steels, and nickel-based super alloys (Udimet), die steels, and cast iron. Typical grain content concentrations used in C.B.N. grinding wheel applications are 40% to 60%. An increase in concentration can assist in form holding but the same principals apply as used with diamond rolls. Too high of a concentration reduces the cutting characteristics. A decrease in concentration produces just the opposite results. The low thermal conductivity of nickel based superalloys present a difficult transfer of heat away from the grinding area. Typical materials ground with diamond abrasives include tungsten carbide, titanium alloys, glass, and ceramics. While conventional abrasives such as silicone carbide can be used to grind titanium and carbide the material removal rates are significantly lower compared to the high wheel speed and hardness of the diamond superabrasives. The high heat generated during diamond grinding with its reactions to iron attacks the carbon in the diamond-grinding wheel, contributing to high wear rates.

C.B.N. crystal structure

The vitrified bonded grinding wheel provides a cooler cutting action. The addition of pore forming agents in the manufacturing process permits greater porosity in the vitrified grinding wheel. After mixing the bond, grain and binders the mixture is placed in a mold and pressed to achieve a predetermined material density. The product is then fired in a kiln, which bonds the materials together. There are typically two bond types used in vitrified grinding wheels, a low temperature bond and a high temperature bond. This control of porosity permits less thermal damage in the cutting zone by allowing an increase of coolant to the arc of contact. The control of abrasive protrusion through pore former burn out can reduce tool deflection and lower cutting forces in comparison to the use of a resin product.

The example presented below explains the general markings of a typical vitrified superabrasive creep feed grinding wheel.

B	**150**	**E**	**100**	**V**	**226**
↑	↑	↑	↑	↑	↑
Abrasive Type	↑	Grade	↑	Vit	Bond Modification
	Grit		Concentration (100=25%)		



This illustration shows a diamond disk being used to generate the required wheel geometry. This type of wheel forming utilizes the machine tools Y and Z-axes with the Cartesian coordinates directed from the Computer Numerical Control (CNC). The advantage of this system is that multiple wheel forms can be generated using a multifunction-dressing device in place of a dedicated form roll. The diamond disk has a longer life than a single point diamond and is ideally suited for prototype parts. Pre-forming the abrasive wheel is generally the preferred method. Diamond dressers are only used to true the superabrasive-grinding wheel. An aluminum oxide abrasive stick is used to condition the wheel and to relieve the bond material. Grit size for the abrasive stick is typically two times greater than the C. B. N. wheel being dressed. The dressing stick can be controlled by electric servomotors or by pneumatics. The design should be rigid in construction and have the ability to precisely control the infeed of the dressing stick and not allow for axial movement that can loosen or disrupt the grain from the bond.

When using Resin grinding wheels with smaller depths of cut the workpiece will rub the bond providing a sharpened wheel. Resin bonded grinding wheels reach their limits in large depths of cut where chip clearance is required. Utilizing the maximum diameter grinding wheel possible also allows the heat to be dispersed, as metallic fillers tend to draw heat away from the contact zone. Nickel, copper, and cobalt coatings are used with resin products to improve bonding strength and increase wheel life.

Finding the sweet spot

The advantages of high performance grinding is that parts can be processed from solid in the hardened state, with better form holding capabilities and minimal burrs to the part. This often eliminates secondary de-burring or straightening operations after heat treatment.

Terminology used by the industry can be confusing. The old industry term, Low Stress Grinding (LSG) was replaces by the term Creep Feed (CF) grinding. Some companies have now begun using the term High Energy Deep Grinding (HEDG) to describe essentially the same process. These processes are basically equivalent and have all been accomplished with both conventional vitrified abrasives and superabrasives. The aim is high material removal rates with reduced heat propagation. As the wheel speed increases in any grinding application, the chips sheared by the abrasive grain decrease and the heat generated in the cut zone also decreases. For example, to match chip load in a process, when the wheel speed is increased by an increment of 20%, the logical step would be to increase traverse speed by the same 20% until maximum chip load capacity is achieved. Most high-speed grinding applications utilize straight oil as the coolant as it lubricates the wheel and surface being ground.

Creep feed grinding is used to remove a large amount of material (vertical infeed) with a slow grinding feedrate. This process allows high material removal rates (MRR) to be accomplished in a very short time as opposed to surface grinding. The typical conventional surface or pendulum grinding operation is used for finishing a hardened steel part. The small arc of contact for a vertical infeed of 0.02 mm (0.000787 inch) is 2.83 mm (0.111 inch). The arc of contact for the creep feed process with a vertical infeed of 3mm (0.118 inch) is 34.64 mm (1.360 inch).

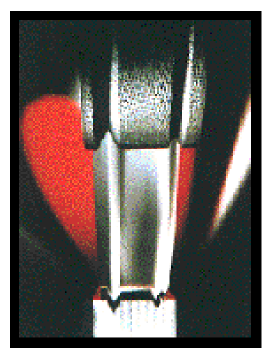
The significant increase in grain contact and slower grinding feed rate yields a much larger MRR. During the creep feed process, there is also an increase of overall heat generated because of friction due to elastic and plastic deformation. The lower grinding feed rate in proportion to the higher MRR distributes the heat evenly over increased grain contact in the arc of cut. A high MRR with increased grinding feed rates creates plastic deformation, which can produce fatigue cracks in the work piece. This occurs when the abrasives normal ability to self sharpen is impeded due to chip overload.

In creepfeed applications less stress is induced in the work piece due to the increase of grain contact, reducing the probability of fatigue cracks. Shot peening is used following some grinding and plating applications to counteract the surface tension stresses. Reciprocating or pendulum style grinding generates increased heat in the contact zone between the wheel and part, resulting in thermal cracks and fatigue. While shot peeing the material with high velocity steel or glass beads, the core of the material is in residual tension and the surface in residual compression. Tangential forces are much greater in creep feed grinding than reciprocating grinding due to the increase in the arc of contact by the deep cut. Creep feed grinding produces steel-wool type swarf, which is easier to remove than the sludge produced in reciprocating grinding.

Creep feed grinding does require high horsepower machines that are extremely rigid with a closed loop system to monitor the process. Machine requirements are high rigidity, precise positioning, minimization of reversal backlash, and machine axes free from stick slip. The resistance to deflection during grinding is called static stiffness and is critical to this process. The high heat in creep feed operations using conventional abrasive, diamond or C.B.N. promotes wear flats in the wheel face, which creates more heat during the grinding operation. Grain selection in any abrasive is important because if the grain cannot penetrate the material, wear is caused by thermal stress resulting in a plowing of material. The desired result is mechanical stress, which fractures the grain particles exposing new cutting edges (self sharpening). Typically, the grain is pulled or sheared from the wheel face during grinding when it becomes dull.

In creep feed grinding higher wheel speeds are required due to the long arc of contact to achieve the higher MMR. When wheel speed is increased the duration of the grain contact is decreased as well as the chip load. Higher surface speeds of grinding wheels alone have provided a substantial increase in productivity. The higher wheel speed allows a higher volume of material to be removed from the workpiece, decreasing the cost per part in relation to machine time.

In superabrasive operation, any significant vibration at the point of contact must be avoided. Most vibration is caused by an out-of-balance or out of round wheel. Machine stiffness and frequency are also contributing factors. The larger heavier machines produce a lower frequency of vibration. The stiffer the machine, the higher the natural frequency. Various damping techniques have been utilized on machine bases in order to absorb the vibrations energy. Examples include: steel weldments, concrete, granite, and the pure mass of thick wall castings.



The development of continuous dress creep feed (CDCF) for the use of conventional abrasives, such as Aluminum Oxide, and Silicon Carbide has allowed higher stock removal rates than the previous intermittent creep feed method. This is accomplished by continuously feeding a rotating diamond roll into the operating grinding wheel periphery thus presenting a freshly dressed wheel surface to the grinding zone at every revolution of the wheel. This maintains a true to profile and sharp grinding wheel that greatly reduces the forces used in the process and permits greater depths of cuts for high volume stock removal. The CDCF process is used when the material machine-ability is low and when wheel form loss or break down occurs. The sharper the grinding wheels the less heat propagation to the material, commonly known as grinding burn. Constant surface footage is an important factor in both creep feed and continuous dress creep feed. A variable speed spindle motor is required in order to accomplish constant peripheral speed throughout the grinding wheel life. A constantly sharp topography on the grinding wheel allows deeper cutting.

Continuous dress can be utilized in external cylindrical plunge applications, which have excellent results when used with flagging instruments for size control, and is not limited just to horizontal grinding. Angular approach cylindrical grinding is where the wheel head is angled and two or more shapes or forms are generated in the grinding wheel. In the above applications rotary dressing devices permit the abrasive machining of complex profiles. Precise dressing process infeed parameters permit the economical use of CD grinding.

A variable speed spindle motor will optimize grinding by allowing surface feet per minute to be adjusted to assist in making the abrasive act harder or softer as needed by the applications engineer. The overhead dressing unit also permits the use of in process dressing (IPD). Utilizing the overhead unit, cycle time is decreased, as less machine motion is required when compared to a rotary dressing device mounted to the machine table.

The positioning accuracy of the overhead dressing system through the use of servomotors and ballscrews, and feedback ability of the linear glass scales to the C.N.C. allow the end-user to monitor the grinding and dressing process.

A sectioned illustration of a precision ballscrew

The rotary dressers rotation also will affect the surface finish of the work piece. Dressing in the uni-directional mode will permit better surface finish and the highest stock removal rate. Dressing in the counter-directional mode produces a less aggressive grinding wheel. In the uni-directional mode, diamond roller dwell should be used with extreme caution so as not damage the precision diamond roll through staying in contact with the grinding wheel for too long a period of time resulting in dulling of the grinding wheel and burning of the work piece.

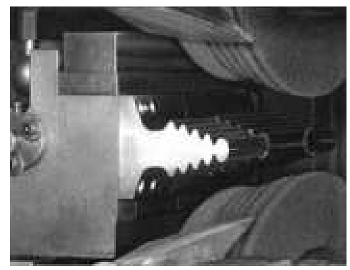
Overhead dressing system

The general practice in continuous dress creep feed is to use reverse plated diamond rolls for their superior accuracy and sharpness. The general practice for grinding wheel selection for tool steels is silicon carbide and aluminum oxide. Silicon carbide is also used for cast iron and titanium alloys. Aerospace alloys, containing nickel, molybdenum, cobalt and high chromium generally use grinding wheels of the aluminum oxide and super abrasives type.

Keeping it cool

Coolant application is also an important consideration. A grinding wheel rotating at a speed of 6500 surface feet per minute or 72 MPH produces an air barrier surrounding the grinding wheel. This air barrier prevents the efficient delivery of the coolant to the grind zone. One school of thought is that a baffle should be used to break the air barrier. When the baffle breaks the barrier, the wheel speed sucks the coolant into the grind zone, which reduces thermal damage to the part. This baffle approach is improved when combined with the use of pressurized coolant that is injected into the pores of the grinding wheel, cleaning the wheel. Typical coolant pressure is 220 p.s.i.. Coolant velocity delivered to the work area should meet or exceed the wheel surface speed at new wheel diameter with coolant nozzle position tractability. It is obvious that nozzle shape and size must be calculated to optimize process conditions with 120 to 140 p.s.i. quite typical.

This dual wheel illustration demonstrates the effective use of coolant ramps in the manufacture of turbine blades.



Another effective solution to coolant application is the use of coolant ramps on each side of the part machined to promote coolant penetration in the arc of cut. The formula below will assist in making this determination to coolant nozzle size.

Known parameters

Wheel operating speed	6000 SFM Surface feet per minute
Coolant pump output	60 GPM Gallons per minute
Wheel Width	2.0 inches

6000 SFM multiplied by 12 equals 72,000 inches per minute. Take the nozzle width of 2.0 and multiply 72,000, which equals 144,000 cubic inches per minute.

There are 231 cubic inches in a gallon. 231 multiplied by 60 GPM equals 13,860 cubic inches per minute. Take the totals of both formulas, 13,860 divided by 144,000 equals 0.0929 nozzle height. The correct nozzle for this application is a 2.0 width with a height of 0.093. This will permit the speed of the coolant to meet the operating wheel speed to break the air barrier.

The HEDG process typically uses a direct plated wheel at higher speed and a faster grinding feedrate than the creep feed process. Direct plate grinding wheels consist of grain adhered to the steel core by a plating process. A common creep feed application for the electroplated wheel is internal form or slot grinding of hydraulic steering pumps. This application is processed in straight oil in a mesh size range of 100/120 through 140/170. The single layer grain wheel does typically have a shorter service life than a vitrified grinding wheel with a .250 layer. In direct plated applications with high surface speeds and coolant nozzle velocity to break the air barrier, there exists the possibility of hydroplaning during grinding. This occurs due to the lack of porosity of the plated wheel as the single layer of crystals with a typically 50% exposure limit the coolants path. Direct plated grinding wheels provide excellent results when used on older equipment that is not equipped with a dressing device. The long service life on dedicated equipment decreases the required wheel change over times. Generally, wheels that must be re-profiled (i.e. resin) off line result in idle spindle time. When equipment is at near capacity issues the use of direct plate C.B.N. will increase machine efficiency.

A balancing act

Wheel balancing has always been treated as an add-on to most grinding machine tools. Chatter in the material ground is one of the most common problems encountered. Vibration signature analysis can be determined with today's technology of microprocessors and sensors. These units can monitor background vibration from additional equipment in the area. This signature analysis technology is similar to that developed by the Navy to search out and identify enemy submarines. Due to the extreme hardness of the superabrasive grain any vibration can lead to increased wheel usage and chatter to the work piece. The vibrations in the contact zone cause the grain to fracture. Self-excited or regenerative chatter is common and can be determined by changing the work speed or wheel speed. Fixture clamping and workpiece hardness are other avenues to pursue in analyzing vibration root causes, after dressing, wheel hardness and background noise has been ruled out.

Using unbalanced grinding wheels over a period of time can cause premature failure of spindle bearings in the machine tool. Surface degradation is also common when using unbalanced grinding wheels. The most common type of corrective action is static balancing. The wheel is mounted on a balancing arbor and placed on two roller bearings or knife-edges that permit the wheel to rotate to the heaviest point down. The wheel weights are then adjusted to correct the out of balance. Another type is the use of a hand held strobe that uses a vibration sensor when tuned to the operating revolutions per minute (RPM) of the wheel. In this process, the objective is to move the weights until the wheel appears to stop during operation. The dynamic balancing unit mounted directly to the wheel flange permits the continuous monitoring throughout the wheel life. Dynamic balance methods can be of the hydro-balancing type or by moving weights driven by micro servomotors.

Multi-axis CNC grinding systems provides the end user with continuous improvement in abilities to reduce manufacturing costs. The ability to accomplish multiple grinding operations in one clamping reduces the setup time required to manufacture today's complex components. The use of multiple fixtures on multiple machines increases the possibility of miss fixturing. The stack-up errors as the part is located and move to another station often result in increased scrap parts, further driving up manufacturing costs.

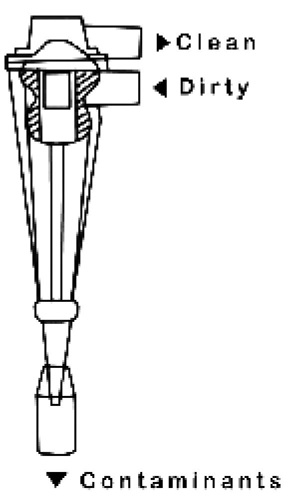
Cost effectiveness

Conventional abrasives traditionally contribute to disposal costs as the abrasive, coolant residue and swarf removed from the grinding operation pose environmental problems. Filter paper costs are increased due to the amount of grinding wheel abrasive deposited on the paper.

When using superabrasives grinding wheels the majority of the swarf consists of workpiece material. This alone will reduce filtration costs since there is a minimal amount of grinding wheel grain being lost to the process. Another benefit of a cleaner grind is that machine maintenance cost per part is reduced. Coolant life is extended when using superabrasive grinding wheels due to the reduced amount of contaminates in the coolant. Factor in the extended wheel life with superabrasives and the result is fewer number of wheels required in inventory to meet production schedules. The infrequent wheel changes with superabrasive grinding wheels provide increased run time available for production. Factories that have multiple grinding machines using conventional grinding wheels are faced with the cost of storing, material handling, and delivery from inventory to the machining area.

The total systems approach

While many engineers pour over specifications of machine tools to determine servo loop closure time and machine accuracies, another important link in the system is often overlooked. Coolant systems are often looked upon as a necessary evil and less time is taken to research system requirements. Coolant or industrial liquids are part of the grinding process, which lubricate, clean and cool both the manufactured part and the machine tool. They also serve to transfer contaminates away from the work area. While performing this function they become contaminated with material generated from the grinding process. Filtration is accomplished by forcing the coolant through some type of media such as filter paper or diatomaceous earth. Other systems use multiple settling chambers and hydro-cyclones to separate the contaminates from the coolant.



Hydro-cyclones are similar in operation to a centrifuge and operate on the following principal. Dirty coolant is carried through the slurry inlet. Rapid rotation of the dirty coolant overflows to the clean outlet while solids are rapidly moved by the vortex inside the cone. Then the solids are forced through the exit orifice at a reduced flow.

In extremely heavy applications of magnetic materials, cylindrical magnetic drums rotate at the liquids surface and use scrapers to remove the material from the drum.

This closed loop system filters the contaminated liquid so that it may be reused in the grinding process. To function successfully, the filtration system must address all coolant failure mechanisms, prevent bacterial degradation, and loss of lubrication. Each of these reduces the life cycle of the coolant. In some cases the coolant is not constantly circulated and a light layer forms on the top, which reduces the oxygen levels and promotes bacterial growth.

When the coolant degradation or bacterial count becomes excessive, the coolant turns rancid. Most water based coolants and oils contain sulfides which encourage bacteria growth and generate acids that result in the rotten egg smell common after inactivity of coolant systems. The use of aeration or a weir to keep the coolant aerated will reduce possibility of bacteria.

Coolant systems used in heavy material removal processes such as creep feed grinding often use refrigeration systems to maintain coolant temperature. The coolant chiller aids in the control of the bacteria growth and most importantly maintains machine and material temperature to maintain process control. A typical operating temperature is 76 degrees Fahrenheit. Coolant temperatures above 80 degrees Fahrenheit reduce coolant effectiveness. With the large heat generating coolant pumps typically used, a chiller is required to protect the system from itself. Loss of lubrication in the system has an impact on wheel life and provides poor size control and corrosion protection. As the coolant temperature increases thermal expansion take place in the machine tool making it difficult to maintain size. This temperature increase then can be transmitted to the hydrostatic oil used in the guide ways or machine bed.

In addition to cooling the cutting area during any grinding operation, two additional requirements of any cutting fluid are to provide good lubricity and sufficient pressure to remove swarf from the wheel. The higher lubricity requirement leads the application toward operating using straight oil as a coolant. The need for better cooling during grinding leads toward a water-soluble type coolant.

Some new types of coolants allow higher percentages of coolant to be used at pressures in excess of 200 pounds p.s.i. without foaming. These new formulations in coolant technology satisfy both requirements for lubricity and cooling.

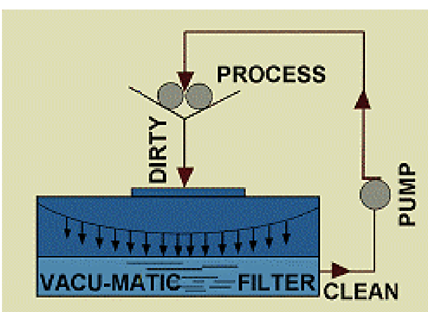
Semi-synthetics are coolants that usually contain a small amount of oil with extreme pressure additives (EP) and water. The emulsion suspends the oil in water with chemicals to prevent separation, or reverse emulsion, of oil and water. Reverse emulsion can occur when charging a system with the coolant concentrate, then adding water and the two never bind. Separation is common. Chlorine, sulfide and phosphate are a common EP additives that are used to promote lubrication and prevent foaming.

The coolant concentration of water and oil must be monitored to maintain the required ratio. The use of deionized or RO (reverse osmosis) water to maintain the system will provide a system free of salts that normally break down the emulsion. The coolant requires disposal as the minerals build up in the system, along with other contaminates such as tramp oils from hydraulic clamping systems or machine lubrication systems and metal particulate.

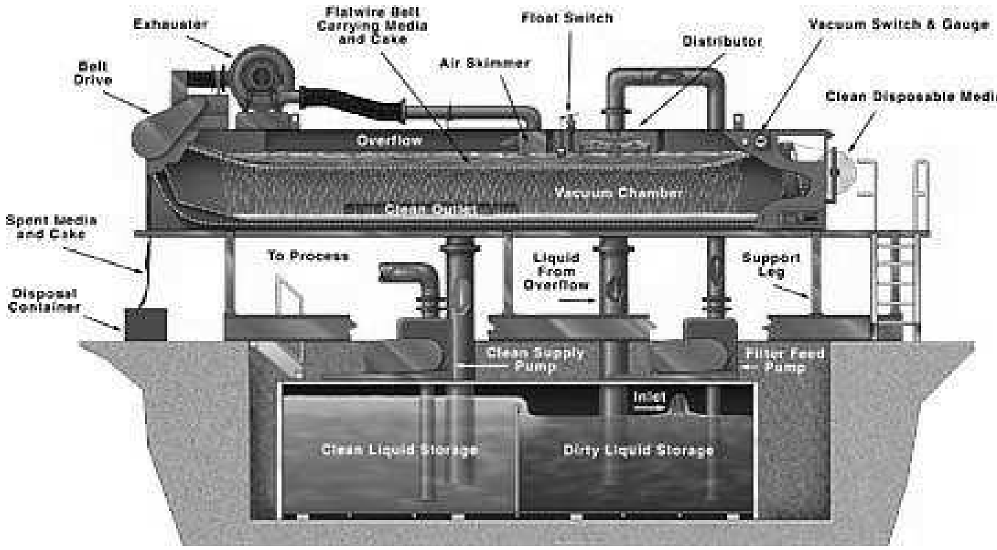
Micro biocides are available from coolant manufactures, which destroy germs and microorganisms. Most coolant technical representatives are chemists and have a greater working knowledge, than the author, of proper coolant testing. Consult your material data safety sheet (MSDS) to determine the exact health issues and chemical make up of the coolant. Contact your local representative when systems are out of normal limits as the machine and system will require a thorough cleaning to purge the bacteria and return the coolant to a longer life cycle.

Contact dermatitis is another major factor in manufacturing. As the coolant becomes contaminated beyond the norm and small particles are present in the fluid, operators are a greater risk for contact dermatitis. The particles suspended in the fluid come in contact with human skin during loading, unloading, maintenance or setups. These particles scratch the skin and break the protective barrier. When bacteria are present, a skin infection is common.

The most common filtration systems are gravity, vacuum, and pressurized. The gravity system uses the discharged dirty coolant from the machine dumped on top of a filter paper media. A cake of swarf is built up as the coolant seeps through the paper. Once a level of the coolant is reached that no longer permits the coolant to pass a float rises up and makes contact with micro switch and an electric motor advances a clean area of paper. The coolant is pumped from the clean tank beneath and reused.



The vacuum system uses a suction pump to pull contaminated liquid to the filter paper located in the bottom of the tank. Once the cake of material has built up and liquid can no longer pass freely a vacuum level is detected, the suction pumps cycles off and the conveyer moves the swarf and filter paper up a ramp to dry before discharged.



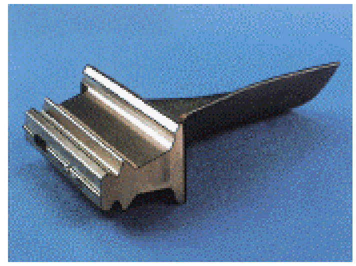
The pressurized filter collects coolant in a sealed chamber and forces the swarf or contaminated liquid through the filter paper. Some pressurized systems use diatomaceous earth as a form of cake to filter the swarf. Once system pressure is achieved in the chamber a blow down and dry of the media takes place before the chamber opens to index the filter paper. Both vacuum and pressurized systems require large clean tanks to support the cycle time of the suction pump and drying cycle of the chamber.

Case Study

Titanium is a common material found in shops working with aerospace and gas turbine engine components. Titanium is also used in the medical field for bone screws and prosthetic implants primarily for the high corrosion resistance and strength to weight ratio. The higher alloy content and hardness of titanium make it difficult to machine with traditional chip-making technologies. When machining titanium, it is quickly obvious that this material is a poor conductor of heat. Higher depths of cut overcome the materials ability to move or deflect the cutting tool. The following example shows how continuous dress creep feed grinding provides a process solution to this difficult to machine material.

The equipment used was of German origin with a 106 H.P. (79kW) grinding spindle drive. The equipment was designed with a fourth axis for CDCF grinding and one automatic positioning coolant nozzle. The coolant temperature was monitored to maintain a maximum 76 degrees with a coolant refrigeration or chiller unit. The coolant type Cimperial HD 90 at 5% concentration. The component machined was a land based turbine blade and the grinding operations consisted of the root form and platform. The platform grind application did not require the use of CDCF as the material amount removed was not significant. Green silicone carbide was the abrasive type utilized. The wheel speed used was 4000 SFM with wheel specification being C609H8AV18. Depth of cut was 0.240 using a 30/40 mesh diamond roll with a 0.85 roll ratio. The grinding table speed was 10.0 inches per minute with a 60% spindle load in the down cut mode.

Encapsulating the aerospace turbine blade is one of the typical methods used for fixturing.



This illustration is of a blade that has been finish ground and removed from the encapsulated block. Typically a break out die is used to separate the blade from the zinc. The zinc can then be recycled for later use.

The lean diet

In the late 1980's the development of fully automated grinding cells was the challenge to manufacturing and machine tool builders. Two companies in the United States were implementing grinding cells that required minimal operator intervention. General Electric in Madisonville Kentucky and their choice of machine tool builder ELB of Germany and Pratt and Whitney in North Haven Connecticut using Hauni-Blohm also from Germany. The concepts were similar in operation for the mass production of turbine blades. In each case turbine blades were presented to the grinding cells to creep feed grind and inspect at various stages of completion. Conventional abrasives were utilized together with rotary diamond dressing rolls. This required automated wheel changers for the multiple wheel packs used during the shift on a daily basis and computer inspection feedback to the grinding cells motion control to generate offsets for size control. The Connecticut facilities system had a smaller in process lot size at the grinding cell than Kentucky by the use of robot pick and place units and palletized robotic shuttles. Kentucky's cell utilized a massive rotary table that indexed parts from one grind station to another with multiple parts in process. Both systems produced millions of blades in the mass production of turbine blades for years and the Hauni-Blohm system was duplicated at Rolls Royce in Indianapolis and throughout the world.

The change over for the various setups required hours even with the highly trained staff of support people. And the business climate was changing in manufacturing with customer demands for smaller lot sizes for just in time delivery. Pratt & Whitney also needed to reduce their costly inventory of finished parts in their central inventory. Process changes were necessary in order to adapt to the changing manufacturing philosophies and customer requirements.

During this period of dedicated grinding cells another facility was taking a different approach. Pratt & Whitney located in North Berwick Maine was beginning to implement lean manufacturing. At this facility utilizing five axes continuous dress mini cells were created supplied by ELB, Germany. Quick production methods with the use of two station rotary tables in each grinder met their corporate requirements for one-piece flow and inventory reduction and flexibility. Production lot sizes had no impact with the mini cell system and grinding wheel and tooling costs were minimized as they dedicated for the individual part or part families. Conventional and superabrasives together with rotary dressing devices were implemented in the mini cell production areas. Setup time for part change over was under thirty minutes with tooling that could move from machine to machine in the case of downtime. This mini cell system is still in place after over a decade of use in meeting Pratt & Whitney's corporate needs. With the completion of the mini cell project, lean manufacturing had found a place in the aerospace industry. The previous high production grinding cells have long been dismantled or are in limited use.

Continuous improvement

With the constant changes in today's conventional and superabrasive grinding technology, machine tool builders are looking for new techniques for their applications. One new innovative use is the Quickpoint™ system, which is also referred to as peel grinding. Peel grinding uses narrow width metal and vitrified bond grinding wheels at speeds up to 28,000 SFM (surface feet per minute) with the wheel head positioned at 0.5^0 perpendicular to the interface of the work piece which is rotating at speeds up to 12,000 rpm. With the wheel head at an angle the machine tool builder is using the grinding wheel similar in presentation to a lathe tool. The benefits are that with the small contact area between wheel and work piece that the heat zone is minimized, along with defection due to reduced cutting forces, while the wheel is traversing the work piece length. Less heat generation permits an increase in traverse speed, which yields an increase in parts per hour. While the process has been defined the benefits of use provide a major setup reduction to the end user. Multiple operations to generate forms can be accomplished while only handling the part once. One grinding wheel can process multiple forms. The requirement of dedicated tooling on multiple machines or setups is eliminated.

The typical metal bond wheels due conduct heat quickly so the use of a custom made superabrasive-grinding wheel is an alternative. This custom grinding wheel can be made up of a resin metal bond combination that provides the benefits of dampening, better truing ability and also a heat sink. Other machine builders and end users will utilize this innovative approach and also implement their own combinations of continuous improvements. Machine tool builders now offer multi axes combination machines that turn and grind components in one fixturing in order to meet growing customer demands.

Conclusion

In closing, the author has discussed multiple different abrasives, coolant system types and the usages of grinding technology in today's industry. The author discussed this with multiple colleagues and we all agreed on one idea. All end users should work with multiple grinding wheel manufactures, diamond roll manufactures and multiple machine tool builders. One supplier source for whatever the product may be will never offer all the solutions. Machine tool builders utilize multiple tooling sources for their various applications for end users. A complete list of wheel, diamond roller manufactures and machine tool builders could create an entire book of reference. The end user owes it to himself not to become complacent and strive for continuous improvement. Remain open to ideas from several suppliers and determine the best solution for your application. That goes for all aspects and facets of finding the sweet spot.