Understanding grinding fundamentals, wheel preparation and grinding fluids.

Abrasive Lessons

Erwin Junker Machinery Inc.

► BY STUART SALMON

PARTS 1 AND 2

Today's manufacturing industry is desperately searching for alternatives to grinding. Among the "new" processes being tried to speed the production of parts are hard turning; dry machining; the use of coated, wear-resistant cutting tools; and high-speed machining.

It should be noted, though, that "high speed" isn't foreign to grinding. An abrasive wheel typically runs at a peripheral speed of around 6,000 sfm. High-speed superabrasive grinding wheels are used in production operations at speeds of 15,000 sfm to 35,000 sfm. And, laboratory testing has been carried out on grinding rigs running in excess of 60,000 sfm—just shy of the speed of sound.

The industry's dislike of grinding is due, in part, to a lack of understanding about the process. Superabrasive and creep-feed (CF) grinding competes, technically as well as economically, with milling, broaching, planing and, in some cases, turning. There are plenty of naysayers at manufacturing engineering companies who keep grinding from competing with those processes, particularly when their expertise lies in traditional machining. But when new materials come along—like ceramics, whisker-reinforced metals and polymers, and multilayer metals with nonmetallic laminates—grinding is often the only process able to do the job.

Abrasive grains—in suitable bonds—break down or resharpen in a controlled manner while in process. If the grinding wheel becomes too dull or loaded with debris, then it can be dressed or resharpened on the machine. No other mechanical machining process resharpens its tools on the machine.

A grinding wheel also can machine surfaces to tolerances on the order of tens of thousandths of an inch, while producing a surface with the finest possible finish and the highest level of integrity.

Unfortunately, grinding has long been regarded as an art. Over the past 40 to 50 years, however, grinding researchers worldwide have studied abrasive machining and gained a comprehensive understanding of the process. They have developed new and

	Hardened Steels	Nickel-Based Superalloys	Gummy Stainless Steels	High-Temperature Alloys	Tungsten Carbide	Aluminum, Titanium	Rubbers, Polymers	Copper Alloys	Plastics	Ferrous Metals	Ceramics, Cermets
Aluminum Oxide (Al_2O_3)	●	●		●						●	
Ceramic Al_2O_3	●	●	●	●							
Silicon Carbide					●	●	●	●	●		
Diamond					●	●		●			●
Cubic Boron Nitride	●	●								●	

The types of materials that are suitable for grinding with conventional abrasives and superabrasives.

improved abrasives, bonding systems and grinding fluids, all of which bring grinding into the realm of science.

To promote a better understanding of grinding, this article will examine some of the fundamentals of the process.

Types of Abrasives

Abrasives fall into two basic groups: conventional (such as aluminum oxide and silicon carbide) and superabrasive (diamond and cubic boron nitride).

CBN and diamond are harder and more wear-resistant than conventional abrasives, but they cost significantly more. An important additional difference is that superabrasives are excellent conductors of heat (diamond conducts heat six times better than copper), whereas conventional abrasives are ceramics. Therefore, they are insulators and do not conduct heat.

Superabrasives also have high thermal diffusivity, which is the ability to quickly shed heat. This makes super-

abrasives inherently "cool cutting." The abrasion resistance of superabrasives is vastly superior to conventional abrasives, but the properties of superabrasives do not necessarily make them candidates for every grinding operation.

Every abrasive has its niche, so it is important to fully understand the properties of each. For example, Al_2O_3 ceramic abrasive—sometimes called "seeded-gel" (SG) or "ceramic abrasive"—generally exhibits better wear resistance and better form-holding capability than fused (conventional) Al_2O_3, but not always. Again, ceramic abrasive has its niche.

Aluminum Oxide. Al_2O_3 is the least expensive abrasive. It is good for grinding hardened steels. Al_2O_3 also can grind nickel-based superalloys when continuously dressed. Al_2O_3 is versatile in that it can successfully grind soft and hard materials at light-to-heavy stock-removal rates and imparts a superior surface finish.

Ceramic Aluminum Oxide. Ceramic Al_2O_3 is very tough and best used where the force on each grain in the arc of cut is high. Ceramic Al_2O_3 is good for grinding hardened steel when cylindrical grinding or reciprocal grinding large surfaces. It is not suited for grinding operations where the arc of cut is long and the force on individual grains is very low, such as ID and CF grinding.

However, a modified ceramic grain that is "extruded" is nicely suited to grinding gummy stainless steels and high-temperature alloys, even when the arc of cut is long. The aspect (length-to-width) ratio of these grains is around 5.

The properties of the SG grain may be complemented by the friability of the fused Al_2O_3 when they are mixed together to form a composite fused/ceramic abrasive wheel. It is, therefore, necessary to know the length of the arc of cut between the grinding wheel and the workpiece to better specify the grinding wheel for the job.

Silicon Carbide. A SiC grain has a naturally sharp and aggressive shape. It is best for grinding hard materials, like tungsten carbide. Because of its sharpness, it also is well-suited to machining very soft materials, like aluminum, polymers and rubbers, as well as softer materials, such as low-ten-

Understanding Superabrasive Concentration

An important detail about the specification of a superabrasive wheel is its grain concentration. The industry seems to have a misconception that a 100 concentration means 100 percent. The number 100 refers to there being 72 carats of grain per cubic inch of wheel.

So, a 50 concentration means there are 36 carats of grain per cubic inch of wheel.

Grains are available in many different sizes. Yet wheels with different sized grains can have the same concentration.

Consider a 75-concentration, 60-U.S.-mesh wheel vs. a 75-concentration, 200-U.S.-mesh wheel. Each wheel has 54 carats by weight of abrasive per cubic inch of wheel. For the 60-mesh grain, 6,900 grains weigh 1 carat, whereas 262,000 200-mesh grains weigh 1 carat. Therefore, the 60-mesh-grain wheel has 372,600 grains per cubic inch and the 200-mesh-grain wheel has 14,148,000 grains per cubic inch.

If we assume that the grains are distributed evenly throughout the grinding wheel, then by taking the cube root of the number of grains per cubic inch, the average number of grains per linear inch can be found. For the 60-mesh grain, the average number is around 72, and for the 200-mesh grain, the average is about 242.

The reciprocal of those numbers gives the average grain spacing. The grain spacing is 0.014" for the 60-mesh-grain wheel and 0.004" for the 200-mesh-grain wheel. If the length of the arc of cut is 0.013", then each grain in the 60-mesh wheel is spaced farther apart than the arc length is long. On the other hand, the grain spacing of the 200-mesh wheel is 0.004", so there would be at least three grains in the arc of cut, along any linear line, at all times. However, the rule of thumb is to ensure that between four and 10 grains are in contact along an average line around the arc of cut.

—S. Salmon
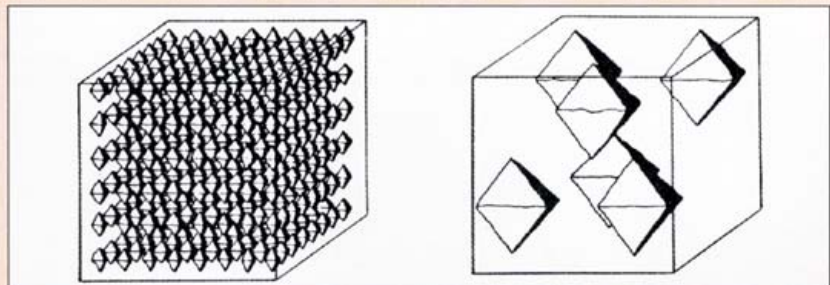
The variety of abrasive grains means there are more smaller grains (left) than larger grains when the concentration is the same.

Pictured are various metal-bonded diamond wheels for ceramic OD and ID cylindrical grinding.

sile-strength steels, copper alloys and plastics.

Diamond. Both natural and synthetic diamonds are used for grinding. Diamond is not a good candidate for grinding ferrous materials. Being an extremely hard form of carbon, it has an affinity for the iron (steel being an iron and carbon alloy) and will wear rapidly. However, diamond is a good candidate for grinding nonferrous materials, titanium and, particularly,

ceramics and cermets.

Cubic boron nitride. CBN, like diamond, is an expensive abrasive. The price of a superabrasive wheel may be 50, or more, times higher than a conventional abrasive wheel. But the superabrasive wheel might grind more than 100 times the number of parts. It can grind the hardest of steels while exhibiting very little wear.

CBN is ideally suited for grinding hard, ferrous materials and jobs such as grinding ID bearing races, especially when the form will remain on the grinding wheel for long runs. CBN also is well-suited to operations where the wheel is changed infrequently. Small batches and wheel changes require dressing and redressing during setup—a major expense. Because CBN reacts with water at high temperatures and wears rapidly, it grinds best with glycols and straight oils.

Bonds

Conventional-abrasive wheels may be made with vitrified bonds, resin bonds or plastic bonds. In addition, superabrasives can be bonded in a sin-

tered metal matrix or plated to a wheel hub with a layer of nickel. Such wheels are impervious and have no porosity.

Care must be taken to apply the grinding fluid properly to plated and metal bond grinding wheels to prevent them from hydroplaning. Significant hydrodynamic pressures in the arc of cut can lift the wheel from the workpiece surface, resulting in poor surface finish and high wheel wear.

The choice of bond and abrasive go hand in hand. For example, CBN might be the abrasive of choice if the wheel form is to remain exactly the same over the life of the wheel and it will stay on the machine spindle until spent. Since CBN conducts heat so well, a metal bond is advantageous. This combination provides a cool-cutting wheel, since the heat flows into the grain and wheel and away with the coolant rather than into the workpiece.

There are two types of metal bond: plated and sintered. Plated wheels are never dressed; they are made to the exact form and grind until spent. Sintered wheels are generally dressed

Glossary of Grinding Terms

Arc of Cut: The arc of contact between the workpiece and the grinding wheel.

Aspect Ratio: The ratio of an abrasive's grain length to its width.

Cermet: A heat-resistant alloy formed by compacting and sintering together a metal and a ceramic material.

Concentration: The amount of super-abrasive material contained in a unit volume of the grinding wheel. The measurement is based on the number of carats per unit volume.

Continuous Dressing: A process where a diamond dressing roll sharpens the grinding wheel by removing dull grits all the time the wheel is machining the workpiece.

Creep-Feed Grinding: A process where a very soft and porous grinding wheel takes a deep cut in one slow pass. Well-suited for difficult-to-machine materials, the process offer a high stock-removal

rate with accurate form retention.

Cylindrical Grinding: A process for machining round components.

Dressing: The removal of material from the periphery of a grinding wheel using a diamond tool.

Dry Machining: A metal-removal operation where coolant is not applied to the cutting tool/workpiece interface.

Friability: The ability of an abrasive to fracture.

Hard Turning: Turning hardened metal on a special lathe with special tooling to eliminate grinding.

ID Grinding: A process that removes metal from the inside diameter of holes or profiles by applying a very small, high-rpm grinding wheel.

Mesh: The mesh number refers to the size of an abrasive grain based on the

number of holes per linear inch of a gauze or wire grid.

Overlays: The number of passes a diamond dressing point makes across the periphery of a grinding wheel.

pH level: Describes the acidity or alkalinity of a chemical solution on a scale of zero (acidic) to 14 (more alkaline).

Porosity: The air pockets within a grinding wheel that make it appear sponge-like.

Reciprocal Grinding: A process where the workpiece is mounted on a table that moves back and forth beneath the grinding wheel.

Swarf: The mass of chips and debris remaining after grinding.

Truing: Application of a diamond tool to a grinding wheel to ensure roundness and concentricity.

by the electrical discharge machining process while off the grinder, and then are mounted like a plated wheel.

Both sintered and plated wheels need to be set up to minimize spindle runout: 0.0005" or less. Minimal spindle runout is especially important for metal bond wheels. Because the grains protrude a short distance above the bond, runout of 0.001" might cause excessive wear to one portion of the wheel while another section's grains remain sharp.

Some plated applications can form very tight radii (0.005" or so), but this bond is generally reserved for more open forms with radii greater than 0.020". Often, plated wheels are applied in high-speed grinding applications and sintered wheels are used on ceramics.

Solid metal wheels have little forgiveness for vibration, runout and fluid flow. If the grinding machine, part and/or fixture lack rigidity and/or the machine is old with less-than-perfect bearings and without an on-machine balancer, then the unforgiving plated wheel may cause wheel-life, surface-finish and surface-integrity problems. A resin bond would be a better choice, based on the condition of the machine tool and vibrational instability. Resin bonds have excellent vibration-damping capabilities. However, the wheel would need to be trued and dressed, and there are costs associated with dressing devices and dressing time.

Vitrified bonds are the most popular bond, as they make for a porous wheel.

Vitrified bonds allow effective application of the grinding fluid to the arc of cut and provide ample chip clearance for the grinding swarf. Vitrified bonds are easily dressed to shape and sharpness with diamond dressing tools.

Preparing the Wheel

Wheel preparation includes mounting, balancing, truing and dressing. It is also where many grinding problems occur.

First, mount the grinding wheel according to the manufacturer's guidelines to ensure good initial balance and minimal runout prior to dressing. Second, take care when mounting a grinding wheel so as not to damage the wheel bore. The bore of a rotating wheel undergoes the highest stress; "wheelbursts" that occur on startup can often be attributed to poor handling and mounting practices. Third, be sure to use the paper blotter/washers provided when mounting vitrified wheels, and, fourth, tighten the flanges with an even torque and tightness.

After mounting, the grinding wheel should be rough-balanced, dressed and fine-balanced prior to grinding. An additional dressing and rebalancing operation may be required if the wheel was initially and significantly out of round or out of balance.

1. 0.001" A typical roughing pass of a single-point diamond. The diamond traverses too fast and misses a portion of the wheel periphery.

2. A second pass is taken after an additional 0.001" infeed. The diamond makes another "start" and does not maintain the same pitch.

3. A third pass that's rapid.

4. The resultant erratic and inconsistent wheel periphery of the third pass.

5. 0.001" The speed the diamond traverses is calculated so that no part of the wheel periphery is missed.

6. 0.001" The traverse speed is calculated so that the pitch of the diamond overlaps. Two to three overlaps are good for a roughing cut and four to six overlaps are good for fine finishing.

7. 0.001" The resultant smooth and consistent wheel periphery from a properly calculated traverse speed.
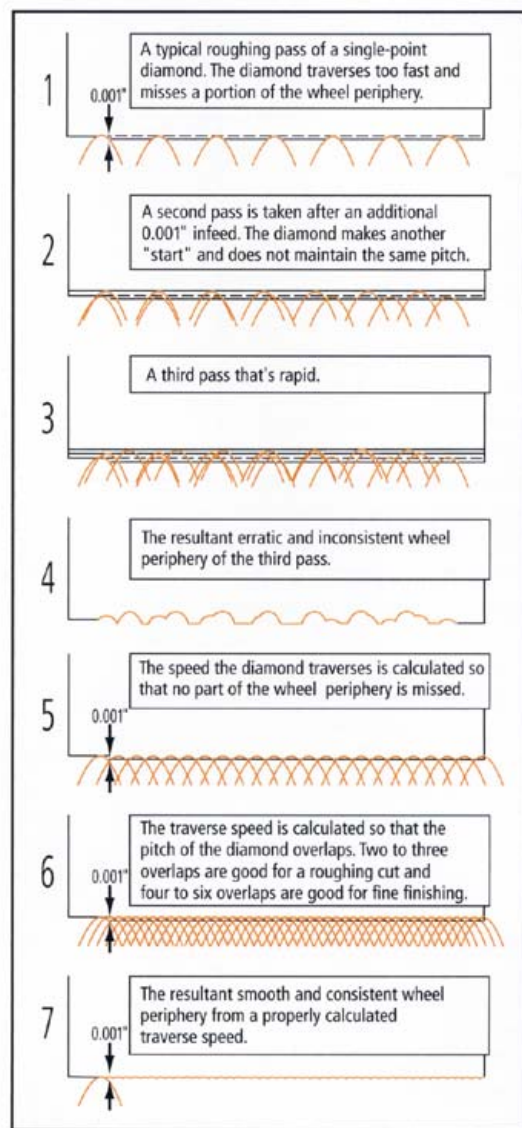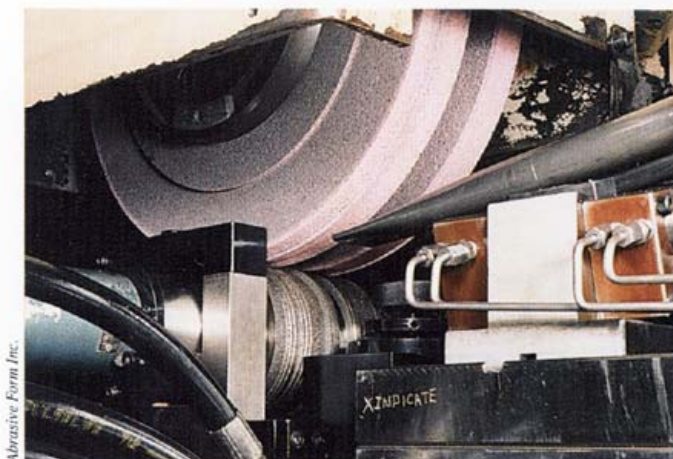
S. Salmon

Figure 1: The use of overlaps, or overlays, ensures a correct and consistent wheel dressing. Two to three overlays are generally incorporated for roughing and four to six for finishing.
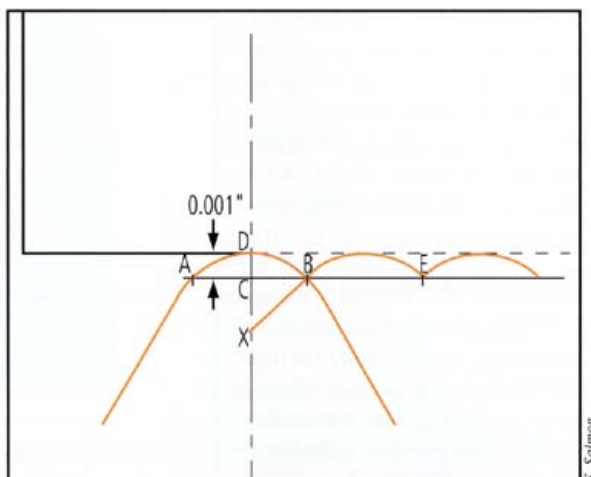

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Creep-feed grinding competes, technically as well as economically, with milling, broaching, planing and, in some cases, turning.

Landis Gardner, a Unova Company
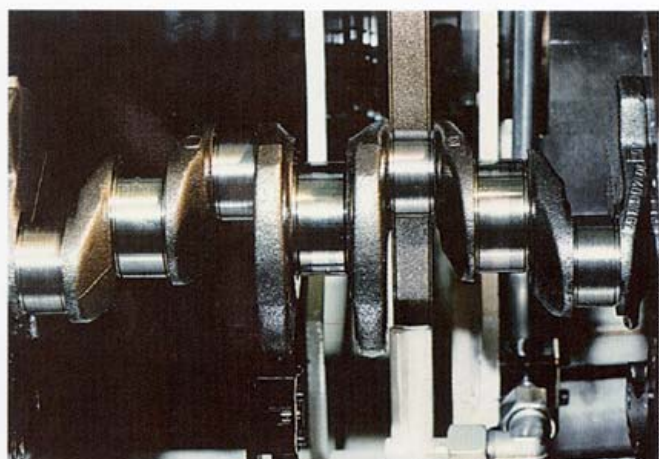
A plated CBN wheel "green-grinds" a crankshaft. CBN is ideally suited for grinding hard, ferrous materials when the form will remain on the wheel for long part runs.

Proper wheel balance will yield con-
sistently good surface finishes and long
wheel life. In addition, proper dressing
will produce both a consistent grinding
wheel surface and grinding action.

The dressing procedure determines
the level of wheel sharpness and the
accuracy of the form on the grinding
wheel. Therefore, it's important to
keep the dressing equipment, whether
it's a single-point diamond in a holder
or a diamond roll dresser in a motor-
ized unit, in precise working order.

Single-point dressing is the most
common way to dress vitrified grind-
ing wheels. It is also the most com-
mon cause of erratic grinding behav-
ior, creating a need to constantly
adjust and readjust the process.

When grinding a workpiece surface,
the wheel typically rough-grinds an
initial amount of stock and then, after
a change in dressing parameters, fin-
ishes the surface. The rule of thumb is
to rapidly traverse the diamond across
the grinding wheel periphery for the
initial roughing pass. For fine finish-
ing, the dresser is traversed at a much
slower speed to achieve a smoother
grinding wheel and, accordingly, a
smoother workpiece finish.

A system of "overlays," or "over-
laps," should be used to ensure a cor-
rect, consistent dress (Figure 1). An
example is a 16"-dia. grinding wheel,
running at 6,000 sfm, being dressed
with a 0.010"-radius, single-point dia-
mond for a rough-grinding operation.
The amount to be dressed, per pass,
is 0.001".

It is typical for the dresser feed to
be too fast, causing the diamond to
miss a large area of the wheel periph-
ery. Multiple passes, on the other
hand, often result in the entire wheel
being dressed, but leave the surface
uneven. That can lead to an aggressive
wheel, but one that wears unevenly
and too quickly.

Dressing should always be perform-
ed at the operational grinding speed.
The only exception is when crush
dressing, which is done at a low speed
of about 300 sfm. A calculation needs
to be made with respect to the dresser
diamond size and the condition
required on the grinding wheel periph-
ery (Figure 2). Generally, roughing

requires two to three overlays and fin-
ishing requires four to six overlays.

Applying Fluid

The proper application of grinding
fluid is essential to successful grind-
ing. The action of the fluid is to cool
and lubricate the arc of cut.

Water-based fluids mostly cool,
while providing some lubrication,
whereas straight oils provide mostly
lubrication and some cooling. Fully
synthetic, water-based fluids are ideal
for sharp and aggressive grinding
wheels when the arc of cut is moder-
ately long and a good flushing action
is required.

Semisynthetics work best when the
wheel is creating an intricate form and
extra lubricity is necessary to avoid
grinding burn. Straight oils perform
best when the form is intricate, the arc
of cut is short and a high degree of
surface finish is required. Glycol-based
fluids are ideal when cubic boron
nitride is the abrasive and straight oils
need to be avoided.

Choosing a grinding fluid can be a
formidable task. The initial cost of the
fluid needs to be considered, of course,
but so does the cost of managing and
disposing of it. Environmentally friend-
ly, or "green," fluids are a hoax. The
virgin fluid, in its drum, may be drink-
able, but once grinding swarf has conta-
minated the fluid, it generally becomes
an environmentally "unfriendly" waste.

Whichever grinding fluid is chosen,
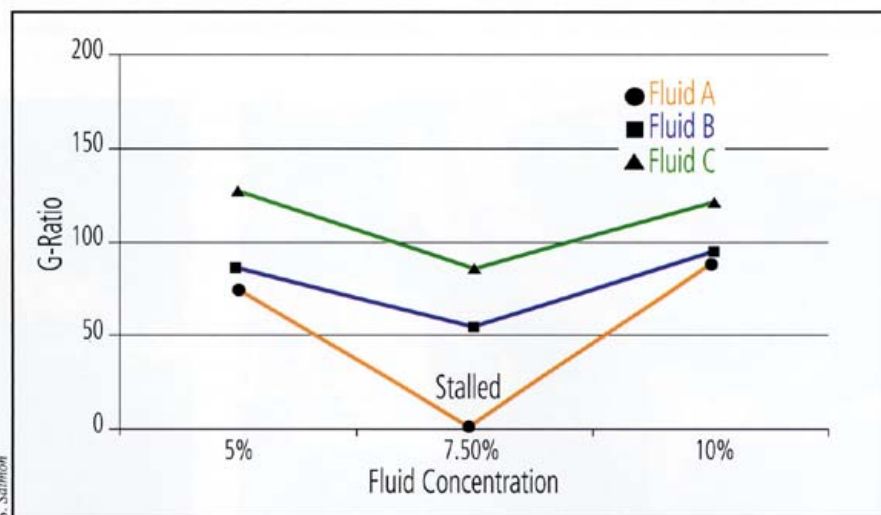it should be filtered and maintained,

Figure 3: Grinding fluids with a known performance at 5 percent concentration (95 per-
cent water) are not as effective at 7.5 percent concentration, but improve at 10 percent
concentration. G-Ratio is the amount of workpiece material removed vs. the amount of
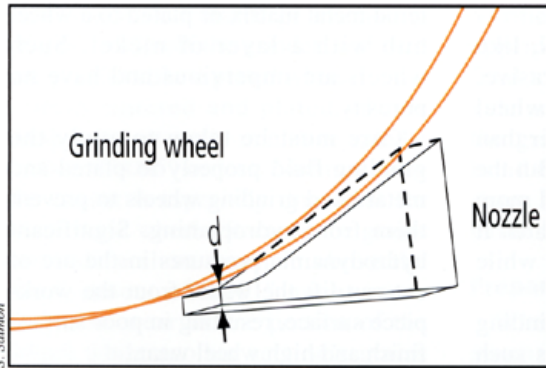grinding wheel used.

Figure 4: The height of the nozzle opening (d) can be calculated to determine the proper nozzle dimensions.

not only with respect to cleanliness, but also to control the concentration, electrical conductivity and pH level.

Recent fluid-performance tests showed that fluid concentration does not affect the grinding process in a linear fashion. It has long been believed that by increasing the concentration of a water-based fluid, the grinding process will improve proportionally. This is not true. Grinding fluids with a known performance at a 5 percent concentration were not as effective as the concentration approached 7.5 to 8 percent, but improved again as the concentration approached 10 to 12 percent (Figure 3).

Of the more than 50 water-based fluids tested, every one followed the same pattern. In some cases, the trend was hardly noticeable. In others, the fluid literally stalled the machine at 7.5 percent while working quite well

at 5 and 10 percent.

Having selected a suitable fluid and fluid management system, it is of paramount importance to apply the fluid to the grinding zone properly. The fluid needs to be applied so that it's present in the arc of cut and not simply splashed or sprayed in the direction of the wheel/workpiece interface. Generally, little fluid enters the arc of cut under flood conditions. The rotating wheel, like a spin dryer, tries to throw the fluid out and away from its periphery.

The porosity of the wheel allows for chip clearance and the transportation of the grinding fluid, but it is the wheel itself that takes the fluid through the arc of cut. The fluid needs to be applied to the wheel periphery at wheel speed for this to happen.

Furthermore, the nozzle needs to be designed specifically to apply the fluid to the right impingement point and at the correct velocity. The nozzle will need to cover the grinding wheel's width, which is known. Therefore, the height of the nozzle opening (d) needs to be calculated (Figure 4). If the nozzle width is 1.5", then the exit area of the nozzle is 1.5d in.^{2}. The grinding speed might be 5,500 sfm, which, when multiplied by 12, equals 66,000 in./min. Therefore, the velocity of the fluid exiting the nozzle is:

$$(1.5d \text{ in.}^2) \times 66,000 \text{ in./min.} = 99,000d \text{ in.}^3/\text{min.}$$

Let's say the pump delivers the fluid at 58 gpm, at a maximum pressure of 110 psi. There are 231 cu. in. in a gallon. Therefore, the pump delivers 231 cu. in. $\times$ 58 gpm = 13,398 in.^{3}/min.

Obviously, what goes in one end of the pipe must come out of the other, so since 13,398 equals 99,000d, the height of the nozzle (d) should be:
0.135" (13,398/99,000).

It is better to make the height of the nozzle opening slightly smaller than the calculated value, as the fluid velocity will drop off slightly after exiting the nozzle. This is particularly important if the nozzle is not right up against the grinding wheel. A nozzle measuring 0.125"×1.5" would be ideal.

The pressure drives the fluid through the system. The resistance to flow might exceed the pump's 110-psi capacity if the nozzle is made incorrectly, or if the path of pipes, joints and elbows through which the fluid flow is contorted. If any of these flow inhibitors exists, the fluid velocity will probably be reduced. Therefore, the flow rate should always be checked using a flow meter. It is insufficient to monitor the flow with only a pressure gage. △

About the Author

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Calculating the length of the arc of cut

The length of the arc of cut is calculated by knowing the radius of the grinding wheel (the distance OC or OB) and the wheel depth of cut (the distance AB.)

For example, if the wheel radius is 10" and the wheel depth of cut is 0.100", then the angle subtended by the arc of cut is the COS^{-1} of angle T, which is OA/OC = 9.900/10 = 0.9900. Angle T is 8.1°. Angle T in radians is (8.1 x 2π)/360 = 0.14154 radians. The length of the arc of cut is the wheel radius multiplied by angle T in radians, or 1.4154" (10 x 0.14154).

—S. Salmon