➤ BY JOHN A. WEBSTER, PH.D., COOL-GRIND TECHNOLOGIES LLC

Coolant Calculus

Directing coolant into the right place,
at the right speed, in the right quantity.

Better coolant application is one of the most effective ways to improve grinding operations. The benefits of improving coolant application include being able to use a harder wheel grade without causing grinding burn, reduce thermal damage to the workpiece and extend wheel life. One of the most important and often overlooked factors in effective coolant delivery is nozzle design. Among the different designs, coherent-jet nozzles offer superior performance and improved operating efficiency.

Thermal Domination

Grinding generates a lot of heat, and if that thermal energy isn't managed correctly, it can lead to workpiece surface damage and poor process economics because of inadequate material-removal rates and excessive wheel wear. Power consumed by the grinding process is partitioned into the wheel (R_s), workpiece (R_w), chip (R_{ch}) and coolant (R_f), the ratios of each depending on the chip size, abrasive grain type, coolant type and material. In shallow-cut grinding of M-50 tool steel at a material-removal rate of 20 cubic mm per second, per mm WOC (Q prime), R_s was shown to be 8 percent, R_w 72 percent, R_{ch} 10 percent and R_f 10 percent. By comparison, when a more thermally conductive CBN wheel was used under the same process conditions, R_s became 30 percent, R_w 45 percent, R_{ch} 20 percent and R_f 5 percent.

Heat that enters the workpiece must be quickly cooled to prevent the development of high local temperatures, phase transformations, cobalt leaching (in tungsten-carbide grinding), and high residual temperatures after the wheel has passed by. Phase transformations are often responsible for tensile residual stresses, white layer formation, reduced fatigue life and surface and subsurface cracking. Process cooling is achieved by applying a cooling

and lubricating fluid, as well as by selecting process parameters that reduce heat generation.

Although the coolant's primary job is to cool the grinding process, it also must:

- cool the grinding wheel (important with resin-bonded diamond and CBN wheels),
- allow the lubricants in the coolant to do their jobs (especially with single-layer superabrasive wheels),
- flush chips from the machine and workpiece area, and
- clean the wheel (especially when grinding ductile materials using water-based coolant).

One of the key elements in coolant application is nozzle design. One design is the coherent-jet coolant nozzle. Effective use of this nozzle involves many factors. Pressure, flow rate, temperature and direction of the jet all influence the fluid's cooling and lubricating ability. Pressure controls fluid velocity, while flow rate and temperature control the rate of heat transfer into the fluid. Proper jet direction allows the fluid to penetrate the air barrier that travels around the wheel. Use of coherent-jet coolant nozzles can

---

Process cooling is achieved by applying a cooling and lubricating fluid, as well as by selecting process parameters that reduce heat generation.

---

optimize all of these elements, leading to improved coolant application. The benefits of improved coolant application include:

- reduced dressing frequency, due to less loading with workpiece material and reduced abrasive grain wear,

- reduced thermal damage of the workpiece material, allowing higher mrr,
- increased effectiveness of the applied flow rate, such that the overall applied flow rate may even be reduced,
- reduced entrained air (foaming), misting and vapor problems,
- reduced disturbance of the jet by the air barrier surrounding the wheel,
- more robust and stiffer setup, and
- no reduction of wheel speed or application of softer wheel grade to alleviate burn.

Nozzle Design

Jet nozzles are the simplest type of nozzle for grinding. Bendable plastic and open metal pipe fall into this category. The jet coming from the ends of these nozzles can be very dispersed, with the jet thickness increasing by more than 10 times within 12" of the nozzle, leading to air entrainment and
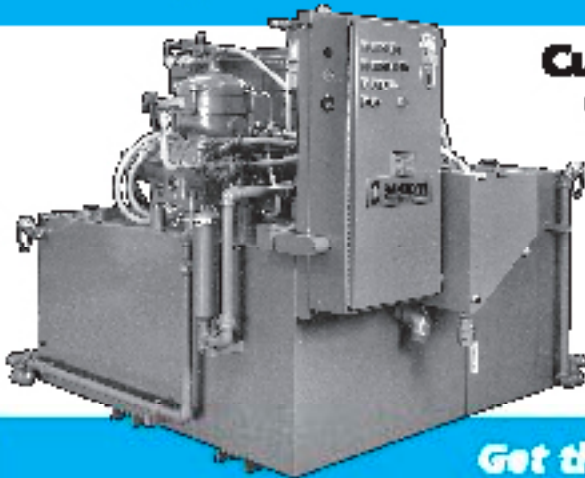
increased foaming. Other disadvantages of jet nozzles include:

- lack of stiffness when subjected to the reaction force of the jet,
- the nozzle must be placed close to the grinding zone to overcome offset from the dispersed jet, risking

damage by the wheel or fixture,

- the nozzle is at the compression fitting holding the pipe, and once formed, the jet is constrained by the tube until it exits, and
- nozzle tubes are often of small diameter to be bendable and coolant velocity down the tube far exceeds the critical velocity of 20 ft./sec. for creating turbulence.

Traditional formed and wedge nozzles also have disadvantages. Formed nozzles are usually created by crushing the tube in a press with an internal shim to control the final aperture, and often include a stabilizer (planar) section after the transition from the input tube diameter to final aperture (round or rectangular) to minimize breakup of

the jet as it exits. Wedge nozzles are often fabricated from welded metal sheet and taper down from the inlet pipe diameter to the desired exit aperture. With this design, the exiting jet can disperse at the same angle as the wedge, putting much of the flow rate where it is not needed, thereby reducing cooling effectiveness.

In contrast, coherent-jet nozzles use a precisely machined internal profile to produce a high-quality jet. An example of coherent-jet nozzle geometry is the Rouse profile. This design requires a contraction ratio (inlet to exit diameter ratio) of at least 2:1. A definition of coherency is a dispersion of two to three times the exit diameter, or thickness, at a distance of 12" from the nozzle. Figure 1 shows the Rouse profile underneath a traditional crushed pipe, or wedge, nozzle schematic. The efficiency of the Rouse design is 95 percent, as defined by the coefficient of discharge. The
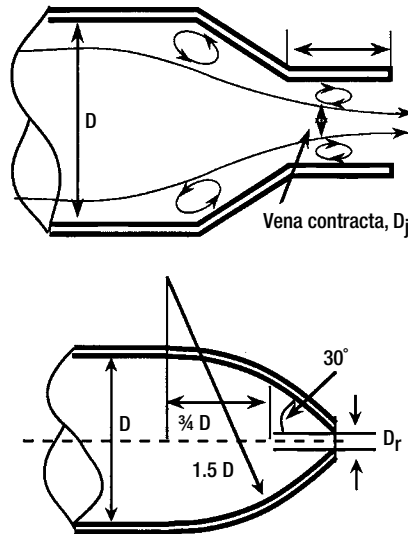

Figure 1: Nozzle geometry based on crushed pipe (upper) and Rouse design (lower).

efficiency of open-pipe, wedge and crushed pipe nozzles can range from 70 percent to 90 percent, depending on the internal transitions. Nozzles where

the actual dimension of the jet is a lot less than the geometric aperture of the nozzle lead to a vena contracta and subsequent air entrainment.

Coherent-jet nozzles enable better grinding performance because they concentrate the coolant into the grinding zone, allowing the wheel pores to be fully filled, thereby minimizing applied flow rate, required coolant tank size and pumping energy. However, coherent-jet nozzles need to be more accurately targeted than dispersed-jet nozzles so they reach their intended target, or zone. A coherent-jet nozzle also concentrates its kinetic energy to break through the air barrier and wet the wheel.

In contrast, the entrainment associated with dispersed-jet nozzles forces air and coolant into the grinding wheel, displacing some of the fluid with the air. In some cases, dispersion is so high that much of the coolant hits the work-

piece and deflects off without effectively cooling the wheel. (See sidebar on this page.)

Pressure Requirements

Nozzles are often crushed to increase the pressure from the pump. In essence, this increases jet velocity. Potential energy in the coolant as it passes through the nozzle is converted to kinetic energy in the form of a jet. While there is some kinetic energy due to the coolant velocity inside the nozzle, it is typically small compared to the potential energy. Bernoulli's equation determines the pressure/velocity relationship and considers the fluid's specific gravity (SG). Kinetic energy is based on the square of the velocity, so to double the velocity, the pressure must be increased 400 percent. The simplified version of Bernoulli's equation is:

$$P = \frac{SG \times v^2}{535,824},$$

where v is in ft./min., SG is dimensionless and P is in psi.

Some manufacturing engineers adopt the "more pressure is better" approach to coolant application. Even when a nozzle pressure of 58 psi is required to match a wheel speed of 6,000 sfm, a pressure of more than 200 psi may be used. When grinding stringy and ductile materials—such as medical-grade stainless steel, Inconel and titanium—wheel cleaning becomes as important as process cooling. These ductile materials tend to load the wheel when the chips are hot, especially with less slippery, water-based coolants, reducing available chip space and increasing required grinding energy. The general consensus in these grinding situations is to apply 600- to 800-psi coolant at a specific flow rate of 2 gpm/in. of grinding width for bonded wheels, and up to 1,500 psi at a similar specific flow rate for single-layer wheels.

What Flow Rate?

Flow rate models have been developed based on a 4° C average increase in temperature of the coolant exiting

the machine over that entering the machine. The energy going into the coolant can come from the abrasive process, chip cooling, wheel cooling bed flush and bearing cooling. Other models use a fixed flow rate of 25 gpm/in. of grinding width. I use a flow rate based upon the grinding power required during the process, because more aggressive cycles require more coolant. The machine controller

or a phase-corrected power meter can be used to determine required grinding power. With conventional abrasive wheels, a flow rate of 2 gpm/hp is effective. For superabrasive wheels, a flow rate close to 1 gpm/hp works well. Coolant must be applied at this flow rate directly into the grinding zone. Additional flow rate is required to clean the wheel and flush the chips from the machine.

Once the flow rate and pressure have been determined, the nozzle aperture can be designed to give optimal flow rate for those conditions. The exit area of a nozzle (A) is calculated from the following flow rate equation, where the velocity of the jet (v) is ft./min., Q is gpm, and A is sq. in. The coefficient of discharge (CD), as mentioned earlier in terms of efficiency, is 0.95 for the Rouse nozzle.

$$A = \frac{19.25 \times Q}{C_D \times v}$$

From this calculated area, the dimensions of a round or rectangular nozzle can be established.

Nozzle System Setup

When determining the hardware required for a nozzle system, consider wheel-wear compensation, adjustability and ease of reconfiguration (if grinding different profiles on the same machine). EDMing and milling have been used to produce profile nozzles for specific wheel geometry, but a combination of round and rectangular nozzles can often yield better results due to the better coherency. These profiled nozzles attempt to bend the flow into a complex profile but often lead to separation of the flow at various positions around the profile. Round and rectangular nozzles do not suffer from this problem but have to be aimed correctly to blend the jets around the profile.

Feed pipes and hoses leading to the nozzle must be large enough to minimize the pressure drop from the pump to the nozzle. The maximum advisable flow rates for common schedule 40 steel pipe are shown in the table below. These flow rates are based on a threshold velocity of 20 ft./sec. through a pipe's ID.

Industrial Case Study

The following case study was taken from a project at a camshaft manufacturer. The cams are manufactured from carburized 8620 steel with a hardness from 58 to 62 HRC. The customer faced a 1 percent scrap rate due to cracking most likely caused by tensile residual stresses from grinding, which may add to the stresses from carburizing, producing stress relief through cracking. This 1 percent scrap rate forced the manufacturer to use fluorescent dye inspection (FDI) to identify cracked camshafts. After analysis, the manufacturer decided to improve tangential coolant application. Because the wheel showed signs of chip loading, a high-pressure pump and nozzle were added to clean the wheel.

The top of Figure 2 shows the original nozzle setup on the two Landis cam grinders fitted with vitrified CBN wheels running at 16,000 sfm and using synthetic water-based coolant. The top nozzle has two apertures, one facing the wheel in a radial direction (1" × 0.075" = 0.075 in.[2]) to scrape off the air barrier and one aiming in a tangential direction to the wheel (1" × 0.078" = 0.078 in.[2]) for process cooling. The lower nozzle (0.7" × 0.077" = 0.054 in.[2]) fires a jet under the cam to quench the grinding energy after the cam passes through the grinding zone. The pressure at each nozzle was 60 psi, with 90 psi at the pump a short distance away, representing a 33 percent drop. At 60 psi, the top tangential nozzle is estimated to supply 18 gpm, the radial nozzle 17 gpm and the lower nozzle 13 gpm.

Schedule 40 pipe (ID, inches)	½	¾	1	1¼	1½	2	2½
Flow rate (gpm)	18	33	54	93	127	209	298

Therefore, a flow rate of 35 gpm was applied to the process and 13 gpm against the wheel rotation, providing a total flow rate of 48 gpm. At 60 psi, the jets from the Landis wedge nozzle would be expected to be dispersed, and they were placed close to the grinding zone to minimize the influence of air entrainment. The radial jet struggled to keep the CBN wheel from loading with hot workpiece material. Typically, vitrified wheels require cleaning nozzles to run at 600 to 800 psi, not 60 psi.

Grinding power was measured using a phase-corrected power meter and data acquisition system, showing that the running wheel power when not grinding was 4 hp, when not grinding plus coolant drag was 7 hp and the instantaneous peak for lobe grinding was 22 hp. Using the superabrasive coolant flow rate model of 1.5 gpm per grinding hp, the 15-hp increase over the running wheel and coolant drag power of 7 hp would imply that at least 23 gpm is necessary for the top nozzle. The combined radial and upper jets of the original nozzle provided just 17 gpm and 18 gpm, respectively.

The redesigned nozzle system shown on the bottom of Figure 2 consisted of a tangential nozzle of 0.95"×0.096" aperture and a high-pressure cleaning nozzle above the tangential nozzle. Mounted on top of the high-pressure nozzle (removed in the photo) is a scraper plate to protect the high-pressure nozzle from external erosion due to chips released from the wheel at high speed. The high-pressure jet also acts as an air barrier scraper to minimize the barrier's influence on the tangential main jet. The tangential nozzle supplies 26 gpm at 110 psi at the pump and 90 psi at the nozzle, representing a pressure drop of 18 percent, but still not matching wheel speed with the jet at 7,000 ft./min. The high-pressure cleaning nozzle was designed to supply 2 gpm over the wheel width, at a pressure of 700 psi. No lower nozzle was fitted.

Using the improved nozzle setup, the manufacturer was able to eliminate FDI inspection, saving $300,000 per

year in labor and consumable costs. The environmental issues of using FDI were also eliminated. The cost of auditing the problem and installing high-pressure pumps for two machines with nozzle and mounting hardware was less than $12,000, providing a 100 percent ROI in 2 weeks.

With more than 60 coolant application installations, coherent-jet nozzles—at optimal flow rate and pressure—can achieve greater throughput, lower wheel wear, reduced dressing and better surface integrity than conventional nozzles. △
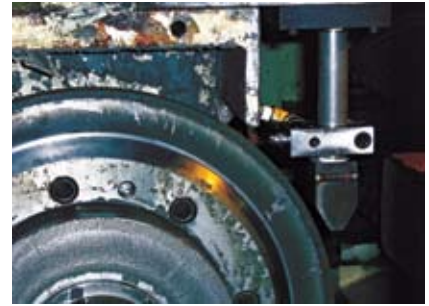

Figure 2: Camshaft profile grinding, original (top) and improved setups.

About the Author
John A. Webster, Ph.D., is a grinding consultant and owner of Cool-Grind Technologies LLC, Storrs, Conn., a turn- *key supplier of coolant application hardware. For more information, call (860) 208-5196, e-mail cool-grind@sbcglob-al.net or visit www.cool-grind.com.*