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Grinding Brittle Materials

By **Thomas R. Shearer**

General Manager, Aggressive Grinding Service, Inc.

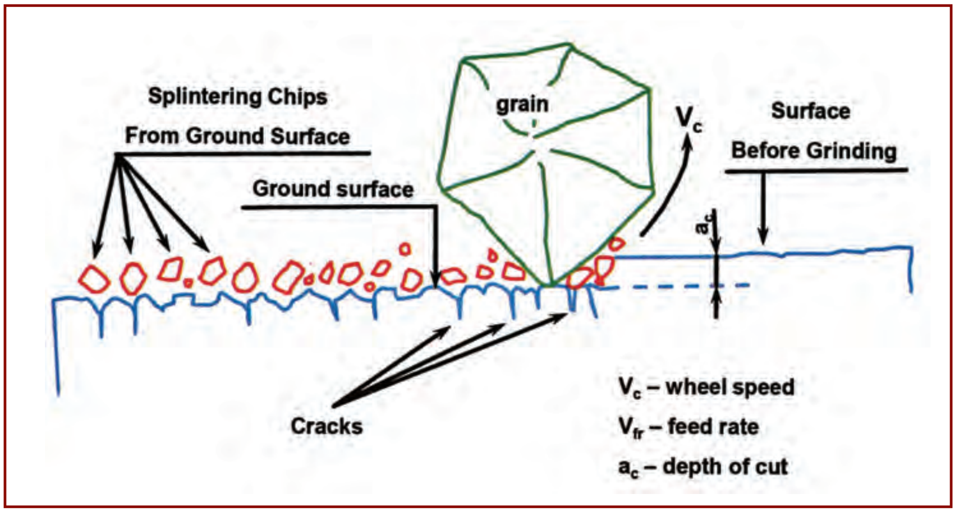


Figure 1. *Material removal mechanism.*

In the industrial world, brittle materials include the range of cemented tungsten carbide grades, the entire family of advanced ceramics—including silicon carbide, silicon nitride, aluminum oxide, zirconia and zirconia-toughened alumina, boron carbide and others—and polycrystalline diamond. From an engineering perspective, a brittle material is one that does not exhibit plastic deformation preceding the initiation of a crack.

When a brittle material needs to be brought to final dimension by hard grinding, it will not exhibit plastic deformation as the diamond grit plows through it to remove material; nor will it exhibit the residual stress profile of a ductile material. Instead, the material will crack, leaving microcracks that remain as subsurface damage. The key to grinding brittle materials is to minimize subsurface damage by following prescribed grinding parameters that will achieve the desired material removal rates and final dimensional accuracy.

Material Removal

Normally, making chips is not considered part of the grinding process, but that is exactly what happens when grinding ductile or brittle materials. In a brittle material, the "chips" are just smaller. The removal mechanism for a brittle material is achieved through micro-fracture and the subsequent removal of the chips by the next passing grain (see Figure 1).

The normal stress distribution profile associated with grinding a ductile material does not apply to grinding a brittle material like an advanced ceramic. Any induced tensile stress, which is usually caused by restricted thermal expansion at high temperatures, has already resulted in microcracking beneath the surface, as in a brittle material (see Figure 2).

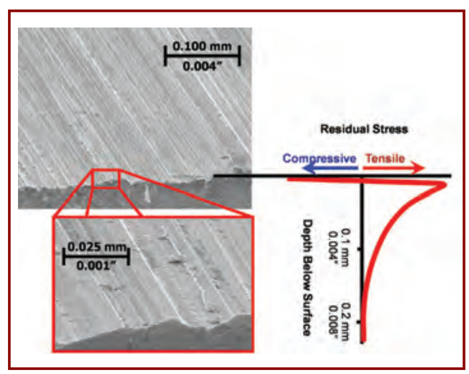


Figure 2. *A brittle material does not follow the ductile material stress profile.*

Grinding Parameters

When using a grinding wheel, the wheel bond, shape of abrasive, grit concentration, depth of cut (DOC) and coolant flow are all important considerations. Making the correct choice for each of these parameters is

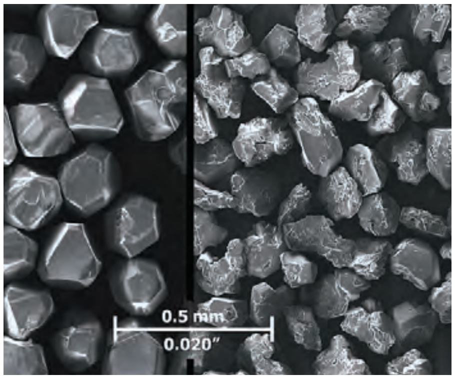


Figure 3. *Blocky (left) vs. angular-shaped grains.*

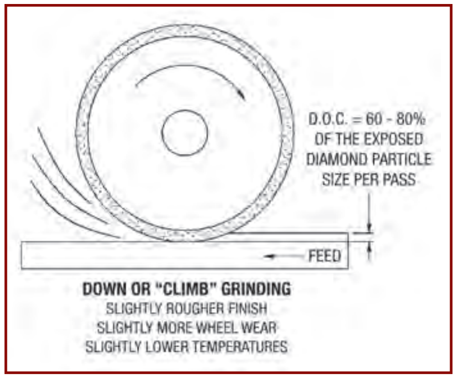


Figure 4. *Schematic of the depth of cut.*

critical when grinding a brittle material. An incorrect choice can result in severe damage to the workpiece, the diamond wheel, or both. Damage to the advanced ceramic workpiece may not be visible to the naked eye but could result in premature failure in operation, as micro-cracks propagate under operational stress.

Wheel Bond

The wheel bond determines the "hardness" or "softness" of a grinding wheel and is indicative of the wheel's ability to retain the abrasive grit. A "softer" wheel generally gives up its hold on the abrasive grains more easily, thereby exposing new grains to the grinding action. In contrast, a "harder" wheel keeps the grains intact longer, thereby exposing more dulled abrasive and greatly affecting cutting ability.

The successful grinding of a brittle material like an advanced ceramic has traditionally consisted of using a resin bond wheel that allows lower tool pressure and provides a finer surface finish. Such a wheel results in the grains being refreshed more frequently and cutting action that causes minimal damage to the sub-surface.

A dulled abrasive grain repeatedly pounding the ceramic encourages even more damage while generating more heat and increasing power consumption. Recent advancements by wheel manufacturers in developing newer, hybrid metal bonds with induced porosity have allowed a harder-bond wheel to act more like a softer-bond wheel with a longer life and equal or better dimensional performance.

Grit Shape and Concentration

The shape of the abrasive grit is usually not a purchasing specification when a grinding house orders a diamond wheel. The wheel manufacturer typically provides a "blocky"-shaped grain or an "angular"-shaped grain based on input from the grinding house about which material is being ground at particular speeds (see Figure 3).

The grinding house specifies bond, diamond grit size and concentration, but it rarely specifies the shape, relying solely on the wheelmaker's decision. Deviating from this common approach and instead specifying an angular shape when grinding advanced ceramics can ensure that minimal subsurface damage occurs. The grain is more likely to fracture and not wear, thus allowing new particles to be exposed and creating a self-sharpening effect that avoids dull or worn grains from causing severe operational damage.

The concentration of grit defines the number of diamond particles in the wheel for a particular grit size. A concentration of 75-100 is common for wheels used in grinding brittle materials. This concentration is ideal for maintaining minimal surface damage and optimal wheel performance.

Table 1 shows the typical concentration number and the equivalent volume percent that the concentration represents. Wheel manufacturers have different concentration recipes for various grit sizes, and concentrations above 100 are commercially available. It is preferable to consult the wheel manufacturer if higher concentrations are desirable.

Table 1. Typical diamond concentration in grinding wheels

Standard Concentration	Typical vol.% of Diamond	Carats (in.^{3})
100	25	72
75	18.75	54
50	12.5	36
25	6.25	18

Table 2. Grit size of diamond particles.

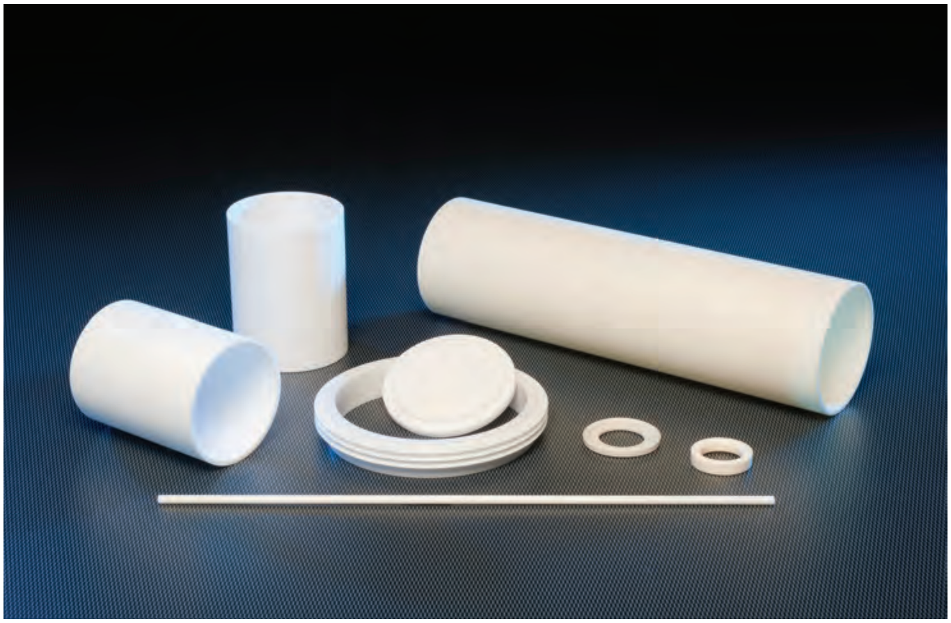
Grit Size	Microns	Inches	Expected Surface Finish (RA)
80	267	0.0105	24-36
150	122	0.0048	14-16
180	86	0.0034	12-14
220	66	0.0026	10-12
320	32	0.0012	8
400	23	0.0009	7-8
600	14	0.0006	2-4
1,200	3	0.0001	1-2

Depth of Cut

The coarser (larger) the diamond grit size in a wheel is, the more the exposed grains protrude from the wheel. The depth of cut of the wheel should be equal to approximately 60-80% of the height of the exposed grain (see Figure 4).

If the wheel is fed into the material that features a DOC equal to the height of the exposed grain, then considerable heat will be generated and the likelihood of greater sub-surface damage will result. In addition, optimum coolant flow to the grinding interface will be compromised due to collapse of the space between the wheel and the workpiece material. A DOC that is greater than the height of the exposed grains generates excessive heat. That condition will result in damage to the material or wheel.

Table 2 shows grit size in microns and inches, as well as the expected surface finish that a particular grit size should impart. In a properly dressed wheel, at least 35% of an exposed diamond particle should protrude from the bond surface. Therefore, based on data in Table 2, a 220-grit diamond wheel that has a typical grain size of 66 microns (0.0026 in.) should have 35% of the height exposed, or 23 microns (0.0009 in.). The DOC should then be 60-80% of the exposed grit height, or approximately 15 microns (0.0006 in.).



Coolant Flow

The purpose of coolant is to dissipate heat from the workpiece by lubricating the workpiece-wheel interface so less friction builds up, resulting in less generated heat. Coolant also helps to reduce wheel wear and improve surface finish, as well as flush away chips and minimize subsurface damage. Conventional wisdom has maintained that a higher coolant flow rate results in better heat dissipation.

In fact, better heat dissipation results from flow velocity, not rate. Therefore, boosting coolant velocity to match wheel velocity is necessary for allowing the coolant to be carried to the grinding interface by the pores in the wheel. Ideally, coolant velocity should match 80-110% of wheel velocity:

$$V_{coolant} = (80 \text{ to } 110\%) \times V_{wheel}$$

This ratio can be achieved by the pressure of the pump and total nozzle area in use, assuming the pump can supply the gallons per minute flow needed to achieve the required velocity. It has been said that, if it were possible to perform a totally submersed grinding operation, a high-velocity flow would still be better at conducting away heat from the grinding interface.

Minimize Damage

Following known grinding parameters can minimize the effect of subsurface damage in a brittle material. An experienced grinder can deviate from some of these parameters, but must use caution in doing so. Such care is necessary because a brittle material shows no forgiveness when grinding stresses exceed the strength of the material: cracks will occur. The severity of such cracks, however, can be limited only by using proper grinding techniques.

References

1. Photos and illustrations used with permission from The Grinding Doc, Jeffrey A. Badger, Ph.D., expert in grinding, independent consultant, Austin, Texas, "The Book of Grinding" and "A Pictorial Odyssey, Parts I and II," Cutting Tool Engineering.
2. Shearer, Thomas R., "Diamond Wheel Grinding 101," Ceramic Industry magazine, June 2006, pp. 17-20.

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Aggressive Grinding Service, Inc.
4413 Route 982 South
Latrobe, PA 15650
P: 724-537-7722
F: 724-537-3893
E: customerservice@ags-fast.com

AggressiveGrinding.com