Maximizing the Grinding Process

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Abstract

This paper discusses conventional abrasives and superabrasives, reviewing both abrasive categories, emphasizing the approach for maximizing the grinding process for use of cubic boron nitride (CBN) abrasives. Abrasive selection and the reason for the selection will also be discussed along with a review of various grinding processes. Among them conventional, creep feed HEDG and "Peel" grinding. The paper discusses what is needed to maximize grinding efficiency such as, machine rigidity, spindle integrity, power considerations, balance parameters, wheel dressing, and coolant concerns.

Included will be a model for using CBN in an O.D. cylindrical application. The model will include projected stock removal rates, dressing intervals anticipated wheel life, and projected wheel cost per part.

Part Material & Tolerances

The part material and the tolerances assigned to parts are important criteria, influencing the decision of all the parameters relative to the grinding process. In fact many times when considering the cylindrical process the part, its hardness and tolerances can be the difference between making a decision to grind or "hard turn".

The type of material, hardness, and the physical tolerances required including concerns for fatigue failure are paramount in deciding what type of abrasives to consider. For example:

- A ceramic material with close dimensional tolerances demands a very stiff grinding system and the selection of a diamond abrasive.
- A soft steel part without consideration for fatigue or extremely tight physical tolerance would give consideration for using aluminum oxide.
- Various ferrous parts with close dimensional tolerances and concern for residual tensile stresses would demand a very stiff grinding system and the use of CBN.

Abrasive Selection

Table 1

Property Comparison Table			
Material Type	**Metallurgical Composition**	**Thermal Conductivity (W/m °K)**	**Hardness Knoop (kg/mm^2)**
Carbon Steel	0.05% C	54	1000
Aluminum Oxide	Al_2O_3*	29	1400 - 2100
Silicon Carbide	SI,C	400	2700
CBN (cubic boron nitride)	B,N	1300	4500
Diamond	C	2000	8000

* Aluminum Oxide, made from bauxite, can have a make up of various additional oxides

Table 2

Abrasive Material Selection Table		
Abrasive Type	**Ferrous Materials**	**Non-Ferrous Materials**
Aluminum Oxide	√	
Silicon Carbide		√
CBN (cubic boron nitride)	√	
Diamond		√

After reviewing table 1 (property comparison table) you would assume that diamond would be the choice for all grinding. However, diamond as well as silicon carbide has a chemical affinity with steels. Reason, diamond when exposed to temperatures of more than 1500 degrees Fahrenheit (815°C) will revert to the carbon state. We know from using thermocouples, that in the grinding zone, the temperature will reach in excess of 1800 degrees Fahrenheit (982°C) regardless of how much coolant is applied. When this occurs, even for a brief moment, the steel will accept the carbon from the diamond.

Cubic boron nitride (CBN) is manufactured from combining the elements of boron and nitrogen (<u>Note</u>: both elements are next to carbon on the periodic table of element). CBN does not revert to its basic elements until reaching approximately 2500 degrees Fahrenheit (1371°C). Even if those temperatures were reached, the boron and nitrogen are chemically inert. The steel and the CBN do not share any chemical affinity.

The major surface integrity problems associated with grinding include tensile residual stress, untempered martensite, overtempered martensite and cracks. The thermal properties of the abrasive have been found directly related to the fatigue life of ground surfaces. Grinding with aluminum oxide abrasives means minimizing the stock removal rate, to avoid potential surface and sub-surface damage from heat generated during grinding. Even with "Low Stress" grinding the conventional abrasives will not impart the compressive residual stress that is found when grinding with CBN.

Note: Low Stress grinding is a process where the grinding wheel is a friable abrasive such as a white aluminum oxide and very soft (normally less than a "G" hardness). Many times the porosity is extremely open (on a scale of greater than 13 using a common structure where 7 is a standard structure or porosity and 10 or greater is an open structure).

Table 2 shows that the choice for grinding ferrous material would be aluminum oxide or CBN and for non-ferrous material silicon carbide or diamond.

Machine Rigidity

Rigidity of the grinder, the wheel spindle, centers, and dresser will be the mirror image of the part geometry you will receive when using CBN or diamond. Fracturing of the abrasive is continually influencing conventional abrasives, aluminum oxide and silicon carbide. This coupled with the dressing process can camouflaging the true machine rigidity or the lack thereof when using a conventional abrasive.

Superabrasives (CBN or diamond) are rigid (hard) and last a long time between dressings. This makes the wheel using these superabrasives an intricate part of the grinding systems.

To obtain the tight tolerances demanded in today's environment, grinding machine manufacturers are utilizing ball screws and servos, hydrostatic, hybrid hydrostatic spindles along with air bearings and ceramic bearings. The demand is only getting tighter. As of this writing I have requests for grinding in angstroms (Å = 10^{-10} meter or, 0.0039 micro inch) before "kiss" lapping. With process controls demanding "six-sigma" the demand for tighter tolerances will only get more demanding.

Spindle Integrity (Balance & Run-Out)

Balance and run-out of the grinding wheel are mechanical properties that must be addressed at the time of each grinding wheel mounting. Regardless of the overall rigidity of the machine, surface finish and grinding performance will not be maximized if the grinding wheel is not running true and is not dynamically balanced. Static balancing will not cut it! Balancing the wheel should always be performed on the wheel spindle using a dynamic balancer. The balance can be either portable or permanent. To achieve consistency of balance throughout the life of the wheel, a permanent balancer is paramount. In other words if you are trying to achieve a specific Cpk this is one less concern for understanding and controlling process.

I would always recommend ordering any grinder with a permanent dynamic balancer as part of the purchase. This can be an O.E.M purchase or a third party purchases. You can retrofit existing machines with a permanent balancer implanting the unit into existing or fabricated hubs. This will allow for one or two side plane balance, depending on the width of the grinding wheel.

Wheel widths of four inches or more should be balanced from both sides using a two-plane balancer.

For truing, the wheel should be mounted and trued to within 0.0005" to 0.001" (0.0127 - 0.0254mm). ***Sometimes the O.D. to I.D. tolerance of the wheel will not allow the wheel to be trued to the recommended levels. This will mean more dressing after the truing process is maximized***. Truing is accomplished by finding the high spot on the wheel with an indicator. Then using a soft mallet and/or a piece of wood tap on the wheel at the marked high spot (marking the position with a marker on the body of the wheel just behind the high position on the indicator), until the indicator is at zero. Repeat this process until you can hold the indicator to < 0.001" (0.0254mm) around the periphery of the grinding wheel.

When you have completed the run-out procedure and completed the dressing procedure, the wheel is ready for balancing. With a good bearings and mass the balance should be ≤ 0.2μ meter displacement. The smaller the displacement the more the part will mirror the geometric tolerance capabilities of the grinder and the better the surface finish. Chatter created from imbalance cannot be dressed out of the wheel face. The limit of the balance will depend on the balancer but, more important, on the limitations of the spindle bearing.

Grinding Wheel Truing & Dressing

Upon completion of the mechanical truing process (run-out), a brake truing device, single point diamond dresser, diamond nib, metal bonded wheel or, rotary diamond dresser will be used to complete the truing process for all bonds except plated. Using one of the aforementioned devices the wheel should be trued until a reading on the indicator of ≤ 0.0002" (0.005mm) has been achieved. The abrasive and the bond type are the most important criteria for deciding the type of truing and/or dressing system to use. For truing only with a point contact such as a single point or specific radius rotary dresser I would never recommend in-feeds of more than 0.0004" (0.010mm) per pass for Superabrasives (CBN or Diamond) or, more than 0.00075" (0.019mm) per pass for conventional abrasives.

Conventional abrasives (aluminum oxide and silicon carbide) can be trued and dressed at the same time, using a single point dresser. The conventional abrasive is quite friable (friability = ease by which an abrasive fractures). This means a quality diamond with a carat size appropriate for the diameter of the wheel its thickness and abrasive grain size. ***Note: Among other options, an alternative to a single point is the "rod diamond", utilizing a man made diamond in the shape of a rod. This is not a PCD (polycrystalline diamond) but a grown diamond.***

Dressing involves the same aforementioned tools as discussed for truing, with the exception of the "brake truing device" and, for dressing resin and metal bonds used with Superabrasives would include but not limited to "the abrasive stick" (typical size ¾" x ¾" x4"). The purpose is to open the wheel face and prepare the grinding wheel surface for achieving both dimensional tolerances demanded by the part geometry and establish a specific finish requirement on the part surface. For dressing I would never recommend in-feeds of more than 0.0001" (0.0025mm) per pass for Superabrasives (CBN or Diamond) or, more than 0.0005" (0.0127mm) per pass for conventional abrasives.

The process for truing and dressing vitrified CBN is very similar to that of conventional abrasives with the exception of in-feed per pass. The plated process (used in Superabrasives) is not a viable option for truing and vitrified diamond is only different in that single point dressing is not applicable and the wheel to roll ratio for the rotary dressing systems is different (> 5:1 roll to wheel). Truing and dressing will also be covered in the following section for bond types.

Plated (CBN & Diamond)

The plated process means only one layer of abrasive. This minimizes the option for truing and dressing (although cleaning can be accomplished, which is similar in some respects to dressing). The inside diameter of the wheel (the hole) must be a very tight fit to the spindle. The relationship of outside diameter to inside diameter must be close. The objective is to minimize the break in time (the amount of time needed to have contact with all the abrasive grains on the periphery of the wheel). However, when not all the abrasive is cutting the stresses on the individual abrasive particles, (those particles that have been doing the cutting) are greatly increased and shortly flats occur increasing the grinding forces and limiting the life of the wheel.

The only time I would recommend the plated process is when the form on the part is so severe as to make any other bond process cost prohibited.

Resin and Metal Bonds

Resin and Metal bonds are closed structure systems and unless outside agents (such as glass spheres) are added, no controlled porosity (chip clearance) can be expected. Because of the lack of porosity and free exposure around the abrasive grains, a two-step process is needed for truing and dressing. With resin you can true the wheel with either a rotary diamond of a silicon carbide brake-truing device. The same is true of Metal bond however for using the rotary diamond special concern must be placed on wheel to roll ratios.

The reason for dressing is to open the wheel and expose a percentage of the abrasive grain to allow for free cutting and chip clearance. The tool of choice is a soft bonded vitrified dressing stick made of friable aluminum oxide or silicon carbide and of a grit size smaller than the CBN or diamond abrasive being dressed. To open the wheel, the stick is first soaked in coolant (to reduce abrasive dust) and then forced into the wheel face. The resistance will be reduced as the bond is eroded and the abrasive is exposed. The best process is to a use a given cubic inch or cubic mm of stick per area of wheel per dress. Although there are studies regarding ratio the going practice is to measure the amount of stick used when you feel no more resistance between the wheel and the stick. This process can be done either by hand or with a mechanical feed into a stationary mounted stick. With the mechanical system (much safer to the operator) the feed must be based on cubic inch or cubic mm.

Vitrified Bonds

In the world of vitrified bonds there are really three distinct types of bonds, sintered bonds, high temperature bonds, and low temperature bonds. The development of inert atmosphere low temperature bonds has allowed the use of vitrified CBN and diamond increase dramatically. As of this writing there are many suppliers that use bond temperatures that are too high for diamond and can cause damage to the CBN grain. When you have a good low temperature system, the manufacturer will be able to supply open structure diamond as well as CBN.

This vitrified bond system for superabrasives is like using a conventional vitrified wheel and substituting the conventional abrasive with CBN and or diamond. The open structure and controlled porosity allows for the grinding of even long chip material such as, inconel 718 in a soft state, as well as fine chip materials like cast iron. Normally hard materials are of the most applicable for using CBN (materials like CPM10V, M4, T15, 8620, etc.). However today, thinking of CBN for only hardened steels is very old school.

This bond is very flexible and can be dressed, depending on the wheel size, with either a single point, rotary single radius diamond (prefer 0.020" Radius), rotary form dresser or, metal bonded diamond wheel approximately 0.060" (1.5mm) wide. If a cup dresser were used, best results would have the cup rim address the wheel at a 35 to 45 degree angle to the wheel face. In-feed of point contact dressing should be less than 0.0001 per pass (0.0025mm). The traverse rate for point contact dressing will vary but a good starting point would be 0.004" (0.1mm) per rotation of wheel. The traverse rate of the dresser using a point contact on CBN only (not diamond) will create the desired surface finish on the part. The faster the dress rate the higher the obtained finish and conversely the slower the dress traverse rate the finer the surface finish.

To maximize the life of the wheel by minimizing the amount dressed on each dressing cycle, an acoustic sensor can be mounted on the dresser or on the spindle body. This system works by picking up the sound through the coolant, as the diamond dresser gets closer to the wheel. Integrated into the machine control system, the acoustic emission creates a footprint of the wheel face and will stop the dressing process when the wheel is in contact with the dresser across the entire wheel face. This minimizes the amount dressed off the wheel and eliminates operator error.

Although the truing and dressing is accomplished in the same operation utilizing vitrified CBN, studies show that the abrasive stick can be utilized to minimize a break-in period known as reaching "steady state". This is not needed often but is still an option in the arsenal of controlling process.

Truing and dressing are critical for the success of vitrified CBN. The in-feed per pass and traverse of the dress are critical for maintaining process control. The operator should never be allowed to make changes without documentation. Also, rigidity of the dresser should not be overlooked; the dresser can pass along inherent weaknesses of its spindle system and imbalance to the wheel face. I cannot emphasize enough the importance dressing has in the success of CBN grinding.

Coolant

The type of coolant and its concentration depends on the material, abrasive, and grinding process. For example, when grinding with diamond and or conventional abrasives the need for lubricity is not as critical (exceptions do exist) as it is when grinding with CBN. Using CBN, I have ground with straight sulfur chlorinated oil and with water soluble oil as low as 3 percent concentration, experiencing little difference in cutting ability. Regarding synthetics, my experience has not been very successful with CBN but, quite acceptable for conventional and diamond application. The decision on coolant type should be made using a coolant expert as a team member, reviewing your process and options.

Coolant flow, coolant pressure, tank size, and filtration are among the most important issues regarding optimization of your grinding system. First, the coolant flow should, in almost all cases, exceed the velocity of the wheel. This can be accomplished with knowing the actual GPM (gallons per minute) at the nozzle exit and designing the nozzle with an opening that will allow the flow velocity of the coolant to equal the velocity of the wheel. The GPM is calculated based on the "P" line or contact width of the wheel to work. The pressure needed is calculated by the velocity of the grinding wheel.

Streamlining the pluming and installing the correct pump designed for the proper line pressure will assure this flow. The nozzle should be designed with a laminar nose to direct the flow in a straight line between the wheel and work piece. This will reduce the amount of misting and create a “fluid horsepower” allowing you to increase stock removal without burning. The nozzle opening is sometimes as small as 0.040” (1mm) and will need good filtration on the coolant return to maintain particle distribution small enough not to disrupt the flow of the coolant from the nozzle.

The tank size will need to be at least 10 times the GPM. This allows enough time for the coolant to circulate and reach room temperature. If oil is used sometimes a chiller will be needed. Temperature variations can cause inconsistencies in part geometry due to thermal properties of the material being ground.

High pressure is a relative term but is not the term that should be used for this process. Rather the amount of pressure needed to meet or exceed the velocity of the wheel. For the most part pressures for grinding are less than 200 PSI (again depending on the velocity of the wheel). For high velocity grinding such as wheel velocities greater than 20,000 SFPM (100M/sec.) the needed pressure is much higher. However, if a scrubber is needed then high pressure (greater than 800 PSI) is utilized. The scrubber would be utilized for long chip material that would have a tendency to attach to the abrasive particles or get caught in the pores of the wheel. Using the high pressure scrubber (GPM is quite low) will keep the wheel clean.

What is accomplished with all of this is increased wheel life, better finishes, decreased cycle times and better control of your processes.

Conventional Grinding Vs Creep Feed and HEDG Grinding

Following is a chart that gives you and overview relative to surface grinding and a comparison of the various processes:

	Pendulum Grinding	**Creep Feed Grinding**	**HEDG Grinding**
Depth of Cut	Low 0.0004 - 0.02 inch (0.01 - 0.5 mm)	High 0.04 - 1.2 inch (0.1 - 30 mm)	High 0.04 - 1.2 inch (0.1 - 30 mm)
Work Speed	High 40 - 1200 in/min. (1 - 30 m/min.)	Low 2 - 20 in/min (0.05 - 0.5 m/min.)	High 20 - 400 in/min (0.5 - 10 m/min.)
Wheel Speed	Low 4000 - 6000 SFPM (20 - 30 m/s)	Low 4000 - 6000 SFPM (20 - 30 m/s)	High 20,000 - 40,000 SFPM (100 - 200 m/s)
Stock Removal Rate	Low 0.01 - 1 in^3/in•min. 0.25 – 10.7 mm3/mm•sec.	Low 0.01 - 1 in^3/in•min. 0.25 – 10.7 mm3/mm•sec.	High 5 +in^3/in•min. 53 + mm3/mm•sec.

In cylindrical grinding the new process being utilized is "Peel" grinding. The process utilizes point-to-point traverse. The new process utilizes high wheel velocity (greater than 20,000 SFPM (100M/sec.) and high work velocities. The traverse is like turning and a common rate is 0.012" (0.3mm) per rotation of the work. The wheel is thin compared to most wheel utilizing the more conventional plunge grinding process with a lead angle for grinding and a flat which acts like a wiper. The "Peel" grinding process allows one wheel to be used for a wide range of part geometry's and stock removal plays less of part in the cycle time.

Normal grinding regardless of application, works on a process that you can only in-feed a relative percentage of the abrasive diameter per down feed (in-feed for cylindrical) of the wheel or rotation of the part. Even in creep feed you are removing with a similar stock removal rate per minute. But, with HEDG and "Peel" grinding you pass the boundary of mechanical interpretation and into a New World of a form of plasticity. This is not a small leap in wheel speeds but a major jump. In surface grinding you are going from 6,000 to a minimum of 20,000 SFPM (100M/sec.).

Present problems are limitations of the wheel manufacturer for developing product that will not burst at those speeds. For example the highest speed I am aware of utilizing vitrified CBN is on a graphite/epoxy core and can only be rated at 40,000 SFPM. Most companies in this country (United States) have a maximum velocity capability of 30,000 SFPM (assuming they are testing each wheel on a speed tester at 1.5 times the recommended operating speed).

I am confident that in the future this process will gain acceptance and the present problems will be worked out. The stock removal rates are so great this will open even more doors for what is being called abrasive machining. The competition between conventional cutting tools and the abrasive cutting tools continues to battle. The only winner will be the productivity of the user.

Recommended Operating Parameters

I have included work sheets entitled "vitrified CBN evaluation for cylindrical grinding" and "cylindrical grinding field evaluation". This is CBN cylindrical model for your review. Calculations for these models are assuming proper coolant flow, a rigid grinder, rigid dressing system and a dynamic balanced wheel. I have calculated certain operating parameters, projected dressing cycles, and wheel life assuming the following:

1. Part diameter of 2.5" (0.1mm)
2. Wheel contact of 2" (50.8mm)
3. Stock removal of 0.015" (0.38mm) on the diameter
4. Wheel velocity of 10,000 SFPM (52m/s)
5. Work velocity of 100 SFPM (0.5m/s)
6. Grinding one part per diameter
7. Roughing in-feed removing 90% of stock or 0.013 (0.33mm) on diameter
8. Finish in-feed removing 10% of stock or 0.002 (0.05mm) on diameter
9. CBN layer 1/8" (~3mm)
10. Redressing will occur when surface finish reaches 18 Ra (0.45 μ)

Conservative projections based on the above parameters are as follows:

- Rouging in-feed at 0.060" (1.5mm)/min. = 6.5 seconds
- Finish in-feed at 0.030" (0.76mm)/min. =4 seconds
- Dwell time (spark-out) = 2 seconds
- Total grind time = 12.5 seconds
- Number of parts per dress = 400
- Number of parts per wheel = 125,000

Summary

CBN and diamond are growing as abrasives of choice for all forms of manufacturing. The flexibility of vitrified bonds is the catalyst behind this rapid market growth and acceptance. New process like HEDG and “Peel” grinding is on the horizon. Customers are demanding higher stock removal rates, closer tolerances, higher cpk and sigma, and finer surface finishes. The demand will be for more rigid grinders, with controlled parameters. The following are things to consider and incorporate in your decision for purchasing grinders and/or updating your present grinders:

1. Rigid and heavy duty grinders with plenty of Horse Power (Kw)
2. Dynamic wheel balancing equipment
3. Rigid dressing systems
4. Coolant type, coolant flow and pressure equal to the needs of your application, nozzle design, pluming, filtration
5. Closed systems with processes dictated by CNC control
6. Decision on what grinding process best meets your needs relative to you parts and production
7. Turn-key process with consideration to automation, robotics and keeping the operator out of the decision loop.
8. Consider new grinding concepts integrated with other disciplines such as hard turning, micro-finishing, conventional abrasives and superabrasives in one small foot print that gives flexibility to your process.

VITRIFIED CBN EVALUATION FOR CYLINDRICAL GRINDING

Distributor: | **Date:**
Customer: | **Machine**
Application: O.D. Grinding

<u>Parameters</u>

Part Diameter Before Grinding:	2.5 **Inches**	0.118 **In^3 material per part**
Stock Removal /diameter:	0.015 **Inches**	
Wheel Diameter:	16 **Inches**	
Wheel RPM:	2400	10,053 **S.F.P.M,.**
Work RPM:	154	101 **S.F.P.M.**
Vs/VW:	100	
Abrasive Size:	80	0.0075 **Inch Diameter**
(80, 140, 170, 230, 270, 325, 400)		
Stock Removal Rate:	0.5 **In^3/in•min ($5.35mm^3$/mm•sec.)**	

Projections:

In-feed Rate (vf):	0.064 **In./Min**
Grinding Cycle Time:	7 **Seconds/width of wheel contact (plunge grinding)**
% Of Abrasive Diam./ROW:	6% **Percent**
Estimated Pcs./Dress:	400 **Per wheel to work contact**

<u>Input Parameters:</u>

<u>Stock Removal Rates:</u>

O.D. Cylindrical Grinding: Q' (Q Prime) = .5 In^3/in•min ($5.35mm^3$/mm•sec.) Good starting point

I.D. Cylindrical Grinding: Q' (Q Prime) = 0.2 – 0.3 inch or 2.14 – 3.21 mm

<u>Vs/Vw</u>:

O.D. Cylindrical: 100 Starting point for most O.D. applications
I.D. applications: 25-50 Starting point for most I.D. applications.

Glossary.-of Terms:

Vs: Velocity of the grinding wheel.
Vw: Velocity of the work
ROW: Rotation of work.

Note: For grinding non ferrous material with diamond I would suggest a starting Q' of $0.2in^3$/in•min ($2.14mm^3$/mm•sec.)

CYLINDRICAL GRINDING FIELD EVALUATION

Distributor: **Date:**
Customer: **Machine**
Application: O.D. Grinding

Work-piece Parameters	
Grind Diameter:	2.5
Grind Length:	2
Stock Removal/side:	0.0075
Material:	1050 steel
Hardness:	55-60 Rc

Wheel Parameters	
Diameter(O.D.):	16
Thickness:	2
Hole (I.D.)	5
Abrasive Depth:	0.125
Specification:	CB80-L150-V
Wheel Cost:	$5,225.00

Truing & Dressing		
Dresser Type:	Rotary Dresser	
Dimensions:	4" diameter	
Specification:		
Rotation direction:		
RPM:	7600	
Infeed per dress:	0.0004	
Diamond Contact Width:	0.02	
Traverse [PM:	10	
#Pieces per dress-	400	
Traverse/R.O. Wheel:	**0.0042**	**Inches**
Diamond overlap:		**5 rotations/pass**

Machine Parameters	
Type/Manufacturer:	
Condition:	New
Balance Reading:	0.09μ m
Wheel RPM:	2,400
Wheel SFM:	**10,053**
Work RPM:	154
Vs/Vw**:**	**100**
Plunge Grinding	
Rough Feed (IPM):	0.064
Finish Feed (IPM)'	0.032
Spark-out (Sec.):	2
Traverse Grinding	
Stock removal/pass:	
Rough Feed (IPM):	
Spark-out (#of passes):	
Oscillation	
Stroke length:	
Cycles/sec.:	
Coolant:	
Flow rate (GPM):	**44**
Concentration-	5%
Nozzle Width:	2
Nozzle opening:	**0.040**
% velocity of wheel:	105%

Results:

Surface Finish: <	**18 Ra**	O.D. of used wheel:	**15.75 In.**
Cycle Time:	**9.8 sec.**	Work starting diam:**	**2.515 In.**
Plunge Grinding		Wheel volume:	**12.46 In^3**
Material removal rate (R)	**0.5 In^3/in•min. (Q')**	Vol. of work/wheel:	**14,762 In^3**
Material removal rate (F):	**0.25 In^3/in•min. (Q')**	Estimated "G" ratio:	**1,185:1**
Traverse Grinding		Estimated Pcs./Wheel:	**125,000 pcs.**
Material removal rate (R):	**In^3/Min./in. (Q)**	Wheel cost /part:	**0.0418 dollars**
Material removal rate (F):	**In^3/Min./in. (Q')**	**Work finished diam. for I.D. Grinding	