Abstract

Discussed is an overview of creep feed grinding using conventional and superabrasive wheels that are formed using a crushform process. Discussed is the methodology of the process and its advantages.

Definition of terms

*Creep feed grinding* - A grinding mode characterized by a low table speed, one or at most two passes over the workpiece, often with large infeeds. To be contrasted with oscillating or reciprocating grinding, with shallow infeeds and a large number of passes. Used here as a synonym to deep grinding, deep feed grinding and plunge grinding.

*Crush forming or Crushing* - The process by which specially designed abrasive or superabrasive wheels can be profiled by forcing them against a high-speed steel or carbide roll with the corresponding negative shape.

*Dressing* - In the case of abrasive or superabrasive wheels, dressing effects the rim/edge topography and restores freeness of cut and cutting capability. Dressing generates sharp, protruding grits and chip clearance space.

*Friability* - The tendency of a grit particle to break up into smaller fragments under load, thus generating new sharp cutting edges.

*Superabrasives* - Term referring either to natural or manufactured diamond, or cubic boron nitride CBN. These abrasives are respectively the hardest, and the second hardest abrasives available. CBN would be the choice for any ferrous materials.

*Grinding Ratio*(G-Ratio) - A measure of wheel life defined as the ratio of the volume of workpiece material ground away (V) to the volume of rim (v) used up in the grinding operation, usually formulated as G=V/v
1/ Introduction

Grinding has traditionally been associated with small rates of metal removal, and fine finishing operations. However, grinding can also be used for large-scale metal removal operations similar to milling, broaching and planing. Creep-feed grinding was developed in the late 1950's.

Creep feed grinding is actually a milling process, using the grinding wheel for the milling cutter. Traditionally in milling operations, you take very slow "creep" feeds. In conventional surface grinding, the table reciprocates back and forth many times, like a pendulum, taking very, very small depths of cut per pass. In creep feed grinding, the table doesn't reciprocate. It slowly feeds across the workpiece to remove a very large amount of stock. Properly applied, this technique promises increased productivity and improved part quality.

A creep feed grinding operation, for example, could replace a number of milling and broaching operations. Apart from the improvement in workpiece quality, the abrasive machining process will offset the cost of capital equipment, consumable tools, resharpening, inspection and inventory of cutters, fixture cost, tool changeover and part handling times, and post-process deburring/finishing operations.

2/ Process Characteristics

In contrast with conventional grinding, the depth of cut, a, per pass or revolution is increased a thousand to ten thousand times, and the work speed, Vw, is decreased in the same proportion. Thus it is possible to grind profiles with a depth of 1.0 to 30.0mm (0.04 to 1.2in) or more in one pass, using workspeeds from 0.75 to 0.025 m/min (30 to 1 imp), and reducing machining times 50 to 80%. See Figure 1.

Compared with conventional grinding processes at the same metal removal rates, deep or creep feed grinding operations are characterized by these technological features:

- Increased total grinding forces
- Reduced average force per individual grit element
- Increased temperature in the wheel-work contact interface
- Reduced temperatures in the newly generated work surface
- Burr-free surfaces
- Superior surface finishes
- Good repeatability
The wheels are mostly friable (softer grade resin bonded with open structure) to keep temperatures low and improve surface finish. Conventionally the abrasive wheel would be formed containing either aluminum oxide or silicon carbide. However, with the introduction of improved crushing techniques, metal and vitrified bonded wheels containing superabrasives (either diamond or cubic boron nitride CBN) have led to significant savings when grinding tungsten carbide and hardened high speed steel. The attraction of the superabrasive wheel thus lies in its abrasive sharpness and hardness (see Table 1) giving it the ability to maintain an accurate form for long periods.

Table 1

<table>
<thead>
<tr>
<th>Abrasives for Grinding</th>
<th>Hardened Steel</th>
<th>Cemented Tungsten Carbide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum Oxide</td>
<td>Cubic Boron Nitride</td>
</tr>
<tr>
<td>Knoop Hardness</td>
<td>1800-2110</td>
<td>4700</td>
</tr>
</tbody>
</table>
Grinders with capabilities for continuously dressing the grinding wheel with crushable rollers are available. The machines used for creep-feed grinding have special features, such as high power, up to 225 kW (300 hp), high stiffness (because of the high forces due to the depth of material removed), high damping capacity, variable and well controlled spindle and work table speeds, and ample capacity for grinding fluids. For typical ranges of speeds and feeds of various abrasive processes, see Table 2.

<table>
<thead>
<tr>
<th>Process variable</th>
<th>Conventional Grinding</th>
<th>Creep-Feed Grinding</th>
<th>Buffing</th>
<th>Polishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel Speed (m/min)</td>
<td>1500-3000</td>
<td>1500-3000</td>
<td>1800-3600</td>
<td>1500-2400</td>
</tr>
<tr>
<td>Work Speed (m/min)</td>
<td>10-60</td>
<td>0.1-1</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Feed (mm/pass)</td>
<td>0.01 - 0.05</td>
<td>1 - 6</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

3/ Advantages of Creep Feed Grinding

The principal advantages of creep feed grinding are:
- High material removal rate, therefore increased productivity.
- Reduced grinding wheel cost due to less wheel wear and fewer number of dressing operations required.
- High dimensional precision and surface integrity.
- Excellent surface quality. Surface quality can be shown to be practically independent of grit size. (Metzger, 1982b)
- Fully hardened parts can be creep-feed ground from solid - thus, in many cases eliminating the need for straightening operations required prior to conventional reciprocating grinding after milling and heat treatment.
- Eliminates costly first operations such as milling, broaching or turning. The form or slot can be creep feed ground to full depth from a solid.
- More parts processed per wheel life due to less wheel breakdown when compared to reciprocating grinding.
4/ Prerequisites of Creep Feed Grinding

Creep feed grinding only makes sense if a number of conditions are fulfilled. For example:

- Must have a stable, rigidly built machine in good mechanical condition (stiffness values in the range of 10-50 N/micron)
- Sufficient spindle power (at least 5 - 10 kW)
- Infinitely variable spindle speed
- Stick-slip free table motion (stepping motor, or even better D.C. drive with pre-stressed spindle) in the range 5 - 1000 mm/min (0.02 - 3.2 sft/min) with favorable damping characteristics
- Efficient cooling setup (ideally abundant flooding of the grinding interface and high pressure cleaning jets on the wheel) with flow rates in the range of 20 - 100 litre/min (5-25 gallons/min). 90% of the spindle power recorded is transformed through friction into heat at the grinding interface, so that a coolant flow of sufficient magnitude should be provided, taking into account the heat capacity of the fluid and allowing for a temperature rise not greater than 5° C approximately. (Ott, 1984)
- Consistent table speed, especially in the lower range
- Integrated dressing devices
- Integrated controlling systems

It should be noted that any attempt trying to retrofit an existing grinder into a deep feed grinder would fail unless all of the above standards are specifically addressed. It would be more cost effective to secure a machine tool that has been specifically designed for creep feed grinding.

5/ Abrasive Selection

Although conventional aluminum oxide wheels can be used for creep feed grinding, a systematic study taking into account labour, capital and wheel costs must be evaluated to determine if a superabrasive wheel is justified. Although they both have their ideal domains of operation, there are characteristics that are not related to the material to be ground, there are significant differences between the two. Most dramatically is the cost difference between the two. Other major differences that can be see is the G-ratio and the machine requirements. See table 3.
Table 3. **Differences between conventional and superabrasive (CBN) grinding wheels**

<table>
<thead>
<tr>
<th>Abrasive</th>
<th>Aluminum Oxide</th>
<th>Cubic Boron Nitride CBN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/ Application domain</td>
<td>Extensive, with variable degrees</td>
<td>Ideal for high speed steels; often suitable for hardened steels and special iron alloys (60 &lt; HRC &lt; 67)</td>
</tr>
<tr>
<td>2/ Surface finish</td>
<td>Can be used to generate rough, fine and superfine finishes</td>
<td>Optimal for rough, high removal, grinding; unsuitable for fine and superfine work</td>
</tr>
<tr>
<td>3/ Characteristics of grinding interface</td>
<td>High temperature and grinding forces due to substantial frictional forces</td>
<td>Low temperature and grinding forces; chip generation through cutting by grit edge</td>
</tr>
<tr>
<td>4/ Wheel lifetime</td>
<td>Very limited in spite of size and weight; low G-ratio (1&lt;G&lt;10)</td>
<td>G-ratio can be very high (larger than 1000), but depends on actual operating conditions</td>
</tr>
<tr>
<td>5/ Precision grinding</td>
<td>Narrow tolerances are difficult to achieve, without reprofiling or feed correction</td>
<td>Owing to minimal wear, excellent precision can be achieved; ideal for CNC machines</td>
</tr>
<tr>
<td>6/ Coolant</td>
<td>No specific requirements</td>
<td>Best: straight oil; good: dry; fair: sulphochlorinated oil emulsion; useable: water + anti-rust additive</td>
</tr>
<tr>
<td>7/ Profile grinding</td>
<td>Limited profile stability, but easy and quick reprofiling possible</td>
<td>High profile stability, but difficult to reprofile after use unless using specifically designed machine with crushing roll, or single point diamond, CNC controlled</td>
</tr>
<tr>
<td>8/ Wheel preparation</td>
<td>Straightforward truing and dressing</td>
<td>Any truing operation must necessarily be backed up by a dressing operation</td>
</tr>
<tr>
<td>9/ Machines required</td>
<td>Any machine will do; machine defects can be accommodated by choosing a softer wheel</td>
<td>Only stable, rigid machines with sufficient spindle power will do; specially designed machines will perform the best</td>
</tr>
<tr>
<td>10/ Operator's skills and qualifications</td>
<td>Need not be very extensive</td>
<td>Caution, precision and finesse are advisable. Experienced operators definitely a plus.</td>
</tr>
<tr>
<td>11/ Bulk price of abrasive</td>
<td>Less than one dollar per pound</td>
<td>Depending on grit type from $ 4,500 to $ 9,000 per pound; $2 to $4 per carat</td>
</tr>
</tbody>
</table>

6/ **Form Dressing of Wheels**

For a number of years now, conventional abrasive wheels have been shaped using the crushform method, as opposed to dressing using a single point diamond tool. This method is typically used when grinding less difficult hardened steels. However, when the workpiece material being ground is extremely hard, the number of components ground between crushings becomes small so reducing the production rate and increasing costs.
7/ Crushing Principle

The principle of wheel crushing is based on the fact that if the abrasive wheel speed and the crushing roll are less than 100 rpm, then the bond that holds the abrasive particles in the wheel acts extremely soft. (Barnard, 1985) There are two types of bonds used today, they are; metal bonds and vitrified bonds. Metal bonds are typically comprised of high-tin bronzes. To make them more friable, they have introduced soft fillers or porosity into the bond. This leads to the ease of crushing and also facilitates the removal of crushing and grinding debris. Vitrified bonds are naturally brittle and therefore highly suited to the crushing operation.

At low speed, when the crush roll is brought into contact with the abrasive wheel, and due to the fact the bond "acts" soft, the abrasive particles will break down microscopically to conform to the shape of the crush roll. Either the crush roll can be driven or the abrasive wheel can be driven, but it is important that the speed be slow and consistent. It is also important that all fractured bond material be removed directly after crushing, but before entering the crush roll again, so as to keep the wheel clean. This also leads to the crushing of finer radii and profiles to the abrasive wheel. To assist in the cleaning process, it is recommended that a high-pressure coolant jet be directed towards the abrasive wheel to clean away any debris before the wheel face re-enters the crushing roll.

See figure 2 for the standard setup of a crushform dresser.

Figure 2.
Figure 4. Typical crush roll design
- The crush roll can be of almost any shape desired.
- The crush roll should be larger in size than the wheel so that all edges of the wheel will be modified by the crush roll.

Figure 5. Typical relationship between crush roll and workpiece
- It should be noted that the wheel must fully encompass the profile of the final workpiece shape.
- Also, the crush roll must be larger than the maximum width of the wheel.

7.1/ Setting up for crushing
To enable the wheel to be successfully crushed, it is necessary for the following procedure to be adopted: (Barnard, 1985)

a) Mount the wheel on the wheel arbor and carry out a static balance.
b) Position the crushform drive unit on the machine table and by the use of dial indicators, accurately locate the unit so that the crush roll shaft is parallel to the wheel spindle within 0.05mm (0.0002") MAXIMUM. Secure the unit to the machine table.
c) Locate the crushform brush unit.
d) Position the coolant pipes to provide adequate supply each side of the roll and also to give a high pressure jet above the wheel. Select a machine with an output of approx. 27 litres/min (7 US gallons/min). this should provide for adequate cleaning.
e) Slide the crush roll onto the drive unit shaft and fit this into the location blocks and secure.
f) Position the wheel so that its impregnation is within the form being crushed (see figure 4). To enable the machine operator to position the wheel more accurately, a microscope with a 10 to 1
magnification can be mounted in line with the wheel. When re-crushing, this is particularly useful as it avoids over-crushing of the wheel thereby reducing associated costs of early wheel replacement.

g) Start up the wheel and bring the brush into contact with the uncrushed wheel. The brush unit pressure to be set at 1 bar (14.7 lbs/in^2). Allow the brush to be ground evenly across its width for 30 sec., then pull the brush away from the wheel.

h) Calculate the roll speed to give a wheel speed during crushing of 0.3 to 1m/sec. (59 SFPM to 197 SFPM). Bring the wheel into contact with the rotating roll and switch on the coolant. Bring the brush unit into contact with the abrasive wheel, set at 1 bar pressure.

i) Feed the wheel into the crush roll at the rate of 0.001mm to 0.002mm/sec. (0.0005 to 0.0001 "/sec.) As the form is created, it will be necessary to increase the brush pressure to 2 bars. On wheels up to 175mm (7") diameter, it will probably be possible to carry out the complete operation without stopping. However, with larger wheels it may be necessary to grind away the sides of the brush.

j) When the full depth has been reached, retract the brush unit and continue to crush for a further 0.05mm (0.002")

k) Disengage the wheel from the crush roll and stop the crushform drive unit. Place a test piece in a vice or fixture and grind at normal wheel speed to determine whether the form is correct. If wear has occurred to the crush roll, then reposition the wheel above the crush roll (repositioning the table accurately). Move the wheel across to a new form and re-position accurately.

l) Repeat from (c) and crush to a new depth of twice the measured error. Following this, the form should be correct and the wheel is now ready for use. No further conditioning of the wheel is necessary.

It should be noted that in reference to item (b), there are specialty machines on the market that eliminate the positioning of the crushform unit because they are a built-in integral part of the machine tool.

8/ Surface Finish

Typical surface finishes using CBN wheels are between 0.3 and 0.4 μM Ra. Typical surface finishes using diamond wheels are a little better, 0.2 to 0.4 μM Ra. (Barnard, 1985)

When grinding with CBN wheels, the surface finish obtained will be visually different than that when using a conventional abrasive wheel. Conventional abrasives break down during the grinding process and produce a burnished surface of low Ra value. This is most often associated with the burning of the surface, which leads to micro-cracks. However, CBN wears in an entirely different way. The abrasive cleaves through one of its six cleavage planes, thereby maintaining a sharp cutting edge.
The grinding process, these cutting edges penetrate the workpiece, producing chips with a burn-free surface. The visual difference is totally different than that one would see produced by a conventional abrasive wheel. In comparison with diamond, which has only four cleave planes, the visual appearance is different again. It is more close to a regular abrasive wheel. So in general, grit size for grit size, a diamond wheel will produce a better surface finish than CBN.

9/ Coolants

In any grinding process, essentially all of the grinding power is dissipated as heat in the grinding zone, at the interface between the workpiece and the wheel. This heat causes the workpiece surface temperature to rise, which may cause thermal damage to the workpiece. Thermal damage is a general term that includes workpiece burn and stresses due to thermal expansion (Lavine and Malkin, 1988).

The heat generated in the grinding zone is removed from that region in a variety of ways:

a) It may conduct downward into the workpiece, where it is carried away (convected) by the motion of the workpiece.
b) It may conduct upward into the wheel or grinding fluid, where it is convected away by the motion of the wheel or fluid.
c) It may be convected away by the chips. This element is not very large due to the total heat within the zone and the small size and heat carrying capacity of each individual chip.

It can be seen that from the point of view of minimizing the grinding zone temperature, it is desirable for the grinding power per unit area of the grinding zone to be small, and the heat transfer coefficients to be large. It should also be noted that as far as the grinding zone temperature is concerned, it makes no difference whether the heat is removed by the workpiece or by the wheel/fluid. All that matters is that the heat is removed effectively (Lavine and Malkin, 1988).

When using crush form wheels containing CBN, the most economic production process for removing heat from the grinding zone would include a coolant consisting of mineral oil. This gives extended life, higher grinding rates and better surface finishes over the normally used soluble oil. Where this coolant is unacceptable, a water soluble oil at 40 to 1 concentration should be used. When a diamond abrasive wheel is being used, it is preferable to use a synthetic chemical coolant. The grinding debris produced when using a diamond wheel is fine, and this in combination with a soluble oil may tend to clog up the wheel, thereby decreasing the heat removal rate of the setup.
Also, the application of the coolant streams to the grinding zone is of great importance in creep feed grinding to maximize the thermal cooling properties. It can be shown that there are three main factors in the approach to the application of the coolant, they are: (Besse, 1987)

a) Nozzle design and location is of the utmost importance in creep feed grinding. This appears to be the single most important consideration. The nozzle size must be constructed precisely so that the speed of the coolant is high enough to match the peripheral speed of the wheel. This then eliminates turbulence and aeration of the fluid, thereby increasing the capacity of the coolant to remove heat from the grinding zone.

b) Increased coolant concentrations improve grinding performance in creep feed grinding by lowering both grinding forces and power requirements, and by increasing wheel life. Surface finish however appeared to be unaffected by coolant concentration.

c) Lower coolant temperatures improve grinding performance. Lower grinding forces and power requirements are the result, along with increased wheel life and improved surface finishes.

10/ Conclusions

The creep feed method has now been developed to such an extent that it can be used as an effective means to increase productivity in mass production, when larger amounts of stock have to be removed and the finish requirements are high. The most outstanding cost advantages can be gained when creep feed grinding is used to replace other operations, like planing, milling, sawing or broaching. It can be shown that production times for a specific case can be reduced from two hours to two minutes, and that grinding wheel life increases by up to 40 times.

It should also be realized that only through the exact implementation of the technology, will these benefits be observed. There must be a co-dependence on the machine builder, the wheel manufacturers and other tools, for the benefits to be observed. Such as, from the machine point of view, the best results have been achieved with pre-loaded, high-precision ball bearings for the spindle bearings. Also, the table drive motor should be a single unit, electro-mechanical drive with infinitely variable speed over the whole range of table speeds from conventional to creep feed speeds.

It is also very important for end users to maintain a knowledge database within their own respective operations, so that there is a continuous forward movement in the technology. It is also important that machine builders, wheel manufacturers, and research institutes contribute to this knowledge base. Creep feed grinding is an exciting field where the full possibilities have not yet been explored.
Figure 6. Typical Creep Feed Grinder

Figure 7. Typical setup of workpiece, abrasive wheel and crush roll

Workpiece

Carbide Crush Roll
References


