CHAPTER 2

REVIEW OF LITERATURE

2.1 GRINDING

Grinding is one of the most versatile methods of removing material from machine parts to provide precise geometry. However, the process is very complex and difficult to study because of the small size of the individual chips produced by hard abrasive particles having wide range of shape, spacing and random geometry (Akira and Tadaaki 1966).

Within the spectrum of machining processes, the uniqueness of grinding is found in its cutting tool. Modern grinding wheels and tools are generally composed of two materials, one is the tiny abrasive particles called grains or grits which do the cutting and the other is a softer bonding agent to hold the countless abrasive grains together in a solid mass (Figure 2.1).

Since grinding wheels can be classified as composite materials, the structural arrangement of the abrasive grain and binder can greatly affect their elastic properties. Brecker (1974) analyzed bond formation during firing of vitrified wheels and observed the cross section of the wheel, from which he concluded that surface tension forces are sufficient to draw the abrasive grains into direct contact.

When high accuracy of the work-piece and the automation of the grinding work are considered, it is necessary to secure the reliability and the reproducibility for grinding wheel as a cutting tool. For this purpose, it is important to choose a grinding
wheel of uniform grade. However, irregularity of grade changes the grinding characteristic on the working periphery of a grinding wheel locally and it affects the dimensional accuracy of work-piece (Shinichi Tooe et al 1987).

Brecker and Shaw (1975) developed a new type of segmental cup wheel for grinding at low traverse speeds. Grinding wheels of this design were shown to provide somewhat better grinding performance, which was attributed to improve access of grinding fluid to the work-piece between the segments.

Snoeys et al (1974) have investigated that cylindrical grinding can be correlated in terms of a parameter called the equivalent chip thickness, which is the product of the wheel depth of cut and the ratio of work speed to wheel speed. Surface roughness, grinding forces and G-ratio were shown to increase with the equivalent chip thickness according to a power function relationship. It should be emphasized, however, that such relationships apply only to particular wheel work-piece combinations and dressing conditions.

Figure 2.1 Grinding wheel showing edge of abrasive grains projecting from the face
Additional information concerning abrasion mechanisms can be inferred from studies of the surfaces generated. Turley et al (1974) found that abraded surfaces typically have severely fragmented outer layers, extending to depths of approximately few microns which experienced nominal strains estimated at several hundred percent. Such severe levels of deformation would also be likely to prevail during chip formation and plowing.

By making a quantitative energy balance, Malkin (1975) showed that the total energy in grinding could be considered as the sum of chip formation, plowing and sliding energies. Plowing refers to work-piece deformation without removal and sliding energy is associated with rubbing between the wear flats and the work-piece surface. Both the plowing and sliding energy contributions become smaller at faster removal rates, so that the minimum specific energy approaches the specific energy for chip formation.

Malkin and Joseph (1975) found that the minimum specific energy in grinding is close to the melting energy per unit volume of work-piece metal. This particular value of minimum energy was attributed to the severe constraint imposed by the highly negative rake angles and strain rates in grinding wheel where the energy reaches this maximum allowable value for adiabatic deformation.

In addition to causing surface damage, grinding heat can affect the precision, which can be obtained due to thermal expansion and distortion of the work-piece. Masuda and Shiozaki (1974) demonstrated how grinding heat in plunge type grinding results in out-of flatness of the finished part. Better flatness was obtained with lesser depths of cut and faster work speed, both of which may cause less grinding heat and with increased coolant flow rate which enhance the cooling of the work-piece and minimize thermal distortion.

Matsuo and Oshima (1973) show the influence of various types of alumina abrasives on the wear of single grains against various work-piece materials.
Van Saun (1974) found in such tests with single grains that adhesion of work-piece metal to the abrasive grains promoted attritious wear by micro fracture. On the basis of an analysis of some of the fly milling data, Scrutton and Lal (1974) proposed that attrition of single abrasive grains occurs by a thermally activated process which is associated with metal adhesion and micro fracture.

Malkin and Anderson (1974) investigated the fraction of the grinding energy conducted to the work-piece. From both energy partition measurements and analysis, it was concluded that virtually all of the sliding and plowing energies and half of the chip formation energy are conducted to the work-piece. Maris and Snoeys (1973) state that almost 60% of the heat energy conducted to the work-piece and this causes work-piece burn. This work-piece burn can also cause some surface quality related problems.

Surface quality consideration calls for burn-free grinding, which imposes a limitation on the allowable process parameters, thereby leading to less efficient grinding (Deiva Nathan et al 1999). In order to strike a balance between quality and efficiency in grinding, it is desirable to have a technique for predicting the burn threshold in real time. In this manner, grinding can be carried out with the desired process parameters for high efficiency and at the same time, the surface quality can also be controlled. This necessitates a detailed study of the temperature developed and the consequent burning phenomena in grinding.

At this point, it appears that practical optimization strategy and reliable mathematical models are still needed to analyze the temperature distribution and thermal damages in grinding.

### 2.2 GRINDING PRINCIPLES

During grinding material is removed from the work-piece surface in the form of small chips by the abrasive particles on the grinding wheel. The material
removal can be visualized by considering a single abrasive grain on the wheel (Figure 2.2). As the grain makes contact with the work-piece surface, the depth of cut is zero.

As the wheel and work-piece revolve, the depth of cut increases to a maximum somewhere along the arc of contact of the wheel and the work-piece and then reduces again when the chip is dislodged from the work-piece. Since the wheel speed is considerably higher than the work speed, the maximum value of depth of cut is reached almost at the point where the wheel leaves the work-piece. This depth of cut is termed as the grain depth of cut.

In Figure 2.2, when the grain is at \( P \) it is just contacting the work-piece and the depth of cut is zero. In unit time \( T \), the grain will advance to position \( R \). In the same unit time \( T \), the point \( R \) on the work-piece would have come to position \( S \). The point \( S \) will be very near to the point \( R \), since the rotation of the wheel is much faster than the work. The chip section removed is represented by \( PRS \). The maximum depth of cut represented by \( SU \) is the grain depth of cut (\( g_d \)).

![Grinding principles](image)

Figure 2.2 Grinding principles
The length traversed by the abrasive grain $PR$ in unit time

$$T = PR = V_s T \text{ or } T = PR / V_s$$

(2.1)

where

$$V_s = \text{Surface speed of the wheel in m/s.}$$

The length traversed by the point $R$ on the work-piece in unit time

$$T = RS = V_w T$$

(2.2)

where

$$V_w = \text{Surface speed of the work in m/s}$$

Grain depth of cut

$$SU = RS \sin (\theta + \phi)$$

(2.3)

where

$\theta$ and $\phi$ are the angles subtended at the centres of the grinding wheel and the work-piece by the point $R$.

Therefore

$$SU = V_w T \sin(\theta + \phi)$$

(2.4)

If there are $Z$ number of grains in unit length, the number of grains in length $PR$ of the grinding wheel is given by $PR.Z$

$$SU$$

Grain depth of cut / grain,

$$g_d = \frac{SU}{PR.Z}$$

(2.5)

$$SU$$

$$g_d = \frac{V_w T}{PR.Z} = \frac{[\sin (\theta + \phi)]}{PR.Z}$$

(2.6)

Substituting for $T$

$$g_d = \frac{V_w}{Z V_s} \sin (\theta + \phi)$$

(2.7)
The wheel can be made to cut harder or softer by reducing or increasing the grain depth of cut. It can be seen from the Equation (2.7) for grain depth of cut, that the work speed and wheel speeds have an influence on the grinding action.

(i) Work speed - By increasing the work speed, the grain depth of cut increases and the bond wears out faster and the wheel appears softer. When the work speed decreases, the wheel appears to be harder.

(ii) Wheel speed - By reducing the wheel speed the grain depth increases and the wheel appears softer. By increasing the wheel speed, the wheel appears harder (Arabatti et al 1996).

2.3 GRINDING PARAMETERS

2.3.1 Influence of process input variables

The grinding process is affected by a very large number of widely varying parameters. Unlike most of the input values like the machine, grinding wheel, machine setting, etc., which can be optimised, the work material which is selected in view of the required properties of the finished product, cannot be changed. Therefore, in order to achieve a well-adjusted grinding process, the variable process input values must be adapted to the material. The grinding process is characterized by grinding power, forces, vibration, temperature, wheel wear and wheel loading (Table 2.1).

The grinding power spent in the process, in other words, the entire mechanical energy is transformed into heat in the contact zone (Konig and Menser 1981). The temperature distribution in the work-piece is largely dependent on the thermal conductivity of the material. These work-piece parameters are not constant but are dependent on the temperature. The height and the distribution of the temperature in work-piece material can be taken as a gauge of the danger of thermal damage. It is well known that thermal damage, cracking and grinding burn can occur to work-pieces when ground under certain conditions. However, it is not so well known that small but finite form errors also result from the high temperatures developed between the grinding wheel and the work-piece (Hahn 1976).
Table 2.1 Influence of process input on grinding process and work quality

<table>
<thead>
<tr>
<th>PROCESS INPUT</th>
<th>Machine</th>
<th>Grinding wheel</th>
<th>Work material</th>
<th>Machine settings</th>
<th>Auxiliary</th>
</tr>
</thead>
</table>

GRINDING PROCESS

- Grinding power
- Grinding forces
- Vibration

Heat generation and Heat distribution

INTERACTION

- Mechanical wear and Chemical wear
- Wheel loading
  - 'Snarl' and built-up chip
  - Grain coating

WORK-PIECE QUALITY

- Accuracy in size - Thermal damage
- Accuracy to geometry - Burning
- Surface finish - Structural transformation
- Roughness - Change in hardness
- Waviness - Residual stresses
- - Cracks
- - Chemical reaction
In the manufacture of the highly stressed critical components where the need for reliability and safety are high, the surface integrity and precision surface form of the ground surface becomes very important. Aircraft jet engine parts, anti-friction bearings in critical locations are the two examples. In order to ensure that surface damage and surface form errors do not occur, it is important to select the operating conditions properly to avoid these effects.

Since the major cause of the surface damage in grinding is due to excessive heat, it is important to identify the basic factors that influence the temperature, which occur on and just below the ground surface during grinding. Under certain conditions, surface temperatures can reach around 1800°C in very localized areas and for very short times. This can cause sub-surface residual tensile stresses and unwanted metallurgical phase changes. The work-piece, the wheel speed, interface force intensity, wheel sharpness, equivalent diameter and cutting fluid all affect the generated surface temperature.

The equivalent diameter \((D_e)\) is that diameter of the wheel, which on a flat surface produces the same contact length as in the internal or external configuration. The wheel sharpness is defined in terms of the metal removal parameter. If this parameter is divided by the wheel surface speed \((V_s)\) we get the sharpness \((S)\) in \(\text{cm}^2/\text{N}\). The sharpness represents the cross-sectional area of the work-piece material being removed by the wheel at any instant per unit normal force. This variable plays an important role in controlling surface integrity. High work speeds, low wheel speeds, low interface force intensity, small equivalent diameter and sharp wheels tend to reduce the thermal stresses.

2.3.2 Grinding power and force

In grinding the chip thickness is very significant with regard to grinding energy and temperatures generated at the surface (Malkin 1984). The specific energy in grinding is very high due to the removal of small amount of material at very high
rate. This is due to the absence of large inhomogenities, crystal defects, grain boundaries and impurities in a very small size of work material (Matsui and Tamaki 1986). The large specific energies associated with grinding process can be partially attributed to the plowing and sliding energies expended in excess of the chip formation energy. In addition, the shear strain involved in chip formation is very large thereby chip formation energy is also very high. In addition to chip formation process, the frictional force is also increased at the tool chip interface.

The forces in grinding are due to cutting or chip formation, plowing and sliding. The contribution of these mechanisms depends on the condition of the wheel. When the grains are sharp without wear flat and the depth of cut is high, the sliding forces are negligible and the grinding force is equal to the cutting force components. When the metal removal rate is very low or cross section of the chips are low or when the wear flat increases, the vertical force increases linearly indicating that the average contact pressure between wear flats and the work is constant. Linear increase in horizontal force indicates the constant coefficient of friction in grinding.

2.3.3 Wheel wear

The geometry of grits on the wheel surface continuously alters due to the influence of cutting mechanisms and forces. The condition of the wheel is also altered due to the wear of the grinding wheel and by the loading of the work material into its pores. Wheel wear and loading brings down the cutting efficiency and the grinding forces increase gradually (Chander et al 1978).

Wear of grinding wheel may be defined as the loss of abrasives from the surface of the wheel and are due to (i) attritious wear of grains (ii) mechanical grain fracture and (iii) rupture of bond or gross pullout of whole grain (Pande and Lal 1976). Attritious wear is a gradual dulling or flattering of abrasive grains by rubbing against the work-piece. This type of wear has much influence on the cutting action of abrasive grain and the cutting forces are dependent on it. Such a wear occurs mostly under mild grinding conditions in precision grinding. It generates wear flats on the grain thus
reducing the cutting efficiency of the grains. Severe grinding conditions subject the wheel material to fracture and the surface is modified constantly due to self-sharpening phenomenon. Grain fracture occurs as a result of mechanical forces associated with chip formation or due to thermal shock induced by instantaneous high temperatures. Gross pullout or bond fracture depends upon the tensile stresses in the bond bridge which in turn depends on the grade of the wheel (Yoshikawa and Sata 1963).

Wheel wear rate is found to be an exponential function of grinding force. As the grinding process is continued the wheel loses its form due to non-uniform removal of material on the wheel surface. Hence the condition of the wheel is continuously altered and a stage has reached after which the grinding performance and efficiency start deteriorating and adversely affecting the work-piece finish and surface integrity.

![Figure 2.3 Relative patterns of wheel wear and forces](image)

Figure 2.3 Relative patterns of wheel wear and forces
The pattern of wheel wear and its associated pattern of forces are shown in Figure 2.3. The wheel wear pattern may be classified into three phases.

(i) Phase A – is intensive wheel wear and it is related to the wheel dressing techniques,
(ii) Phase B – is a constant time-rate of wear under good grinding conditions remains constant over long period. This is the optimum condition for economic grinding practice and
(iii) Phase C – results when either the wheel is overloaded or excessive vibrations occur and wheel wear occurs due to bond post rupture, whole grits being dislodged from the wheel.

Wheel wear measured from the reduction in wheel diameter does not give accurate estimate of the wheel wear. From the wear particle size distribution analysis of the wheel wear can be ascertained accurately but the procedure is cumbersome (Grisbrook et al 1962).

The rate of wheel wear depends upon the work speed, wheel speed and grinding depth of cut. Employing reduced wheel speeds can reduce wheel wear. Low work speeds will reduce the wheel wear for the same metal removal rate but it may cause thermal damage to the work-piece (Malkin 1971).

2.3.4 Loading of grinding wheels

The quality and efficiency of grinding process is largely dependent on the condition of the cutting edges as well as on the condition of the pores on the wheel surface (Konig and Aachen 1978). Frequently loading of the grinding wheel with chips occurs when ductile or high adhesion materials like aluminum, titanium and stainless steel are machined. Due to loading, outer surface of the wheel becomes glazed and results in excessive rubbing. Chips in the grinding wheel will alter the grain edge geometry and the friction process occurring during grinding operations.
The loaded wheel will result in increased cutting forces and grinding power consumption, which in turn may lead to a breakdown of the grinding wheel structure.

The loaded wheel also generates more heat, which in turn affects the surface integrity of the work-piece such as surface roughness or surface topography and surface metallurgy. Alterations of the surface layers include plastic deformation, micro cracking, phase transformations, micro-hardness changes, tears associated with built up edge and residual stress distribution (Shah and Chawala 1979). To ensure consistent results in grinding, one has to continuously investigate the condition or the modifications occurring on the wheel and control them suitably.

Wheel loading is one of the important parameters, which determines the useful life of a wheel in precision grinding (Srivatsava et al 1985). If the cutting efficiency of the process is to be improved the wheel has to be provided with new sharp grains with porosity for chip flow. The wheel is dressed to remove the clogged chips on the wheel material so that new grains with sharp edges appear. One has to monitor continuously the wheel condition and control them suitably to achieve consistent performance in grinding.

2.3.5 Balancing of grinding wheels

If wheels become out of balance through wear and cannot be balanced by truing or dressing, they should be removed from the machine and discarded. Wheel should be tested for balance occasionally and re-balanced if necessary (Figure 2.4).

Wheels that are out of balance not only produce poor work but may put undue strains on the machine. Small wheels may be balanced by milling a short recess on the inside of the flanges and filling with lead. Large wheels should be placed on a balancing stand and balanced by moving weights around a recessed flange.
Nowadays, grinding wheel mounts are provided with devices to enable balancing to be done whilst the wheel is running and between grinding operations.

### 2.3.6 Wheel truing

Truing is the process of changing the shape of the grinding wheel as it becomes worn from an original shape. Owing to the breaking away of the abrasive and bond (Figure 2.5).
This is done to make the wheel true and concentric with the bore, or to change the face contour for firm grinding. Truing and dressing are done with the same tools, but not for the same purpose. Satisfactory method of truing a wheel is by the use of a diamond tool in a similar manner.

2.4 CHARACTERISTIC TERMS USED IN GRINDING

2.4.1 Grindability

It is regarded as the property by which the metal can be removed easily, i.e., the removal of metal should be done as rapidly as possible consistent with less wheel wear, free of grinding cracks and burns and securing good surface finish.

2.4.2 Sensitivity

It indicates the degree of susceptibility to surface cracking

2.4.3 Finishability

It is regarded as the property by which a good surface finish can be obtained easily.

2.4.4 Grinding ratio

It is the quick method of evaluating the grinding wheel performance. Grinding operation removes metal very delicately, leaving a finished surface of superior dimensional accuracy and good surface texture. If it is carried out properly, there will be very less metallurgical damage due to the rise of pressure and temperature of the material being ground. Comparing with any other machining operation the damage depth of the finally ground surface is very small, grinding can
also remove the surface layer previously damaged by any machining operation without introducing any serious damage to the new surface (Jain and Gupta 1991).

Grinding ratio (GR) is an important ratio in grinding which gives the performance of a wheel. It is the ratio between the volume of metal removed from the work-piece to the wear of the grinding wheel.

\[
GR = \frac{\text{Volume of metal removed}}{\text{Volume of wear of tool}} = \frac{\delta x}{\delta y}
\]

The grinding wheel wears more rapidly than the tools used in other machining operation. Grind ratio is the commonly used parameter for evaluating the performance of the grinding wheel.

In the graphical representation, the wear of the wheel is taken on Y-axis and the volume of metal removal is taken on X-axis (Figure 2.6).

![Figure 2.6 Calculation of grinding ratio](image)
In the beginning of the curve it is observed that the volume of metal removed is more in comparison to wear of the wheel. At the beginning, the abrasive particles are firmly wound on the wheel and the surfaces are rough so that the removal of metal takes place moderately.

After sometime, the abrasive particles begin to lose contact due to the rise of pressure and temperature and the surfaces also attain moderate finish and hence the metal removal rate is consistent but the wheel wear is very less. In this region the graph is having very less slope and the curve is normally a straight line. During the latter stage the wear of wheel is at much faster rate than the removal of metal. This is because more and more abrasive particles start falling down due to wear and tear and surfaces also become smoother. The smoother is the surface, the more difficult it becomes to remove any layer from it and the curve takes a steep trend.

2.5 TYPES OF GRINDING

Grinding is performed by refractory abrasive particles of relatively uncontrolled geometry producing many small chips at very high speed. The entire field of grinding may be divided into two regimes:

Stock removal grinding (SRG)
Examples of SRG includes, snagging and cutting-off operations.

Form and Finish grinding (FFG)
Examples of FFG includes, surface grinding, internal grinding and cylindrical grinding.

The first regime involves those processes where the main objective is to remove unwanted material without regard for the quality of the resulting surface. The abrasive cut-off operation and the conditioning of slabs and billets in the steel industry (snagging) are typical processes of this type. In these cases, undeformed chip
thickness is relatively large and wheel wear is so rapid, that it is not necessary to dress the wheel periodically to remove wear flats and metal adhering to the tool face.

The second regime involves those operations where form and finish are a major concern and wheels must be periodically dressed to provide sharp cutting edges that are properly arranged in space and relatively free of adhering metal. The mean undeformed chip thickness in form and finish grinding is relatively small and this gives rise to important differences in the metal removal mechanism from that in metal cutting.

2.5.1 Cylindrical grinding

Cylindrical grinding designates a general category of various grinding methods which have the common characteristic of rotating the work-piece around a fixed axis while grinding outside surface section in controlled relation to that axis of rotation (Figure 2.7).

The form of the part or section being ground in this process is frequently cylindrical, hence the designation of the general category. However, the shape of the part may be tapered or of curvilinear profile, the position of the ground surface may also be perpendicular to the axis and it is possible to grind concurrently several surface sections, adjacent or separated, of equal or different diameters, located in parallel or mutually inclined planes, etc., as long as the condition of a common axis of rotation is satisfied.

2.5.2 Size range of work-piece and machines

Cylindrical grinding is applied in the manufacturing of miniature parts, such as instrument components and at the opposite extreme for grinding rolling mill rolls weighing several tons. Accordingly, there are cylindrical grinding machines of
different types and each adapted to a specific work size range. Machine capacities are usually expressed by such factors as maximum work diameter, work length and weight (Erik Oberg 1996).

2.5.3 Plain - universal and limited purpose cylindrical grinding machines

The plain cylindrical grinding machine is considered to be the basic type of their general category and is used for grinding parts with cylindrical or slightly tapered form. Limited-purpose cylindrical grinders are needed for special work configurations and for high volume production where productivity is more important than flexibility of adaptation. Examples of limited-purpose cylindrical grinding machines are crankshafts and camshaft grinders, polygonal grinding machines, roll grinders, etc.

![Diagram of cylindrical grinding operations](image)

(a) Cylindrical traverse grinding  (b) Form grinding with table traverse
(c) Plunge cylindrical grinding  (d) Taper grinding by tilting the table

Figure 2.7 Types of cylindrical grinding operations
2.5.4 Plunge type grinding

In traverse grinding the machine table carrying the work performs a reciprocating movement of specific travel length for transporting the rotating work-piece along the face of the grinding wheel. At each or at alternate stroke ends, the wheel slide advances for the gradual feeding of the wheel into the work. Only the stroke length of the machine table generally limits the length of the surface that can be ground by this method.

Table 2.2 Plunge grinding

<table>
<thead>
<tr>
<th>Work material</th>
<th>Infeed per revolution of the work (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roughing</td>
</tr>
<tr>
<td>Steel soft</td>
<td>0.0005</td>
</tr>
<tr>
<td>Plain carbon steel hardened</td>
<td>0.0002</td>
</tr>
<tr>
<td>Alloy and tool steel hardened</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

In large roll grinders the relative movement between work and wheel is accomplished by the traverse of the wheel slide along a stationary machine table.

In plunge grinding the machine table, after having been set is locked and, while the part is rotating, the wheel slide continually advances at a preset rate, until the finish size of the part is reached. The width of the grinding wheel is a limiting factor of the section length, which can be ground in this process. The plunge type grinding is required for profiled surfaces and for the simultaneous grinding of multiple surfaces of different diameter or located in different planes (Table 2.2).

2.5.5 Work holding on cylindrical grinding machines

The manner in which the work is located and held in the machine during the grinding process determines the configuration of the part which can be adapted for
cylindrical grinding and affects the resulting accuracy of the ground surfaces. The method of work holding also affects the attainable production rate, because the mounting and dismounting of the part can represent a substantial portion of the total operational time.

Whatever method is used for holding the part on cylindrical type of grinding machines, two basic conditions must be satisfied: (1) the part should be located with respect to its correct axis of rotation and (2) the work drive must cause the part to rotate at a specific speed around the established axis. The lengthwise location of the part, although controlled, is not too critical in traverse grinding; however, in plunge grinding, particularly when shoulder sections are also involved, it must be assured with great accuracy.

2.5.6 Operational data for cylindrical grinding

In cylindrical grinding, similarly to other metal cutting processes, the applied speed and feed rates must be adjusted to the operational conditions as well as to the objectives of the process. Grinding differs, however, from other types of metal cutting methods in regard to the cutting speed of the wheel in grinding. It is generally not a variable and should be maintained at, or close to the optimum rate.

In establishing the proper process values for grinding, the prime consideration is the work materials, its condition (hardened or soft) and the type of operation (roughing or finishing). The other influencing factors are the characteristics of the grinding machine (stability, power), the specifications of the grinding wheel, the material allowance, the rigidity and balancing of the work-piece, as well as several grinding process conditions, such as wet or dry grinding, the manner of wheel truing, etc.
Variables of the cylindrical grinding process, often referred to as grinding data, comprise the speed of work rotation (measured as the surface speed of the work), the infeed (in inches per pass for traverse grinding, or in inches per minute for plunge type grinding). This data is for the purpose of stating the values in setting up a cylindrical grinding process, a brief listing of basic data for common cylindrical grinding conditions and frequently used materials is presented in Table 2.3 (Erik Oberg 1996).

### Table 2.3 Basic process data for cylindrical grinding

<table>
<thead>
<tr>
<th>Work material</th>
<th>Material condition</th>
<th>Work surface speed (fpm)</th>
<th>Infeed, (inch / pass)</th>
<th>Traverse for each work revolution, in fraction of the wheel width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roughing</td>
<td>Finishing</td>
<td>Roughing</td>
<td>Finishing</td>
</tr>
<tr>
<td>Plain carbon steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annealed</td>
<td>100</td>
<td>0.003</td>
<td>0.0005</td>
<td>½</td>
</tr>
<tr>
<td>Hardened</td>
<td>70</td>
<td>0.003</td>
<td>0.0003 to 0.0005</td>
<td>¼</td>
</tr>
<tr>
<td>Alloy steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annealed</td>
<td>100</td>
<td>0.003</td>
<td>0.0005</td>
<td>½</td>
</tr>
<tr>
<td>Hardened</td>
<td>70</td>
<td>0.003</td>
<td>0.0002 to 0.0005</td>
<td>¼</td>
</tr>
<tr>
<td>Tool steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annealed</td>
<td>60</td>
<td>0.003</td>
<td>0.0005</td>
<td>½</td>
</tr>
<tr>
<td>Hardened</td>
<td>50</td>
<td>0.003</td>
<td>0.0001 to 0.0005</td>
<td>¼</td>
</tr>
</tbody>
</table>

#### 2.5.7 Operating conditions

The success of any grinding operation depends on the proper selection of various operating conditions like wheel speed, traverse feed, infeed, area of contact, grinding fluids, etc.
2.5.8 Wheel speed

If the wheel speed is increased at a constant longitudinal or rotary feed rate, the size of the chips removed by a single abrasive grain is reduced. This reduces the wear of the wheel. If the wheel speed is reduced, the wear is increased. From this it is clear that from the point of view of wear, it is better to operate at higher wheel speeds (Opitz and Guhring 1968). However, this is limited by the allowable speeds at which the wheel can be worked, as well as the power and rigidity of the grinding machine. Normally, the grinding wheel speed ranges from 20 to 40 m/sec. The wheel speed also depends upon the type of grinding operation and the bonding medium of the grinding wheel (Table 2.4): for example, resinoid bonded wheels can be generally used at higher peripheral speeds than vitrified bond wheels.

2.5.9 Work speed

Work speed is the speed at which the work-piece traverses across the wheel face or rotates between centres. If the work speed is high, the wheel wear is increased but the heat produced is reduced. Hahn et al (1956) have stated that high work speeds are effective in reducing checking and cracking of heat sensitive materials and may also influence the life of the tool or part. On the other hand, if the work speed is low the wheel wear decreases but the heat produced is more. The ratio of wheel speed to work speed is of much importance and it should be maintained at the proper value. Low work speeds result in local overheating and bring about deformation or tempering of the hardened work-piece. This in turn affects the mechanical properties of the work-piece and very often micro-cracks will appear on the work-piece. The increase in work-speed is limited by premature wheel wear and vibrations induced by wear. Generally, if the wheel wears increases the work speed should be reduced. If the heat produced is high and clogging occurs, especially with hard wheels, the work speed should be increased.
Table 2.4 Recommended bonds and wheel speeds for different grinding operations

<table>
<thead>
<tr>
<th>Type of grinding</th>
<th>Wheel speed (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough grinding wheels with vitrified bond</td>
<td>25</td>
</tr>
<tr>
<td>Rough grinding wheels with resinoid bond</td>
<td>45</td>
</tr>
<tr>
<td>Surface grinding wheels with vitrified bond</td>
<td>20-25</td>
</tr>
<tr>
<td>Internal grinding wheels with vitrified bond</td>
<td>20-35</td>
</tr>
<tr>
<td>Centreless grinding wheels with vitrified bond</td>
<td>30-45</td>
</tr>
<tr>
<td>Cylindrical grinding wheels with vitrified bond</td>
<td>20-35</td>
</tr>
</tbody>
</table>

2.5.10 Down feed or infeed

If the infeed is high, the wheel wear increases and the surface finish deteriorates, thus affecting the dimensional and geometrical accuracy of the ground work-piece. The material removal rate, however, increases if the infeed is high.

2.5.11 Traverse feed

The traverse feed or cross-feed rate is governed by the width of the wheel and the work speed. Normally, the traverse-feed rate is adjusted to two-thirds to three-fourths of the wheel width while grinding steels and three-fourths to five-sixths of the wheel width while grinding cast iron. Heavier cross-feeds increase the wheel wear and produce rougher finish and slower cross-feeds reduce the wheel wear and produce finer finish (Arabatti et al 1996).

2.5.12 Area of grinding contact

The area of grinding contact between the wheel and the work affects the choice of grit size and grade. The area of contact is relatively large in the case of internal grinding and surface grinding and also when large diameters of work are
ground with a small diameter wheel. A larger area of contact produces a lower unit pressure. On larger areas of contact and lower unit pressure, a soft grade wheel provides normal breakdown of the grit, ensuring continuous free cutting action. In addition, coarser grit is preferred to provide adequate chip clearance between the abrasive grains. When the area of contact becomes smaller and the unit pressure, which tends to break down the wheel face becomes greater, finer grit and harder grade wheels should be used.

2.6 SELECTION OF GRINDING WHEELS

2.6.1 Abrasive materials

In earlier times, only natural abrasives were available. From the beginning of previous century, the manufactured abrasives primarily silicon carbide and aluminum oxide have replaced the natural materials, even natural diamonds have been almost completely replaced by synthetics. Superior and controllable properties and dependable uniformity characterize the manufactured abrasives.

Both silicon carbide and aluminum oxide abrasives are very hard and brittle. This brittleness, called friability, is controllable for different applications. Friable abrasives break easily, thus forming sharp edges. These decreases the force needed to penetrate into the work material and the heat generated during cutting. Friable abrasives are most commonly used for precision and finish grinding. These abrasives resist fracture and last longer; they are used for rough grinding, snagging and off hand grinding.

* Aluminum oxide abrasives are used for grinding plain and alloyed steel in a soft or hardened conditions (Figure 2.8).
* Silicon carbide abrasives are selected for cast iron, nonferrous metals and nonmetallic materials.
* Diamond is the best type of abrasive for grinding cemented carbides. It is also used for grinding glass, ceramics and hardened tool steel.

* Cubic Boron Nitride (CBN) is known by several trade names including Borazon (General Electric Co.), ABN (De Beers), Sho-bon (Showa-Denko) and Elbor (USSR). CBN is a synthetic super abrasive used for grinding hardened steels and wear-resistant super-alloys. CBN grinding wheels have long lives and can maintain close tolerances with superior surface finishes.

2.6.2 Bonding properties and grinding wheel grades

The four main types of bonds used for grinding wheels are the vitrified, resinoid, rubber and metal.

Vitrified bonds are used for more than half of all grinding wheels made and are preferred because of their strength and other desirable qualities. Being inert, glass-like materials, vitrified bonds are not affected by water or by the chemical composition of different grinding fluids. Vitrified bonds also withstand the high temperatures generated during normal grinding operations. The structure of vitrified wheels can be controlled over a wide range of strength and porosity. Vitrified wheels, however, are more sensitive to impact than those made with organic bonds.

Resinoid bonds are selected for wheel subjected to impact, or sudden loads or very high operating speeds. They are preferred for snagging and roughing operations. The higher flexibility of this type of bonds essentially filled thermosetting plastic helps it to withstand rough treatment.

Rubber bonds are even more flexible than the resinoid type and used for producing a high finish and also for resisting sudden rises in load. Rubber bonded wheels are commonly used for wet cut-off wheels because of the nearly burr free cuts they produce and for centreless grinder regulating wheels to provide a stronger grip and more reliable work-piece control.
Heat treated steel...
High carbon steel...
Medium carbon steel
Cold rolled steel...
Bronze
Mild steel
Aluminium
Cast iron
Brass
Copper
Zinc
Tin

Figure 2.8 Efficiency of grinding of various metals by Al₂O₃ and SiC wheels

Metal bonds are used in CBN and diamond wheels. In metal bonds produced by electrodeposition, a single layer of super-abrasive material (diamond or CBN) is bonded to a metal core by a matrix of metal, usually nickel. The process is so controlled that about 30 to 40 percent of each abrasive particle projects above the deposited surface, giving the wheel a very aggressive and free-cutting action. With proper use, such wheels have remarkably long lives. When dulled, or worn down, the abrasive can be stripped off and the wheel renewed by a further deposit process. These wheels are also used in electrical discharge grinding and electrochemical grinding where an electrically conductive wheel is needed.

In addition to the basic properties of the various bond materials, each can also be applied in different proportions, thereby controlling the grade of the grinding wheel. Grinding wheel grades commonly associated with hardness, express the amount of bond material in a grinding wheel and hence the strength by which the bond retains the individual grains. The grades of the grinding wheels are designated by capital letters used in alphabetical order to express increasing "hardness" from A to Z.
2.6.3 Marking system for grinding wheels

A standard marking system is used by all grinding wheel manufacturers to identify the type of abrasive, grain size, grade, structure, bond and other properties of a grinding wheel. The marking system consists of symbols, which pertain to the following parameters:

(1) Manufacturer's additional symbol for the abrasive (optional),
(2) Type of abrasive,       (3) Grain size,       (4) Grade,
(5) Structure (optional)   (6) Type of Bond and
(7) Manufacturer's own wheel identification mark.

If it is necessary to show special grain combinations, the manufacturers may add an additional symbol to the regular grain-size number. A typical example of marking a grinding wheel is shown in Figure 2.9.

2.7 GRINDING FLUIDS

The goal in all conventional metal removal operations is to raise productivity and reduce costs by machining at the highest practical speed consistent of surface of satisfactory accuracy and finish. Many machining operations can be performed in dry conditions. The proper application of a cutting fluid generally makes possible, higher cutting speeds, higher speed rates, greater depth of cut, lengthened tool life, improved surface finish, increased dimensional accuracy and reduced power consumption.

Selecting the proper cutting fluid for a specific machining situation requires knowledge of fluid functions, properties and limitations. Cutting fluid selection deserves as much attention as the choice of machine tool, tooling speeds and feeds.
<table>
<thead>
<tr>
<th>Nature of Abrasive</th>
<th>Type of Abrasive</th>
<th>Grain Size</th>
<th>Grade</th>
<th>Structure</th>
<th>Type of Bond</th>
<th>Manufacturer's Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>A</td>
<td>36</td>
<td>L</td>
<td>5</td>
<td>V</td>
<td>23</td>
</tr>
</tbody>
</table>

- **Manufacturer's symbol including the exact nature of the abrasive (optional):**
  - ALUMINIUM ABRASIVE - A
  - SILICON CARBIDES - C

- **Spacing from the closet to the most open:**
  - Very Fine: 220, 240, 280, 320, 400, 500, 600
  - Fine: 100, 120, 150, 180

- **Soft**
  - A
  - B
  - C

- **Medium**
  - D
  - E
  - F
  - G
  - H
  - I
  - J
  - K
  - L

- **Hard**
  - M
  - N
  - O
  - P
  - Q
  - R
  - S
  - T
  - U
  - V
  - W
  - X
  - Y
  - Z

**Figure 2.9 Standard marking system for grinding wheels**
In recent years a wide range of grinding fluids has been developed to satisfy the requirements of new materials of construction and new tool materials and coatings. The most commonly used grinding fluids are water-based emulsions and grinding oils. Nearly all-grinding operations can be carried out with emulsifiable oils. Flood applications of the grinding fluid, completely covering the wheel work interface with a stream of fluid, are most commonly used. It is important that the fluid is directed to the interfaces so that it can enter and create a film of low shear strength between the wheel and work. The quantity of fluid should be ample and may amount to 15 to 20 litres/min for a normal medium sized grinding machine. Generally, the feed quantity of the coolant depends on the length of contact between the grinding wheel and the work-piece. Larger the contact area, more should be the quantity of coolant. The width of the stream should be more than the width of the grinding wheel. In internal grinding, the contact area is much larger than in external cylindrical grinding and hence copious flow of coolant should be ensured.

Because of the very high speeds involved in grinding, a film of air encloses the wheel surface and prevents the penetration of the fluid to the cutting zone. This air stream can be pierced by supplying the fluid under pressure or by the design of special nozzles. The nozzle should be as near the work-piece as possible. Another method of supplying the grinding fluid is through the voids in the grinding wheel. The fluid is supplied at the center of the wheel and it moves out through the wheel under the action of centrifugal force. The main disadvantage is that the fluid is continuously expelled all along the perimeter of the wheel, instead of only at the cutting zone. Further, since the pores in the wheel are extremely small, the fluid should be finely filtered to prevent clogging in the wheel (Guo and Malkin 1992 a).

2.7.1 Types of grinding fluids

There are four basic types of grinding fluids, each has distinctive features, as well as advantages and limitations. Selection of the right fluid is made more complex because the dividing line between types is not always clear. Most machine
shops try to use as few different fluids as possible and prefer fluids that have long life, do not require constant changing or modifying, have reasonably pleasant odors, do not smoke or for in use and important are neither toxic nor cause irritation to the skin. Other issues in selection are the cost and ease of disposal. The major divisions subdivisions used in classifying grinding fluids are:

a) **Cutting oils**, including straight and compounded mineral oils plus additives.
b) **Water miscible fluids**, including emulsifiable oils, chemical or synthetic fluids and semi chemical fluids.
c) **Gases, paste and solid lubricants.**

Since the cutting oils and water-miscible types are the most commonly used cutting fluids in machine shops, discussion will be limited primarily to these types. It should be noted, however, that compressed air and inert gases, such as carbon dioxide, nitrogen and freon are sometimes used in machining. Paste, waxes, soaps, graphite and molybdenum disulfide may also be used, either applied directly to the work-piece or as on impregnate in the tool such as in grinding wheel (Metals Handbook 1998).

### 2.7.2 Cutting oils

Cutting oils are generally compounds of mineral oil with the addition of animal, vegetable or marine oils to improve the wetting and lubricating properties. Sulphur, chlorine and phosphorous compounds, sometimes called extreme pressure (EP) additives, provide for even greater lubricity.

### 2.7.3 Mineral oils

This group includes all types of oils extracted from petroleum such as paraffin oil, mineral seal oil and kerosene. Mineral oils are often blended with base stocks, but they are generally used in the original form for light machining operations
on both free-machining steels and non-ferrous metals. The coolants in this class should be of a type that has a relatively high flash point.

2.7.4 Water miscible fluids

Emulsions or water miscible fluids are a suspension of oil droplets in water. Blending the oil with emulsifying agents (soap and soap-like materials) and other materials makes these suspensions.

These fluids combine the lubricating and rust prevention properties of oil with water's excellent cooling properties. Their properties are affected by the emulsion concentration, with "lean" concentrations providing better cooling but poorer lubricating and with 'rich' concentration having the opposite effect. Additions of sulphur, chlorine and phosphorus, with cutting oils, yield "extreme pressure" grades.

2.7.5 Soluble oils

Types of oils or paste compounds which from emulsions when mixed with water, soluble oils are used extensively in machining both ferrous and non-ferrous metals.

Care should be taken in selecting the proper soluble oil for precision grinding operations. Grinding coolant should be free from faulty materials that tend to load the wheel, thus affecting the finish on the machine parts. Soluble coolants should contain rust preventive constituents to prevent corrosion.
2.7.6 Chemical fluids

These are the solutions composed of organic and inorganic materials dissolved in water inactive types and are usually clear fluids combining high rust inhibition, high cooling and moderate lubricating properties with low surface tension.

They may also contain chlorine and sulphur compounds for extreme pressure properties, cooling properties and very good rust inhibition. Sulphur, chlorine and phosphorus are also sometimes added.

2.7.7 Selection of cutting fluid for cylindrical grinding

Soluble oil emulsions or emulsions made from paste compounds are used extensively in precision grinding operations. For cylindrical grinding, one part of oil to 40 to 50 parts of water is used. Solution type fluids are recommended for many applications where a fine surface finish is required on the ground surface. Mineral oils are used with vitrified wheels but are not recommended for wheels with rubber or shellac bonds.

Under certain conditions the oil vapour mists caused by the action of the grinding wheel can be ignited by the grinding sparks and explode. To quench the grinding spark a secondary coolant line to direct the flow of grinding oil below the grinding wheel is recommended.

2.8 METALLURGICAL EFFECTS ASSOCIATED WITH GRINDING

When a metal is ground, its surface is not only plastically strained by the grits, but is also heated. It is the plastic flow induced by the stress ahead of a grit which causes chips to be produced when the grit is favourably placed and which leaves the work-piece surface in a state of plastic strain. Much redundant work is done
in removing metal in this way, so that a large power is commonly developed at the contact between a grinding wheel and a work-piece. If this rises too much, it cannot be dissipated without an excessive rise in work-piece temperature, which may cause grinding burn or cracks. Clearly, the metallurgy of the work-piece influences the stresses and power developed at the contact under given grinding conditions. It also influences the temperatures and thermal stresses, which a work-piece can withstand without damage.

2.8.1 The nature of grinding damage

Tarasov (1950) investigated the microstructure and hardness changes, residual stresses and occurrence of tiny surface cracks or heat checks in the ground surfaces of hardened steels which are generally attributed to the unsatisfactory grinding practice, such as the use of too hard a wheel, or a dull wheel, or the rate of stock removal is excessive. Tarasov's approach addressed not only the surface cracking of hardened steels but also its connection with related problems, such as grinding burn and soft skin. He showed that the grinding process is capable of affecting the metallurgical and physical condition of the surface layers and in turn, the original metallurgical condition of the steel could affect the way it would respond to grinding.

When hard materials such as hardened steels, cast cobalt alloys and cemented carbide are ground under abusive conditions and the surface is found to be cracked after grinding. These cracks are found to be shallow and bear some relationship to the grinding marks. In fact, they are found to be primarily perpendicular to the grinding marks. If the crack pattern is more pronounced, there might be cracks joining the perpendicular ones and forming a network. In case of hardened steels, Tarasov investigated the carbide network, which initiates the cracks. He also found the proper heat treatment process to eliminate such network, which minimize cracking. He investigated the metallo-graphic features of burn in several
steels using a taper sectioning technique. They confirmed that burn is as described above in a fully hardened 18:4:1 tool steel and showed that the martensite formed during rehardening burn etches white. Beneath this white layer was a thin transition zone in which the prior austenite grain boundaries etched white and the grain centres dark. Beneath the transition zone was a dark etching tempered zone gradually merging with the structure of the substrate. Cast iron, both grey and white and AISI 52100 steel were also studied. Rehardening burn could be induced on the hardened steel and on the grey iron, but did not occur in soft steels or white iron. Burnt specimens were examined visually after macro etching. Abusively ground soft steel work-pieces showed dark etching flecks, which the authors suggested, were zones of high residual stress, preferentially attacked by the etchant. Rehardened zones were usually slightly harder than the substrate, whereas tempered zones were softer. The dark flecks on the soft steel were of similar hardness to the substrate (Malkin and Fedoseev 1991).

Torrance (1978) gives details of the changes produced in C1023 work-pieces ground in creep feed. This is a nickel-based alloy designed for service at temperatures approaching 1000°C, so temperatures of this order must be generated in the contact before burn becomes noticeable. When burn does occur, the γ' precipitates responsible for the alloy's high temperature strength are dissolved to a depth of up to 1 mm beneath the surface. If the work-piece is then heated to its service temperature, the deleterious sigma phase is precipitated in the burnt zone. Surface changes of much smaller depth were also observed on correctly ground work-pieces, their nature depends on the grinding conditions.

2.8.2 Metallurgical factors

Some investigators have claimed that metallurgical factors influence steel's susceptibility to grinding damage. Tarasov (1950) states that many authors have found steels containing residual austenite to be prone to grinding cracks. He suggests that this may be due to stresses set up by the transformation of residual austenite to
martensite under the influence of grinding strains. The increasing chromium content in low alloy steels favours cracking and more alloying elements are added to retain the austenite.

Littman and Wulff (1955) confirmed that the hardness changes induced in AISI 52100 by grinding burn were consistent with the temperature rises linearly with the energy input to the grinding zone and it falls off very steeply with depth beneath the surface.

2.8.3 Grinding mechanics and contact temperatures

Hahn (1966) has studied the way tensile residual stress is generated in an abusively ground work-piece, suggesting that it arises in the following way: as the work passes through the arc of cut, its surface is heated locally, causing it to expand against the constraint of the cool surrounding material. If the temperature rises sufficiently, the heated spot will soften and flow plastically under the thermal stress. When it emerges from the arc of cut, it will be rapidly quenched by the bulk of the work-piece and by the coolant. The hot spot contracts during the quench and is left in a state of tension. In steels, martensite may be formed during this cycle. Since a volume increase occurs, the stress is modified to leave the martensite in compression.

The stress developed in this way in a given material depends mainly on the temperature reached in the arc of cut and quenching rate. Both depend on grinding conditions. The problem of grinding damage may therefore be treated as a heat transfer problem, the work of Jaeger (1942) being used to relate contact temperatures to the power developed in the arc of cut. The problem is extremely complex, since the heat generated in the arc of cut is partitioned in an unknown way between wheel, work, chip and coolant. A detailed treatment has been given by Des Ruisseaux et al (1970) who allowed for cooling of the work-piece by convection and consider the effect of coolant application, wheel speed and work speed on work-piece temperature.
They showed that this could be calculated by ignoring the effects of individual grits and treating the arc of cut as a band heat source.

Another difficulty with this approach is that the lower tendency to grinding burn at higher infeeds is not predicted. Presumably, the partition of energy changes as the infeed is increased, a higher proportion going to material, which is eventually removed. This kind of consideration has led other authors to place more emphasis on the mechanics of grinding in predicting burn. Hahn (1955) introduced an empirical wheel sharpness factor to allow for this but does not consider the effect of coolant. He does, however, predict the same behavior as Des Ruisseaux (1970) at constant wheel sharpness in the absence of coolant. Malkin (1978) found that for a given material grinding burn occurs when the total wears flat area on a grinding wheel exceeds a fixed level, independent of wheel grade. The grinding forces are proportional to the wear flat area and the constant of proportionality rise sharply at burn. However, it appears that the burn referred to here is rehardening burn, temper burn, which can be extremely damaging in hard components, is not considered. Malkin's work stresses the importance of the detailed interaction of grit and work-piece in determining the partition of energy. He divides forces into cutting, ploughing and rubbing components. Cutting energy may be partly carried off with the chip but rubbing energy goes to the work-piece, so a high rubbing energy favours burn. Anything, which reduces the rubbing energy, such as lubrication or wheel sharpness reduces the tendency to burn.

The literature cited above shows that it is primarily the generation of high temperatures, which causes grinding damage. Where the work-piece is kept cool, damage is minimized. Unfortunately, the thermal analysis of grinding is hampered by an inadequate knowledge of grinding mechanics, so that no one theory of grinding damage can be considered complete. It was hoped that metallurgical changes on the surface layers of both burnt and normally ground work-piece would indicate more clearly the mechanics of the grinding process.