Module

5

Abrasive Processes (Grinding)

Lesson

27

Basic principle, purpose and application of grinding

Instructional Objectives

At the end of this lesson the students would be able to

(i) understand basic principle of grinding.
(ii) recognize purpose and application of grinding.
(iii) understand cause of development of force during grinding.
(iv) understand variation of grinding characteristics with grinding conditions.
(v) illustrate various methods of wheel conditioning.

27. Grinding

Grinding is the most common form of abrasive machining. It is a material cutting process which engages an abrasive tool whose cutting elements are grains of abrasive material known as grit. These grits are characterized by sharp cutting points, high hot hardness, chemical stability and wear resistance. The grits are held together by a suitable bonding material to give shape of an abrasive tool.

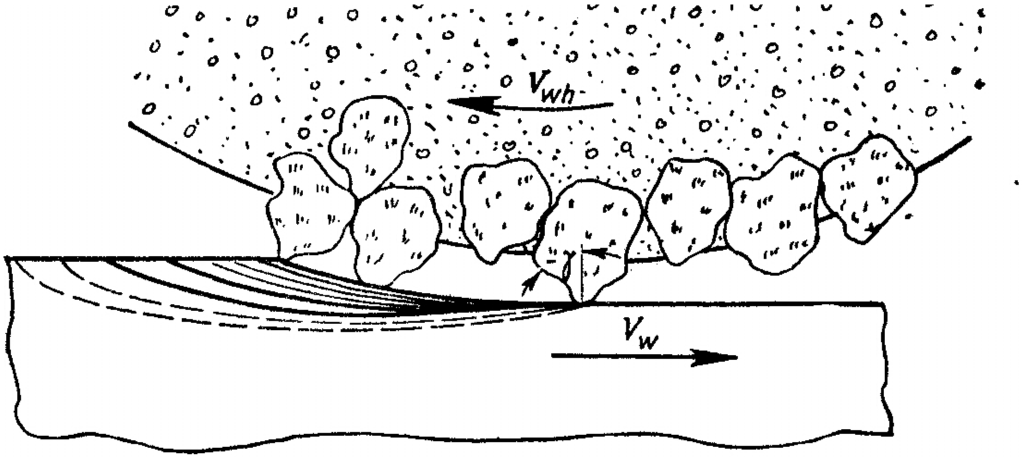


Fig. 27.1 *Cutting action of abrasive grains*

Fig. 27.1 illustrates the cutting action of abrasive grits of disc type grinding wheel similar to cutting action of teeth of the cutter in slab milling.

27.1 Major advantages and applications of grinding

Advantages

A grinding wheel requires two types of specification

- dimensional accuracy
- good surface finish
- good form and locational accuracy
- applicable to both hardened and unhardened material

Applications

- surface finishing
- slitting and parting
- descaling, deburring
- stock removal (abrasive milling)
- finishing of flat as well as cylindrical surface
- grinding of tools and cutters and resharpening of the same.

Conventionally grinding is characterized as low material removal process capable of providing both high accuracy and high finish. However, advent of advanced grinding machines and grinding wheels has elevated the status of grinding to abrasive machining where high accuracy and surface finish as well as high material removal rate can be achieved even on an unhardened material. This is illustrated in Fig. 27.2.

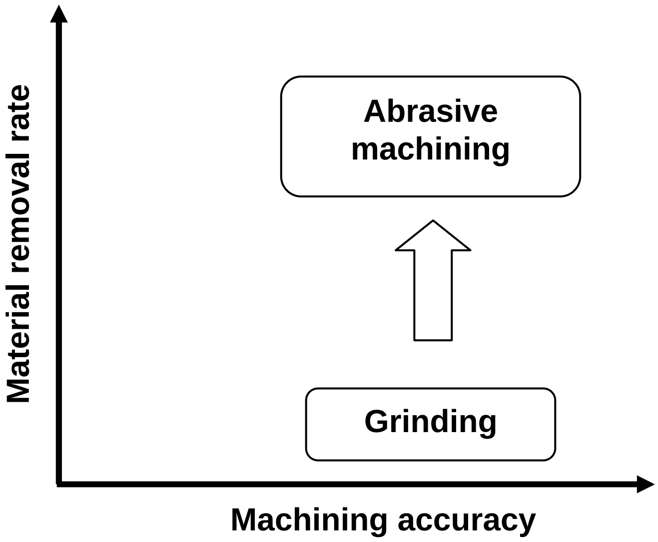


Fig. 27.2 *Elevation of the status of grinding to abrasive machining*

27.2 Grinding wheel and workpiece interaction

The bulk grinding wheel-workpiece interaction as illustrated in Fig. 27.3 can be divided into the following:

1. grit-workpiece (forming chip)
2. chip-bond
3. chip-work piece
4. bond-work piece

Except the grit workpiece interaction which is expected to produce chip, the remaining three undesirably increase the total grinding force and power requirement.

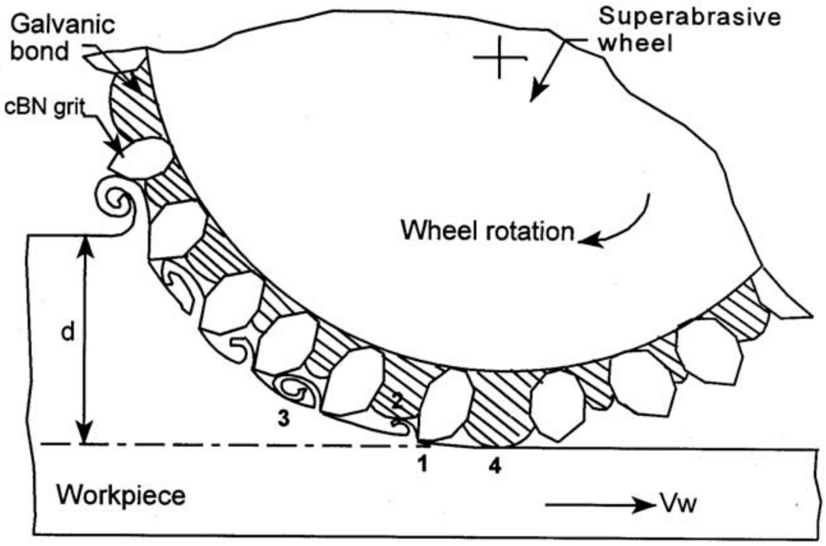


Fig. 27.3 *Grinding wheel and workpiece interaction*

Therefore, efforts should always be made to maximize grit-workpiece interaction leading to chip formation and to minimize the rest for best utilization of the available power.

27.3 Interaction of the grit with the workpiece

The importance of the grit shape can be easily realized because it determines the grit geometry e.g. rake and clearance angle as illustrated in Fig. 27.4. It appears that the grits do not have definite geometry unlike a cutting tool and the grit rake angle may vary from $+45^0$ to -60^0 or more.

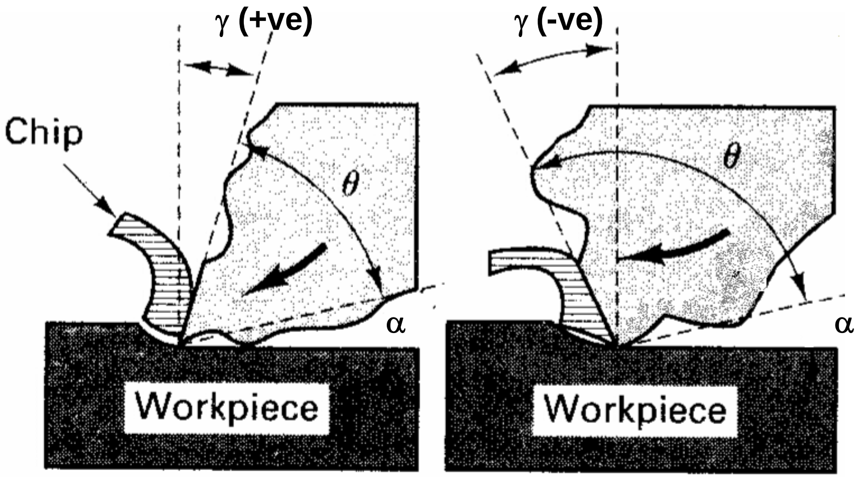


Fig. 27.4 *Variation in rake angle with grits of different shape*

Grit with favourable geometry can produce chip in shear mode. However, grits having large negative rake angle or rounded cutting edge do not form chips but may rub or make a groove by ploughing leading to lateral flow of the workpiece material as illustrated in Fig. 27.5.

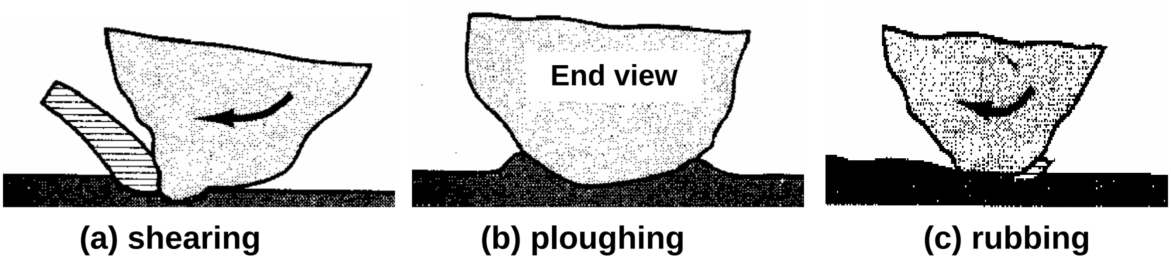


Fig. 27.5 *Grits engage shearing, ploughing and rubbing*

27.4 Effect of grinding velocity and rake angle of grit on grinding force

Figure 27.6 shows the role of rake angle on cutting force. A negative rake angle always leads to higher cutting force than what is produced with a cutting point having positive rake angle. The figure further illustrates that at low grinding velocity this difference in grinding force is more pronounced. It is interesting to note that the difference is narrowed at a high grinding velocity and the grinding force became virtually independent of the rake angle. This is one of the reasons of conducting grinding at a very high velocity in order to minimize the influence of negative rake angle.

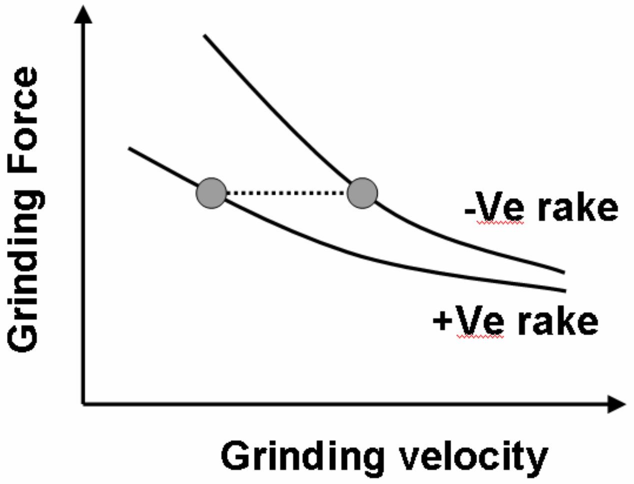


Fig. 27.6 *Variation of grinding force with grinding velocity and rake angle of grit*

27.5 Variation of critical grit depth of cut with grinding velocity

Grinding is a combination of rubbing, ploughing and cutting (actual chip formation) with contribution of each being highly governed by grit geometry, work material characteristics, grinding loop stiffness and the grinding velocity.

It is evident that specific energy in sliding or ploughing is more than that required in cutting or chip formation. It is the common experience in grinding that a certain level of grit penetration into workpiece is required before chip formation can start. Figure 27.7 illustrates variation of critical grit depth of cut with cutting velocity to initiate chip formation in grinding. It can be seen from this figure that magnitude of critical grit depth of cut required to initiate cutting becomes less with the increase of grinding velocity.

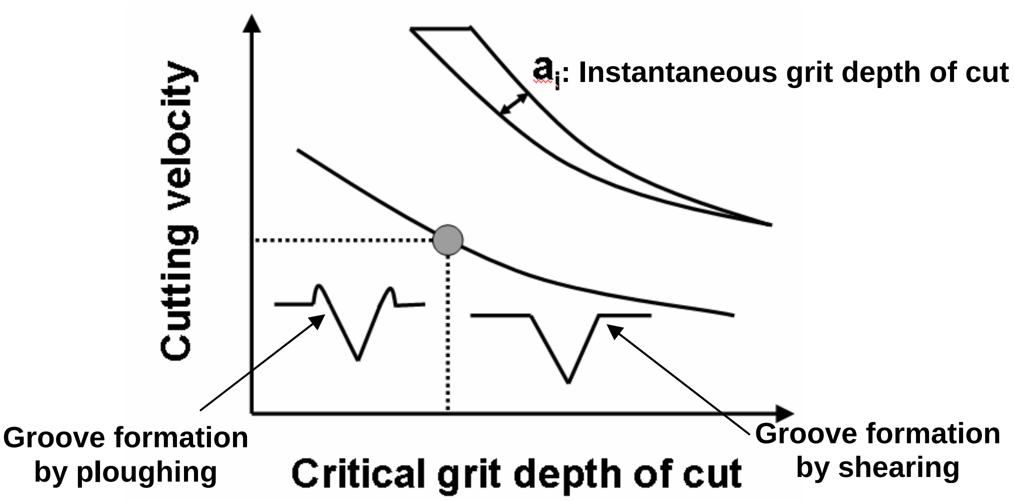


Fig. 27.7 *Variation of critical grit depth of cut With grinding velocity*

27.6 Various stages of grinding with grit depth of cut

Figure 27.8 illustrates the various stages of grinding and grinding force with grit depth of cut. At a small grit penetration only sliding of the grit occurs against the workpiece. In this zone rise of force with increase of grit penetration is quite high. With further increase of grit penetration, grit starts ploughing causing plastic flow of the material also associated with high grinding force.

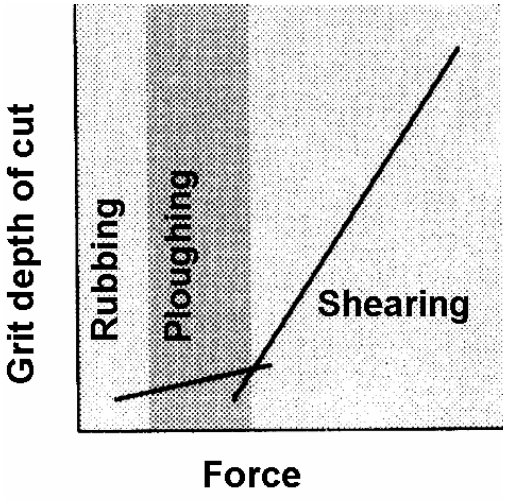


Fig. 27.8 *Various stages of grinding with grit depth of cut*

It can be seen that with further increase of penetration, the grits start cutting and the rate of rise of force with increase of grit depth of cut is much less than what can be seen in the sliding or ploughing zone.

27.7 Change in effective grit geometry due to material loading at the grit tip

Grit geometry may undergo substantial change due to mechanical or chemical attrition leading to rounding or flattening of the sharp cutting points. This happens when the work material has hard or abrasive constituent or where the workmaterial or environment chemically attacks the grit material. However, Fig. 27.9 shows that a chip material adhered to the tip of grit because of some chemical affinity can also change the effective rake angle of the grit leading to high grinding force, temperature and poor performance of the grinding wheel.

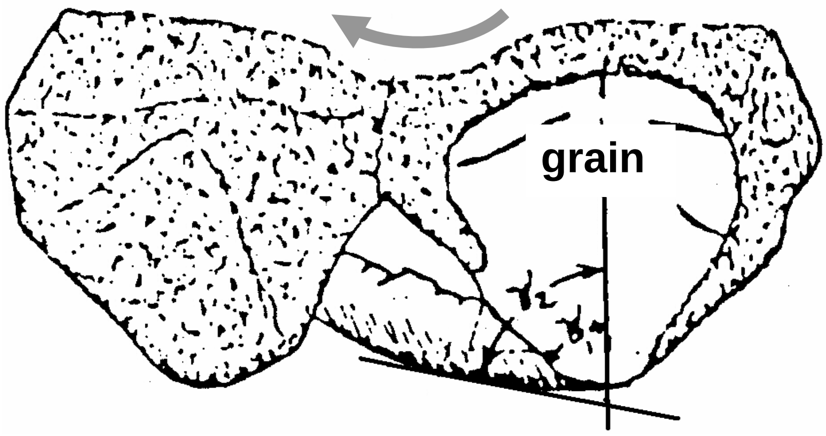


Fig. 27.9 *Change in effective grit geometry due to material loading at the grit tip*

27.8 Chip accommodation problem in grinding

During grinding the volume of chip produced by each grit must be accommodated in the space available ahead of it. Absence of adequate chip storage space can lead to wheel loading, thus terminating the use of the wheel much before its expectedly long service life.

The requirement of chip accommodation space in a grinding wheel is analogous to the chip space required ahead of each tooth of a broaching tool as illustrated in Fig. 27.10. Uncut layer of length ‘L’ after deformation has to be accommodated freely in the chip gullet to avoid breakage of the tooth.

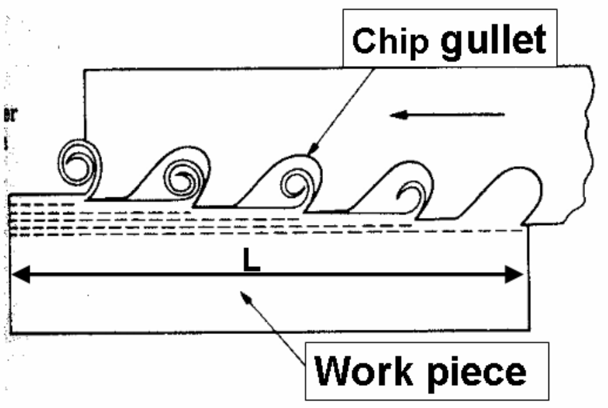
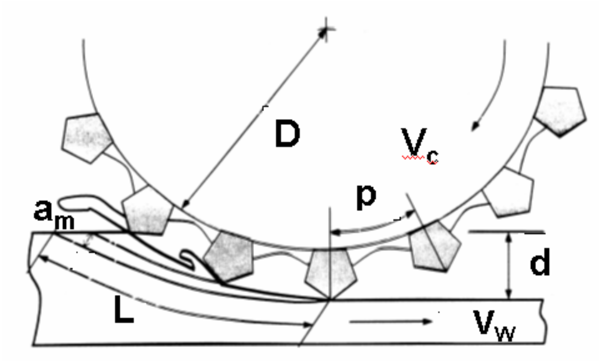


Fig. 27.10 *chip formation an accommodation during broaching*

27.8.1 Grit depth of cut and wheel-workpiece contact length

Volume of chip produced by individual grit depends upon the maximum grit depth of cut, wheel workpiece contact length and grit width of cut. Figure 27.11 shows a grinding wheel with a single layer configuration having tip of all the grits in the same level, engaged in up grinding mode.



Maximum uncut chip thickness , a_m

$$a_m = 2\frac{V_W}{V_C}.p.\sqrt{(d/D)}$$

Length of undeformed chip , L $\boxed{L = \sqrt{(d.D)}}$

Fig. 27.11 *Maximum grit depth of cut and length of undeformed chip*

The figure further shows the maximum grit depth of cut or thickness of the undeformed chip which depends on grinding velocity, workpiece speed, wheel depth of cut, wheel diameter and circular pitch of the grits. The length of the undeformed chip, however, depends only on the wheel depth of cut and its diameter. The volume of the chip produced by each grit depend on both 'a_m' and 'l_c ' as shown in Fig. 27.12.

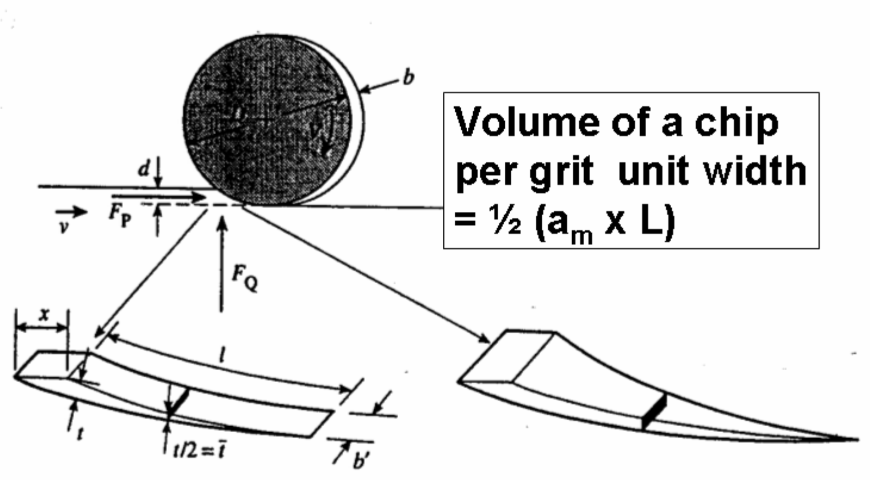


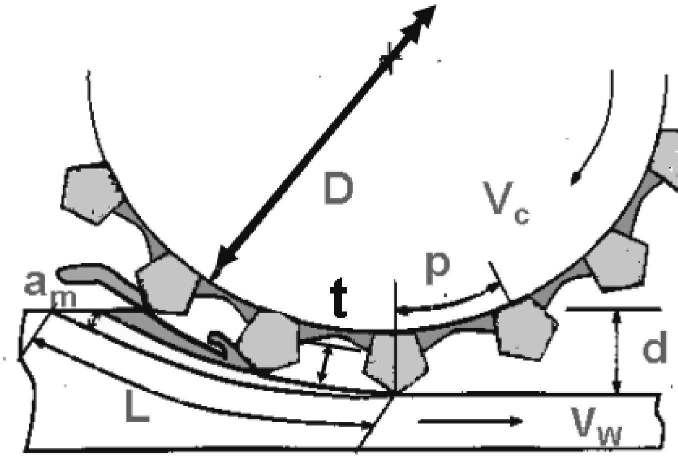
Fig. 27.12 *Volume of chip produced by a grit*

27.8.2 Determination of grit spacing and grit protrusion

Following three constraints are to be considered while determining spacing of grit and its protrusion:

- Chip volume
- Chip thickness
- Chip length

Various parameters involved in determination of grit space and its protrusion are shown in Fig. 27.13.



D : wheel diameter
V_c : grinding velocity
V_W : table speed
d : wheel depth of cut
p : circular pitch of the grits
t : protrusion of grit from bond level
a_m ; max^m undeformed chip thickness
L : length undeformed of chip

Fig. 27.13 *Different parameters involved in determination of chip spacing and grit protrusion.*

Chip volume Constraint
Chip storage space available per unit time = $V_c\ b\ t$
$V_c\ b\ t > V_w\ d\ b$
Or, $t > (V_w/V_c)\ d$

Chip thickness constraint
Chip produced by each grit = $\frac{1}{2}\ a_m \times L \times b$
No. of grit participating per unit time = V_c/p
$(\frac{1}{2})\ a_m\ L\ b\ (V_c/p) = V_w db$
rr, am = $2. (V_W/V_C)\ .\ d.\ (p/L)$
Therefore, $t > 2. (V_W/V_C)\ .\ d.\ (p/L)$

Chip length constraint
undeformed length of the chip $L = \sqrt{(d.D)}$
$Ld = \varsigma L$ where, ς = chip reduction coefficient
$p > Ld$, where ς = grit spacing

27.9 Specific energy consumption in grinding

Fig. 27.14 illustrates that specific grinding energy starts to decrease with increase of material removal rate because rake angle of the grit becomes favourable (less negative). However, after attaining a certain material removal rate, the specific energy may start increasing as shown in the same figure. This may happen because of the chip accommodation problem with large volume of chip, which promotes large chip-bond and chip-workpiece sliding leading to increase in grinding force.

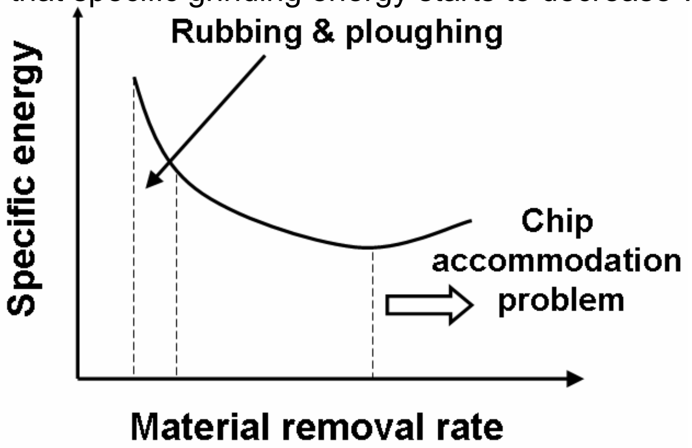


Fig. 27.14 *Variation of specific energy with material removal rate*

27.10 Grinding wheel performance against materials with different hardness

In machining, under identical conditions, the cutting force increases with the shear strength of the material. However, in case of grinding a different observation can be made as shown in fig. 27.15. A hardened material exhibited higher value of normal force than an unhardened material while the latter showed higher tangential grinding force than the former.

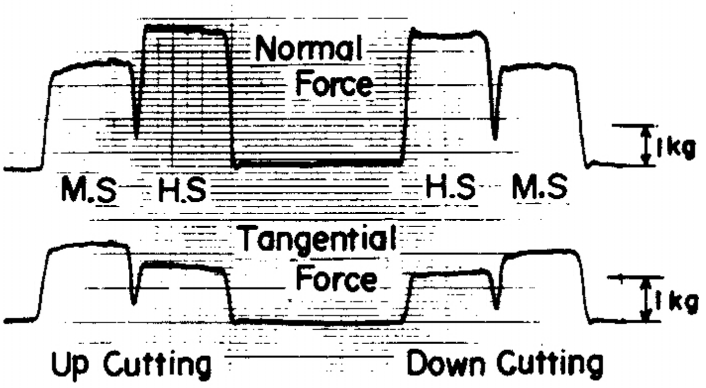


Fig. 27.15 *Force during grinding mild steel and hardened steel*

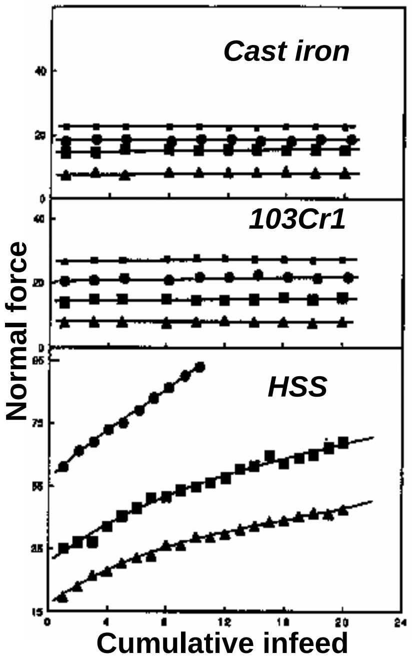


Fig. 27.16 *Grinding behaviour of cBN wheel against diff. materials*

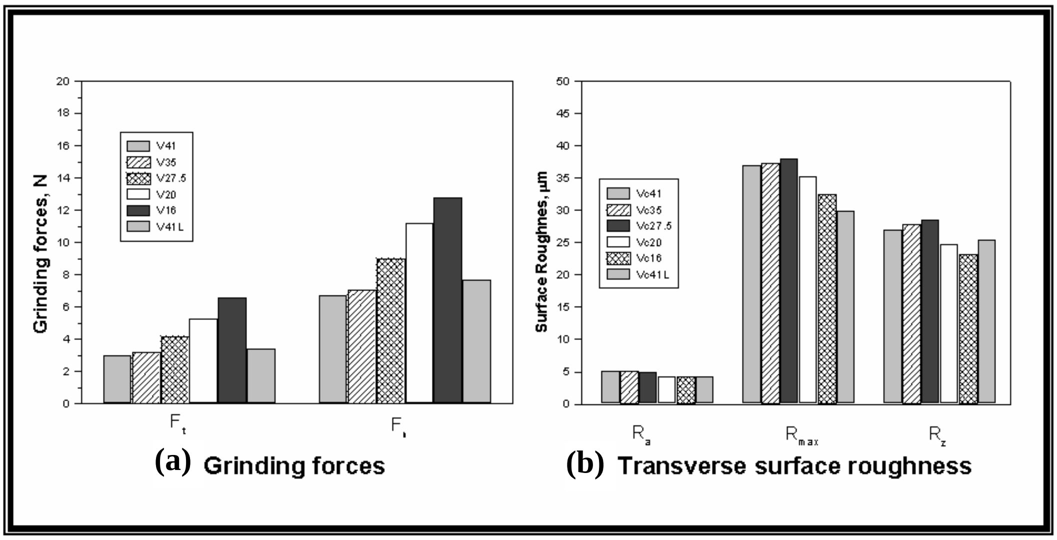
Resistance to penetration could be translated into high normal force in case of hardened material, In case of grinding unhardened material force due to rubbing and ploughing may be more and can account for large tangential force. In addition, enhanced bond-chip and chip-workpiece rubbing with relatively long chip of unhardened material may also contribute towards escalation of the tangential force.

Grinding behaviour of a wheel is best understood with a wheel having just a single layer of abrasive grains bonded to a metallic core. Figure 27.16 shows steady grinding force with such a wheel during grinding of grey cast iron and unhardened bearing steel with gradual increase of cumulative infeed. This observation simply suggests that the grit geometry did not change significantly and wheel loading was also absent. This is true for all the infeeds.

However, situation was different when HSS (High speed steel) was ground. The grinding force showed clearly an increase with passage of grinding. The rate of increase of force also enhanced with increase of infeed. HSS being harder than unhardened bearing steel is expected to create less chip accommodation problem and can not be the cause of increase of grinding force. Hard constituents like carbides of W, Cr and V caused attrition wear on the grit tip leading to grit rounding and flattening. The irreversible change on the grit geometry was the main cause of gradual increase in grinding force with HSS.

27.11 Effect of grinding parameters on grinding force and surface roughness of the workpiece

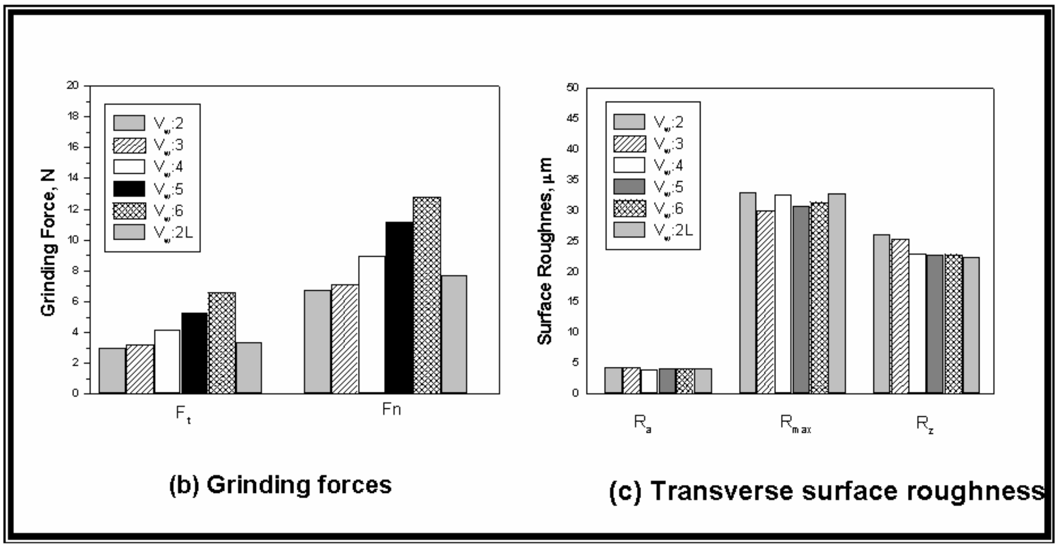
Figure 27.17(a) indicates progressive decrease in grinding force with increase of grinding velocity. The opposite trend is observed when workpiece traverse speed on wheel depth of cut is increased.



(a) **Grinding forces** **(b)** **Transverse surface roughness**

Fig. 27.17 *Effect of grinding velocity (m/s)*

This is indicated in Fig. 27.18(a) and Fig. 27.19(a). The variation of uncut layer thickness with grinding parameters causes the variation in force per grit as well as in total grinding force.

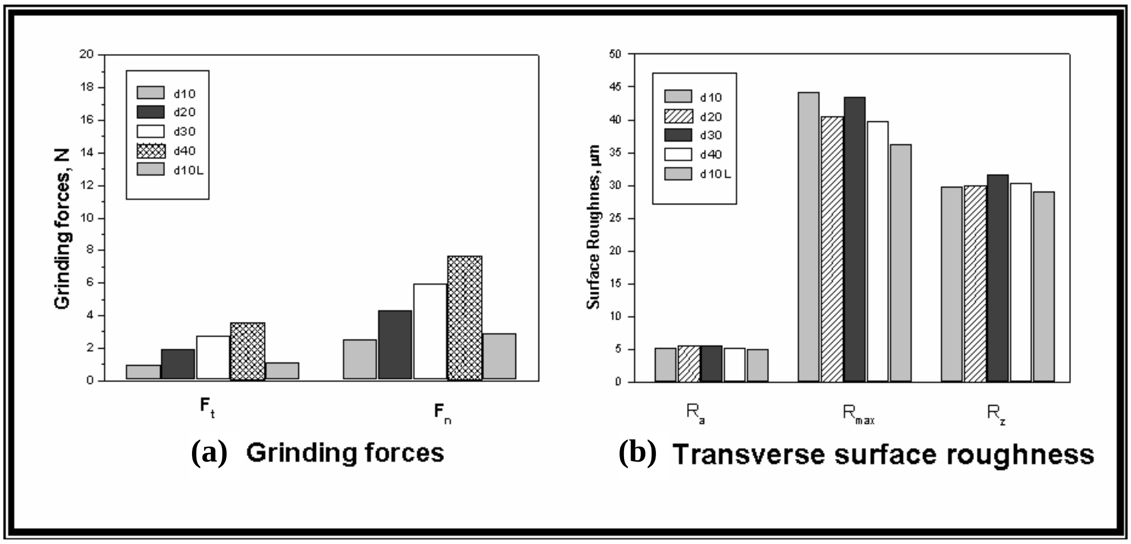


(b) Grinding forces **(c) Transverse surface roughness**

(a) **(b)**

Fig. 27.18 *Effect of table feed (m/min)*

Surface roughness of the workpiece in the transverse direction is a subject of major concern. Surface roughness in longitudinal direction is mostly found to be significantly low. The transverse surface roughness of a workpiece depends mainly on the grit geometry, over lap cuts made by the grits and lateral plastic flow of the work material.



(a) **Grinding forces** **(b)** **Transverse surface roughness**

Fig. 27.19 *Effect of depth of cut (µm)*

Grinding parameters like grinding velocity, traverse speed or wheel depth of cut affects the grinding force which in turn can cause fracture, rounding or flattening on few overlying grits thus, bringing more number of underlying grits into action. This change in topographical feature of single layer wheel, in various levels, affects the surface roughness of the workpiece as illustrated in Fig. 27.17(b), 27.18(b) and 27.19(b). Grinding force increases with decrease in grinding velocity while the same increases with increase in table speed and depth of cut. Accordingly a trend is observed on decrease of surface roughness with decrease in grinding velocity and increase of both traverse speed and wheel depth of cut.

Exercise 27

Questions

Q1: Why is high velocity desired in grinding?

Q2: How may the specific grinding energy vary with material removal rate in grinding?

Q3: How is chip accommodation volume is related to material removal rate?

Q4: On which factors does the transverse roughness of workpiece depend during grinding?

Q5: Why does single layer grinding wheel show progressive rise of force during grinding of high speed steel?

Answers:

Ans 1:
It is desired to off set the adverse effect of very high negative rake angle of the working grit, to reduce the force per grit as well as the overall grinding force.

Ans 2:
Specific grinding energy will start decreasing with material removal rate because rake angle of the grit becomes more favourable with increase of grit depth of cut. However, if increase of material removal rate causes chip accommodation problem in the available inter-grit space then specific energy may increase.

Ans 3:
Volume of chip accommodation space ahead of each grit must be greater than the chip volume produced by each grit to facilitate easy evacuation of the chip from the grinding wheel.

Ans 4.
It mainly depends on the shape of the grits and overlap cuts made by the grits in the transverse direction. Lateral plastic flow of the material as a result of ploughing also influences the surface roughness.

Ans 5
The geometry of grit undergoes irreversible change in the form of rounding or flattening due to wear caused by rubbing action of hard carbides present in high speed steel.