ABRASIVE CUTTING

I. INTRODUCTION

Abrasive have been used as cutting tools since the dawn of civilisation. In the early stages of industrialisation, there was a tendency to move towards other cutting materials, but this process has recently stopped and, in fact, there is now a trend to replace many conventional cutting operations with abrasive methods. In advanced industrial countries, almost 25% of all machining operations are done with abrasives and this percentage is expected to rise to 50% in the next decade. This fantastic growth is due to the on-going research in the abrasives industry which has resulted in the development of sophisticated abrasive products and processes catering to enhanced requirements in terms of productivity, accuracy and quality. The chart shown in table below gives an idea of the vast scope of abrasive grinding processes. These range from traditional precision finishing operations through fettling and cutting off, to the latest primary stock removal processes used in steel plants. Most engineers are aware of the extreme precision which can be achieved by grinding, lapping or superfinishing, but few may be acquainted with the fact that automatic grinding machine can remove as much as 200kg/hour of material.

II. ABRASIVE MATERIALS

In the early stages of abrasive cutting, the products were made with natural materials like sand, emery, corundum etc. A great impetus to development was the manufacture of synthetic abrasive – aluminium oxide and silicon carbide. These two abrasive materials were gradually refined to achieve the optimum characteristics in terms of hardness, friability, sharpness, thermal resistance etc. The increasing use of high alloy steels, aero-space alloys, carbide tools and ceramics led to the development of new abrasives like synthetic diamond, boron carbide and boron nitride. The growth of the metallurgical industry and increasing popularity of grinding for metal conditioning led to the development of Zirconium Oxide as an abrasive material suitable for extremely heavy duty operations.

III. ABRASIVE PRODUCTS

The numerous abrasive cutting operations require a wide variety of abrasive products differing in size, shape and composition. The shape and size are easily chosen from the machine manufacturer's recommendations but the selection of specifications (composition) pose considerable problems. Unlike other operations, abrasive tools have to be selected

SCOPE OF ABRASVIE CUTTING PROCESSES

VERY ROUGH GRINDING	ROUGH GRINDING	PRECISION GRINDING	FORM GRINDING	OTHER ABRASIVE PROCESSES
1) Automatic Steel Conditioning	1) Pedestal	1) Cylindrical	1) Thread	1) Polishing
2) Swingframe	2) Bench	2) Surface	2) Gear	2) Lapping
	3) Portable	3) Internal	3) Profile	3) Honing
	4) Cutting-Off	4) Centreless	5) Drill Fluting	4) Superfinishing
	5) Floor Polishing	5) Tool & Cutter	6) Spline	5) Sanding
	6) Saw Gumming	6) Roll	7) Track	6) Tumbling
		7) Crankshaft	8) Cylindrical Angulare (Wheal head)	7) Electro-Chemical grinding
		8) Disc		
		9) Knife		
		10) Camshaft		

very carefully from a somewhat bewildering variety which are available. The five main parameters in abrasive product specifications are :

1. The type of abrasive
2. The grit size
3. The grade (or hardness)
4. The structure
5. The bond

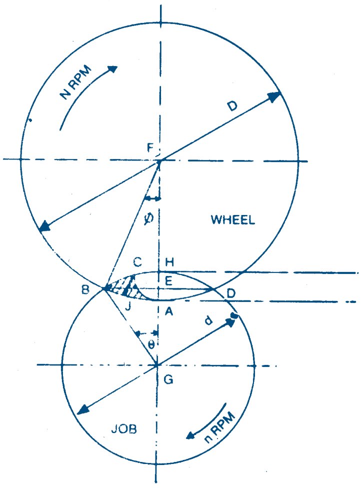
Each of these parameters can be varied over a wide range as shown in table 2. The initial choice, based on operating factors, require specialised knowledge and experience and is best left to the abrasive specialist. However, unlike other tools, the performance of abrasive products tends to be more susceptible to variations in operating conditions. As such, there is a definite need to optimise speci-fications on the shop floor by conducting proper trials. The shop engineer should be in a position to understand grinding problems and arrive at optimum solutions. This requires a basic knowledge of the grinding process.

IV. MECHANICS OF THE GRINDING PROCESS

Basic research in metal cutting invariably starts with the mechanics of chip information, because this helps to clarify the environment in which the cutting tool functions and the significance of various process parameters. The grinding wheel is a composite tool consisting of many thousands of cutting edges (grains) oriented in haphazard directions and therefore, does not lend itself to easy analysis. However, a simple analysis is possible if the grinding wheel is considered as a milling cutter and the abrasive grains as the individual teeth. This may be an over-simplification, but it does help in understanding the importance of the process parameters at least in qualitative terms.

A simple mathematical analysis for the case of plunge cut cylindrical grinding is given in Fig. 1. Let us assume that the grinding wheel is fed into the job to a radial depth of ‘t’. An abrasive grain on the wheel periphery will take time ‘T’ to cover the arc-of-contact ‘AB’. During the same time, the point‘B’ on the job will advance to the point ‘C’ along the arc ‘BC’. Thus a portion of material equal to the shaded triangle ‘ABC’ will be removed by the grain. The arc length ‘BD’ can be equated to the chord length ‘BD’ since the segment is very small. Then the arc-of-contact ‘AB’ is roughly equal to the length ‘BE’. From elementary geometry it can be seen that:

Fig. 1



$$
\begin{aligned}
BE^2 &= BF^2 - FE^2 = (FA)^2 - (FA - EA)^2 \\
&= 2.FA.EA - EA^2 \\
&= EA\,(2FA - EA) = EA.D
\end{aligned}
$$

By analogy $BE^2 = EH.d$

$$\therefore\ t = EA + EH = \frac{BE^2}{D} + \frac{BE^2}{d}$$

$$BE = \sqrt{\frac{tDd}{D+d}} = AB \text{ ... Equation (1)}$$

The above approximate expression shows that arc-of-contact increases with the increase in any of the values ‘t’,’D’ or’d’, i.e. with an increase in the depth-of-cut, diameter of wheel or job.

Each individual grain removes a triangular shaped chip and the depth-of-cut, increases from zero to a maximum of ‘CJ’ along the arc-of-contact. With sufficient accuracy the points ‘C’ and ‘J’ can be shifted on to the tangents at the point ‘B’. Then we have:

$$CJ = BC \operatorname{Sin} (\theta + \phi)$$

Each grain could have a maximum depth-of-cut equal to ‘CJ’ only if individual grains on the wheel periphery, were spaced at a distance equal to the arc-of-contact. In actual conditions the grains are much closer together and the individual depth-of-cut is much less than ‘CJ’. If we assume for simplicity that the grains are equally spaced and that there are ‘m’ grains per units length, then the number of grains along the arc-of-contact will be ‘m’. ‘AB’. The average depth-of-cut of each grain ‘a’ is therefore,

$$a = \frac{CJ}{m.AB} = \frac{BC}{AB}\ \sin\frac{(q + f)}{m}$$

The arc lengths ‘BC’ and ‘AB’ are the distances covered by points on the job and wheel surface in the same time ‘T’ substituting for the arcs in terms of diameter and r.p.m. we have:

$$a = \frac{p\ dnT}{p\ DNT}\ \sin\frac{(q + f)}{m}$$

or

$$a = \frac{dn}{DN}\ \sin\frac{(q + f)}{m}$$

...Equation (2)

Using the expression for ‘BE’ from (1) and neglecting small quantities of the second order we can derive an expression for sin (q + f).

The equation (2) can be brought to the form

$$a = \frac{2}{m}\ \frac{dn}{DN}\ \text{Ö}\overline{\text{ö}\frac{1}{D} + \frac{1}{d}\ \text{ö}\ t}$$

...Equation (3)

The above expression for the average grain depth-of-cut ‘a’ is extremely useful in understanding the effect of various process parameters. It is important to appreciate that the grain depth-of-cut characterises the peak to valley height (i.e. surface finish) of the ground surface and also the magnitude of cutting forces acting on the grain. The magnitude of cutting forces has a crucial bearing on the break down of the abrasive grains and bonding material and thus, determines the extent of the wheel wear, glazing, heat generation, etc. If these points are kept in view, one can arrive at the following important conclusions on process parameter selection and on ways of resolving various grinding problems:

a) **Use larger wheels and higher speeds for faster production.** It is evident that faster production is possible only if ‘t’ can be increased without increasing ‘a’ to a level at which the cutting forces would be prohibitively high. The obvious way to achieve this result is to compensate increase in ‘t’ by increasing the wheel diameter and speed. This is why there is a trend in modern grinding practice to continuously increase wheel size and speed. For example, crankshaft wheel sizes have steadily risen from 600mm to 1,200 mm diameter over the last few decades. Again vitrified wheel speeds in the ball bearing industry have risen from 30 m/sec to 80 m/sec. and in some cases upto 120 m/sec.

b. **Use greater depth-of-cut and higher work-speed to compensate for ‘hard cutting action’.** The so-called 'hard cutting action' occurs when the operating parameters are too mild to enable abrasive fracture and shedding of dull grains. Increase in depth-of-cut and job speed enhances the cutting forces and facilitates normal wheel wear. For example automatic grinding cycles are specifically selected in such a way that the roughing feed is high enough to cause wheel wear (and expose fresh sharp cutting edges) while the finishing feed is low enough to cause a slight dulling of the cutting edges which improves surface finish. An obvious corollary of the above rule is to decrease the depth-of-cut and work-speed when the wheels act ‘soft’.

c) **Use finer grit sizes for better surface finish and harder job materials.** The finer the grit size of the wheel, the more are the number of abrasive grains and bigger the value of ‘m’. It is quite clear from the equation that this decreases the value of ‘a’ and results in a better surface finish. At the same time, the cutting forces are prevented from increasing because the lower the depth-of-cut compensates the increased sheer resistance of harder materials. It should be noted that at an increase in bonding strength (hardness) can also help to withstand the higher cutting forces on harder materials but there is a danger of retaining blunt grains too long and burning the job.

Thus, it will be no exaggeration to say that the mathematical analysis of grain depth-of-cut is an invaluable aid in understanding the day-to-day problems in the Correct Selection and Use of Grinding Wheels.

V. CHARACTERISTIC FEATURES OF THE GRINDING PROCESS

a. *Heat and residual stresses*

A characteristic feature of the grinding process is the extremely high temperature in the cutting zone. This fact will be immediately evident even to a casual observer from the shower of sparks (which are actually molten globules of metal) flying off from the job. The reason for this phenomenon lies in the nature of chip formation as discussed earlier. The abrasive grains usually have a large negative rake angle and a considerable radius at the cutting edge when compared to the depth-of-cut. Therefore there is a tendency for the grains to initially slide over the metal (before 'biting' into it), and in the process to generate intense frictional heat at the point-of-contact. Actual measurements have shown that instantaneous temperature of 1,200° K and higher are reached. The poor thermal conductivity of the wheel and the short duration of heating combine to concentrate the heat generated in a thin surface layer of the work piece. The high local temperatures and quenching action of the coolant result in changes in the metal microstructure on the surface and leads to the formation of large residual stresses. In extreme cases these stresses can cause metal failure in the form of cracks, etc. On the other hand, it is important to appreciate that grinding parameters can be varied to induce moderate residual streees, which are beneficial in terms of the wear resistance and the static and the fatigue strength of the parts. This aspect of the process which can help in eliminating subsequent strain hardening operations (like burnishing etc.) needs to be further investigated and applied in practice.

b. *Cutting Forces*

The question of cutting forces is particularly important in precision grinding operations since it is linked to the problem of achieving the desired accuracy and surface quality. Various theoretical methods have been suggested to determine the magnitude of cutting forces based on the mechanics of chip removal and properties of the material being ground. However, these analytical methods are perforce, approximate as the tool geometry and other parameters are not constant as in the case of milling, turning etc. Investigations have shown that the abrasive grains in a grinding wheel act as miniature cutting tools with an average negative rake angle of 45°. This factor in conjunction with the unfavourable orientation of the grains and low depth of cut, results in high normal (radial) forces during grinding. Thus, for example, the ratio of the normal 'Py' to the tangential component 'Pz' of the cutting force is usually in the vicinity of $Py/Pz=2$ during grinding with a free cutting wheel. This ratio increases as the wheel glazes and may reach a value of 4 to 5. In comparison turning with a tool having 15° positive rake angle and 45° plan angle would give a ratio $Py/Pz\text{-}0.4$. In other words, the nature of distribution of cutting forces in grinding differs radically from other metal-removal processes. This poses various problems in designing the machines and achieving the necessary levels of accuracy.

c. *Power and energy requirements*

The material removed in grinding is in the form of a very large number of minute particles, as opposed to the substantial large chips formed during other machining processes. This results in considerably higher specific energy requirements. Moreover, the frictional losses are also much higher. As a consequence, the consumption of energy in grinding is much higher than in other processes like turning and milling. Since there is a definite tendency in India to use low-power motors on grinding machines, it may be worthwhile mentioning the basis of power selection for various operations. The power of the wheel-head motor for operations involving line contact can be calculated from the equation:

$$W = \frac{Pz.V.B}{102}$$

Where

W – Power in KW
Pz – tangential cutting force in Kg.per.cm width of wheel face
V – Wheel speed in m/sec.
B – Wheel width in cm.

Thus, the power needed is a function of the wheel size and speed as well as the unit cutting forces. For conventional grinding applications, the wheel speed are 30-35m/sec. (for vitrified wheels) and 48m/sec. (for resinoid wheels). The following table will give the idea of the value of 'Pz' for various types of machines:

Type of machine	Pz (Kg/cm)
Portable Bench and tool grinding	1
Cylindrical, Surface Grinding	2-3
Pedestal Grinding	3-4
Swingframe Grinding	5-6

An important corollary of the above expression for power is that their higher speeds can be advantageously used to reduce the cutting forces while increasing the power and material removal rate.

d. Wheel Wear

Tool wear is an universal feature common to all machining processes, but nowhere does it reach such high levels as in grinding. As a consequence, wheel cost is a major factor in the overall picture of grinding costs.

Grinding wheel wear occurs mainly as a result of the following phenomenon :

i. Wear of the cutting edges.

This is due to mechanical attrition as well as due to adhesion and diffusion processes. Mechanical attrition and adhesion can be reduced by increasing the high-temperature hardness of the abrasive grains, while the diffusion wear process can be minimised by the suitable selection of abrasives having the least chemical affinity to the material being cut. This is the reason why aluminium oxide abrasives are used on steels and silicon carbide abrasives on non-ferrous material. Wear can also be reduced by using cutting fluids with high pressure and chemically active additives which reduce friction and form a protective coating on the interacting surfaces.

ii. Chipping of the edges.

This can be minimised by the use of tougher grains having stronger shapes (blocky as against acicular). Considerable research work in this area has led to the development of a large variety of synthetic abrasive products tailor-made to suit specific grinding operational requirements.

iii. Failure of the bonding material and release of abrasive grains.

This happens due to the erosion of the bond material between the grains; softening of organic bonds due to heat in the cutting zone; fracture of the bonding material under repetitive shock loads; and cyclic stresses set-up in the wheel body due to elastic deformation of the wheel, etc. These forces are being combated by the use of improved bonding materials which have better adhesion and compatibility with the grains, and higher strength and heat resistance.

Since grinding wheels are consumed rather rapidly, a correct selection of specifications is possible only if wheel wear can be quantitatively evaluated. For this purpose, it is conventional to determine the grinding ratio which is the ratio between material removed and wheel-wear. This ratio is a valuable aid for the comparison of wheels provided due care is taken to keep all the other operating parameters constant during the test.

This provision is important because changes in operating conditions can drastically alter the grinding ratio and lead to erroneous conclusions.

e. Cutting efficiency

The cutting efficiency of a grinding wheel is the ratio of the material-removal-rate to the normal (radial) component of the cutting force. The necessity of considering the material-removal-rate is obvious whereas the reason for considering forces may not be so evident. Actually the force factor is equally important since it is correlated with such parameters like dimensional, geometrical accuracy, surface quality, power consumption etc. It has been found experimentally that the above ratio (cutting efficiency) decreases exponentially between dressings of the grinding wheel. This, of course, mainly applies to precision grinding operations and not to snagging operations where self dressing wheel is used. The decrease in cutting efficiency usually results in increased cutting forces as the feeds, which govern the material-removal-rate, are usually maintained at the constant level. Increase in the cutting forces, in turn, results in increased power consumption, greater deflections of the machine spindle and work-piece (causing errors of form), higher heat generation (causing burns, cracks and dimensional inaccuracy due to thermal expansion), and vibrations (causing chatter marks and poor surface finish), etc.

It is usually difficult or impossible to determine grinding forces, except in laboratory conditions. Therefore, for all practical purposes, it is preferable to evaluate cutting efficiency as the ratio of the material-removal-rate to the power consumed. This is simple and merely requires the use of a watt meter in the motor circuit.

f. Wheel Dressing.

The wheel dressing operation during grinding is the equivalent of tool sharpening and has the objectives of:

1. removing the blunt grains from the wheel and exposing a layer of fresh, sharp cutting edges.
2. removing the surface layer which has been clogged with chips; and
3. restoring the wheel form.

The conventional dressing methods using crush dressers, diamond tools, crusher rolls and grinding wheels or sticks are too well known to require elaboration. However, it is worth mentioning that there is a widespread tendency to remove excessive material during dressing, even though a cut of 0.05mm to 0.1mm (total for all passes) is usually sufficient for restoring cutting efficiency. An interesting development in the dressing field is the introduction of diamond rollers for the continuous dressing of wheels on automatic machines. The economics of this method are under investigation, but there is no doubt as to its advantage in high-precision grinding.

VI. JOB QUALITY IN PRECISION GRINDING.

The quality of jobs produced by precision grinding operations are characterised by accuracy, surface finish and surface quality. Increasing sophistication in the ball-bearing, automobile, instrumentation, aero-space and other high-tech industries has resulted in a reduction of production tolerances to a few microns and fractions of microns. It is evident that such accuracy is unattainable with ordinary manually operated machines. Therefore, the trend abroad is to use in-process gauging to ensure accuracy under mass-production conditions. It is worth emphasizing that numerous models of simple mechanical and pneumatic in-process gauging systems are readily available at low cost and can be advantageously used for production grinding. These systems offer a viable alternative in many cases to the imported electronic systems whose high cost seems to have acted as a deterrent to wide-spread use. Surface finish and quality are particularly important in grinding. It is worth discussing here the factors which affect surface finish in grinding.

i. Spark-Out

During grinding, the technological system comprising o the work-holding fixture, job and wheel are subjected to deformations under the action of the cutting forces. Thus, for example, the job deflects to a considerable extent in cylindrical grinding while the wheel spindle deflects appreciably in internal grinding, etc. Even if the wheel feed is stopped at a given moment, material removal continues due to the gradual decrease in the value of deflection of the various parts. This process of material removal without in-feed of the wheel is referred to as 'spark-out'. Research in grinding has shown that the rate of material removal and depth-of-cut decrease gradually (exponentially) during spark-out. The final value of the depth-of-cut approaches zero. It is evident, therefore, that the depth of scratches left by individual grains is extremely small, resulting in a very good surface finish.

A point which is often overlooked is that spark-out should not be continued too long. It has been established that the surface finish improves during spark-out upto a maximum point and then starts deteriorating. This is because low-amplitude vibrations due to imperfect balancing etc., begin to have a detrimental effect when the depth-of-cut falls below a certain value (at greater depths of cut the effect is negligible).

ii. Method of Dressing

The influence of the dressing operation on the surface finish is extremely high. Even a fine grit wheel if coarsely dressed, can result in a very poor finish. The dressing operation helps to produce an even surface on the wheel and precludes the possibility of individual grains protruding excessively from the surface. Moreover, diamond dressing at very slow feeds results in a generation of flat surfaces on the individual abrasive grains. Both these characteristics of diamond dressing result in better finish.

The most important parameter of the dressing operation is the feed. In one experiment, for example, change in the dressing feed from 500 mm / min to 100 mm / min while grinding with a 46 grit wheel resulted in improving the surface finish from 1.2 microns to 0.3 microns Ra. All other parameters were, of course, kept constant.

iii. Grit Size

The influence of grit-size on surface finish is well-known. However, the popular belief that 'fine' grit-size is the solution to all surface finish problems is not justified. The earlier analysis of the chip-removal process shows that a finer grit-size does result in a smaller grain depth-of-cut and therefore, in an improved finish. But it should also be noted that a fine grit wheel removes material slowly and increases in the feed-rate can cause prohibitively high cutting forces.

iv. Cutting Parameters

Cutting parameters influence surface finish in the following ways:

a) Traverse cylindrical grinding gives a better finish than plunge grinding. This is because the leading edge of the wheel during traverse grinding removes a greater portion of the material and the trailing portion works with a very small depth-of-cut and produces a good finish. Moreover, reversal of the job movement at the end of each pass, results in intersecting scratch-lines which facilitates the elimination of peaks on the profile. For the same reason modern machines have a wheel oscillating device for use during plunge grinding.

b) Increase in wheel speed improves surface finish because each unit area of the job surface comes in contact with a greater number of grains. Besides this, the depth-of-cut of each grain decreases as the speed increases and this also contributes to a better finish.

c) Decrease in the work-speed has an effect similar to increase in wheel-speed and improves surface finish.

v. Bond Material

During grinding, the bond material between the abrasive grains rubs on the job surface. Organic bonds, being non-crystalline and relatively soft, have a polishing effect, which improves surface finish. Hard crystalline vitrified bonds on the other hand tend to scratch the job surface and impart a poorer finish. The polishing action is best with rubber bonds. In this case the resilience (compressibility) of the bond prevents the individual grains from penetrating too deeply into the work and eliminates the possibility of deep scratches.

vi.Cutting Fluids

The influence of cutting fluids on surface finish is comparatively small. It has been found that fluids with higher lubricating properties (e.g. cutting oils) give a better finish. The reason lies in a reduction of the plastic deformation taking place in the cutting-zone and other complicated phenomena. A point to note is that the cleanliness (absence of suspended particles) of the fluid is extremely important. Poor filteration of the fluid can lead to fishtail marks, scratches and bad finish, even in the best of conditions. This can also stick and clog up the pipe resulting in an inadequate quantum of coolant flow.

The above analysis should be considered in its proper perspective. The importance attributed to any one particular factor, is only relative and can change depending on the operating conditions. Thus, it would be feasible to use a medium grit wheel with a long spark-out for getting good finish on a general purpose machine. For mass production it would be advisable to split operations into roughing and finishing, carrying out the latter operation with a fine grit wheel. Operations requiring extreme precision would necessitate critical attention to all the factors mentioned above. A balanced approach to surface finish problems is preferable to any rule-of-thumb.

VII.AUTOMATION OF THE GRINDING PROCESS

The grinding process has been traditionally used as a means of achieving mass-production scales with high accuracy and surface finish on precision components. These operations have for long been the exclusive domain of highly skilled operators. However, the trend towards mass-production and sophistication in industry has necessitated the development of automatic machines which do not depend on skilled labour. Development work has been concentrated on in-process gauging systems and automatic cycles, which are peculiar to the grinding process, as well as on the mechanisation of loading and unloading operations. In-process gauging is perhaps, the most important prerequisite for automation as it eliminates the frequent measurements (and consequent loss of time) which are necessary during manual operations. The enormous variety of electrical, pneumatic, electronic and digital read-out in-process gauging equipment which are presently available, precludes the possibility of any serious discussion within the scope of a short article. It should, however, be mentioned that the purpose of in-process gauging is not merely to achieve the required work-piece size, but what is equally important, to also give intermediate signals for controlling the multi-step automatic grinding cycles.

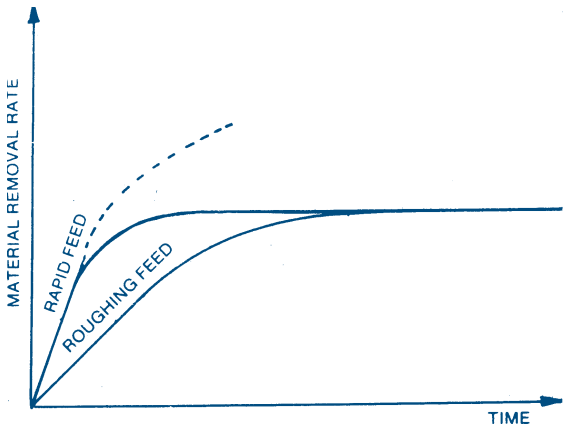
a. Automatic Grinding Cycles

The accuracy and productivity of the grinding process depends to a great extent on the use of automatic grinding cycles. The logical considerations which have formed the basis for development of grinding cycles are as follows :

i. Minimum time should be wasted on non-productive cycle elements like approach and initial contact between work-piece and wheel. This is extremely important as the low feed-rates used in grinding can lead to considerable time-loss if the rapid feed motion of the wheel-head is not corelated to the blank size. For example, the radical machining allowance within a batch may vary between 0.2 and 0.5 mm, and consequently, at a roughing feed of 1.5 mm/min. there would be an extra unproductive approach time of 12 secs. for the smaller blanks as compared to the larger blanks. Such time losses can be minimised by using rapid plunge feeds of 5-10 mm/min., to cover the gap between the moment when the fast hydraulic approach stops and cutting starts. The change to roughing feeds is actuated by a current relay in the motor circuit.

ii. The technological system comprising the machine-fixture-tool-workpiece has a finite rigidity and tends to deflect gradually till stable cutting conditions are established. Thus, for example, the cutting forces and material-removal-rate increase gradually (exponentially) from the moment when the wheel (at constant in-feed) touches the work-piece. There is a considerable period of low-intensity material removal before the wheel can remove metal at a rate commensurate with the selected roughing feed. This period can also be reduced by using rapid plunge feeds for the fast build-up of force and material removal and then switching over to the appropriate roughing feeds (See Fig. 2).

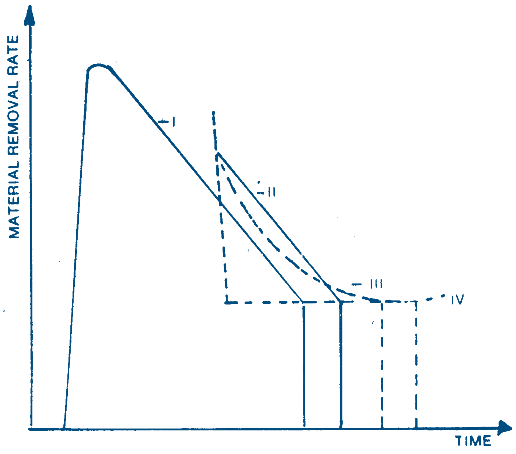
Fig. 2



iii. The material-removal-rate is theoretically limited by the necessity of avoiding a defective surface layer (burns, cracks etc.) on the finished work-piece and ensuring the requisite geometric accuracy and surface finish. Since the depth of penetration of surface defects depends on the material-removal-rate, the optimum cycle would be one where the material-removal-rate is built-up rapidly to a high value and then decreased gradually in such a way that the instantaneous depth of surface defects equals the instantaneous value of the grinding allowance. The rate of material removal at the end of the cycle should ensure the desired surface quality.

iv. The technological system also imposes certain restrictions on the material-removal-rate as the horse-power and deflections cannot be increased indefinitely to meet the theoretically optimum, productivity limits. This necessitates the use of stepped cycles which are optimum within practical constraints (Fig. 3, curve II).

Fig. 3



v. There are further constraints in designing mechanisms and feed-back control systems for varying the feed continuously on the basis of values of instantaneous machining allowances. Therefore, in the interests of simplicity and reliability, a 'spark-out' stage is sometimes preferred (Fig. 3, curve III).

vi. During initial development work of grinding cycles, the last cycle element was usually 'spark-out', i.e.: in-feed, was stopped (or reduced) and further material removal occurred due to a spring-back action of the system. However, research showed that the 'spark-out' process was unstable because the magnitude of cutting forces (and material-removal-rate) fluctuated at the moment of wheel retraction due to a variation in cutting efficiency, etc. This results in size and surface quality variations. The development of sophisticated mechanisms which reduce the 'stick-slip effect' has made it possible to achieve the controlled low feed-rates which are necessary for getting a fine surface finish. Therefore, modern automatic machines usually incorporate multi-step feed cycles without spark-out (Fig. 3, curve IV). This has the advantage of using relatively simple electrical relay control systems. A reverse-feed stage is incorporated before the finishing-feed stage so as to reduce the deflections in the system and enable a constant material-removal-rate immediately prior to the retraction of the wheel. This precaution eliminates any size variation due to a delayed response of the gauging device and also results in stable values for surface finish.

VIII. RECENT TRENDS IN THE DEVELOPMENT OF ABRASIVE CUTTING

The basic trend in the development of abrasive cutting processes has been to find ways of improving the rate of stock-removal so that abrasive processes can replace conventional machining methods.

In the precision grinding area, the main limitation on the rate of stock-removal is the undesirability of excessive cutting forces. From the equation for power mentioned earlier, it is evident that the cutting forces are directly proportional to the power consumed and inversely proportional to the cutting speed. Therefore, the obvious way to increase material-removal-rate is to increase the available power and cutting speed simultaneously so that cutting forces are kept at a relatively low value. This approach which is termed as "Abrasive Machining" has been successfully adopted in the latest range of precision grinding machines used in the ball bearing, automotive and other high-tech industries. Some typical examples include the new models of Newall crank-shaft grinders, 'Famir' track grinding machines, Cincinnati Twin-Grip centreless grinders, Norton High-Speed cylindrical grinders, etc. These machines can finish grind parts from blanks made of bar stock, forgings or castings without any preliminary machining.

In the semi-precision grinding field there are numerous jobs which are rough machined and ground to obtain accurate locating surfaces. A significant proportion of such jobs are cast housings which pose considerable problems in conventional machining because of the hard cast surface and sand inclusions, etc. This is an area in which 'abrasive machining' concepts have paid significant dividends. A large number of segmental surface grinding machines with power ratings of 100-150 HP and more are available which can effectively replace milling and planing machines. The advantages gained from this changeover are both in terms of unit costs and productivity.

The grinding process has gradually attained a pre-eminent position in the steel conditioning field. Concerted efforts by machine and abrasive manufacturers (mainly Norton Co., USA and Centromaskin Co., Sweden) have resulted in the development of automatic steel conditioning equipment incorporating such features as a 300 HP motor, wheel speed of 80m/sec. automatic control of speed, power etc. The wheels used for this process are made with the sophisticated zirconium oxide abrasive and a special hot-pressed resinoid bond.

A significant trend in the recent years has been the introduction of diamond, cubic boron nitride (popularly known as Borazon) abrasive product for a wide range of precision applications. These two new abrasives deliver a dramatic improvement in performance vis-a-vis conventional abrasives when grinding some special materials like carbides, ceramics, high-alloy tool steels, granite, marble etc. It is expected that these two abrasives will gradually replace conventional abrasives in many precision grinding operations.

IX. CONCLUSION

Abrasive cutting processes have reached a stage of development where they offer a viable alternative to most other conventional cutting methods. Therefore, it is imperative that production engineers keep abreast of developments in this field. Needless to say, the abrasives industry in India is making every effort to supply quality products conforming to the best in international standards.