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Exploring Precision Machining Processes to Improve Manufacturing Systems

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Introduction

About this Free Book

Exploring Precision Machining Processes to Improve Manufacturing Systems is a FreeBook brought to you by CRC Press - Taylor and Francis Group. It contains a collection of curated content from some of our bestselling books and leading experts. We hope you enjoy it.

Finishing is the final operation after a part is sized and shaped. Currently in high tech industries, there is a demand for nano level surface finishing of components. This process is done to improve the surface finish, to remove the recast layer, or to remove surface and sub-surface defects. The result is low friction, longer product life, and low power requirements. Equally important is the aesthetic aspect of the product. This subject is growing very fast from the technology as well as a science point of view. **Nanofinishing Science and Technology: Basic and Advanced Finishing and Polishing Processes**, edited by Vijay Kumar Jain, provides information on a subject that is very limited out in the marketplace, particularly books that deal with both the science as well as the technology aspects.

Grinding is a crucial technology that employs specific abrasive processes for the fabrication of advanced products and surfaces. **Handbook of Machining with Grinding Wheels, Second Edition,** authored by Ioan D. Marinescu, Mike P. Hitchiner, Eckart Uhlmann, W. Brian Rowe, and Ichiro Inasaki, highlights important industry developments that can lead to improved part quality, higher productivity, and lower costs. While the first edition focused on the basics of abrasive machining technology and presented a unified approach to machining with grinding wheels, the second edition ties in the continued need for traditional processes in conjunction with the latest applications. This book highlights new research topics that include: nanotechnology, alternative energy, and additive manufacturing, compares related approaches, and provides numerous references throughout the book.

Completely revised and updated, this second edition of **Fundamentals of Machining Processes: Conventional and Nonconventional Processes**, authored by Hassan Abdel-Gawad El-Hofy, covers the fundamentals machining by cutting, abrasion, erosion, and combined processes. The new edition has been expanded with two additional chapters covering the concept of machinability and the roadmap for selecting machining processes that meet required design specification.

Metal Cutting Theory and Practice, Third Edition, authored by, David A. Stephenson and John S. Agapiou, shapes the future of material removal in new and lasting ways. Centered on metallic work materials and traditional chip-forming cutting methods, the book provides a physical understanding of conventional and high-speed machining processes applied to metallic work pieces, and serves as a basis for effective process design and troubleshooting. This latest edition of a well-known reference highlights recent developments, covers the latest research results, and reflects current areas of emphasis in industrial practice.

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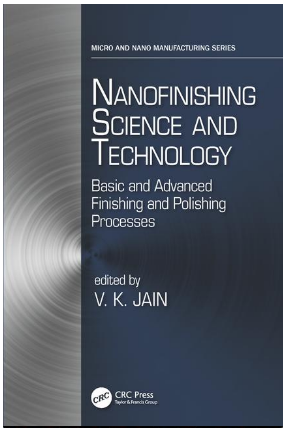
Nanofinishing: An Introduction



1

Nanofinishing: An Introduction

1.1 Introduction

Finishing is mostly the last operation in the manufacturing sequence of a part. It is an important operation to achieve certain surface properties on the part to fulfil its functional performance requirements. This operation is quite expensive and time consuming. In recent years, extensive technological developments have taken place in the field of nanofinishing. Traditional finishing processes (TFPs) have many constraints with reference to the size and shape of the parts that can be finished, the surface integrity of the finished parts and the level to which the surface finish can be achieved. To overcome some of the constraints of the TFPs, advanced finishing processes (AFPs) have been developed to the extent that they are being used on the shop floor of medium and large scale industries. There is a specific need of such processes especially in case of free-form surfaces which need flexible finishing tool to achieve nanometre level surface finish without any surface and sub-surface defects. Some of the examples where we come across the free-form surfaces are human implants as shown in Figure 1.1.

The AFPs would be required to finish some of the human implants with- out any surface and sub-surface defects. The nanofinishing processes can be classified in the following categories:

Classification of nanofinishing processes Traditional nanofinishing

processes

1. Grinding
2. Honing
3. Lapping

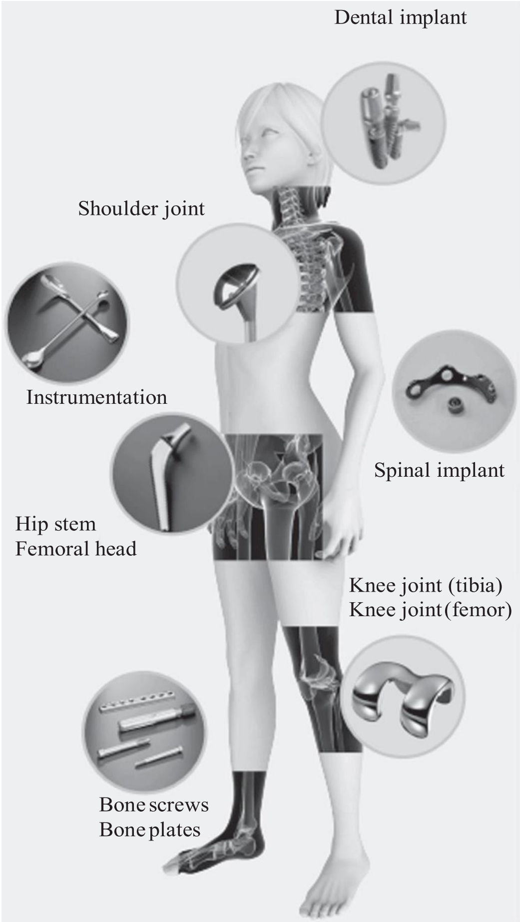


FIGURE 1.1
Human implants that would require high level of Finish.

Advanced nanofinishing processes

General advanced nanofinishing process

4. Abrasive flow finishing (AFF)
5. Elastic emission finishing (EEF)
6. Elastic abrasive finishing (EAF)
7. Focused ion beam finishing (FIBF)

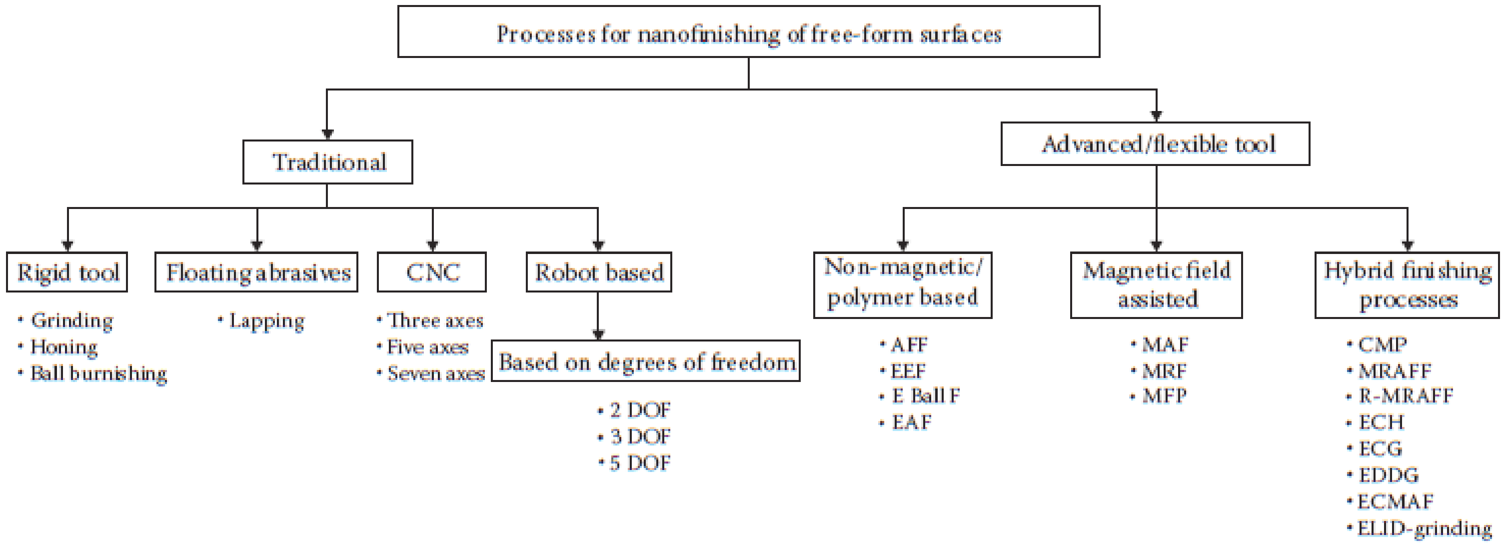
Magnetic field assisted advanced nanofinishing processes

8. Magnetic abrasive finishing (MAF)
9. Double-disk MAF (DDMAF)
10. Magnetorheological finishing (MRF)
11. Magnetorheological AFF (MRAFF)
12. Nanofinishing of free-form surfaces using ball end magneto- rheological tool (BEMRT)
13. Magnetic float polishing (MFP)

Hybrid advanced nanofinishing processes

14. *Electrochemical grinding (ECG)
15. *Electrochemical MAF (ECMAF)
16. Electrochemical honing (ECH) of gears
17. Electrolytic in process dressing (ELID) grinding
18. Chemomechanical polishing (CMP)
19. Chemomechanical MRF (CMMRF)
20. Electric discharge diamond grinding (EDDG)

In this chapter, a very brief introduction to the working principles of different nanofinishing processes is given. Detailed scientific analysis and working principles are discussed in the individual chapters in this book. The shape, size and finish requirements of a component play an important role in the selection of a particular type of nanofinishing process. For example, regular shapes such as cuboids, cylinders, spheres, etc., and their combinations can be comparatively easily finished by TFPs as well as AFPs. However, nanofinishing of free-form surfaces is comparatively difficult because it requires continuously varying relative motion between the workpiece and the finishing tool in three or more axes. For example, knee joint, hip joint, turbine blades, etc., have free-form surfaces and they cannot be finished so easily and uniformly by TFPs and some of the AFPs. In view of this requirement, engineers have tried to utilize the capabilities of CNC and robots to achieve a relative motion very close to the free-form surface coordinates. Keeping this in view, the nanofinishing processes for free-form surfaces can be classified as shown in Figure 1.2.



AFF : Abrasive flow finishing
CMP : Chemomechanical polishing
DOF : Degree of freedom
EAF : Elastic abrasive finishing
E Ball F : Elastic ball finishing
ECG : Electrochemical grinding
ECH : Electrochemical honing
ECMAF : Electrochemical magnetic abrasive finishing
EDDG : Electric discharge diamond grinding
EEF : Elastic emission finishing
ELID-grinding : Electrolytic in process dressing grinding
MAF : Magnetic abrasive finishing
MFP : Magnetic float polishing
MRF : Magnetorheological finishing
MRAFF : Magnetorheological abrasive flow finishing
R-MRAFF : Rotational-magnetorheological abrasive flow finishing

FIGURE 1.2
Classification of nanofinishing processes for free-form surfaces.

1.2 Traditional Nanofinishing Processes

This category consists of TFPs, mainly grinding, honing and lapping, that can produce nanometre level (or nano level) surface finish on different kinds of workpieces with certain constraints such as size, shape, complexity, work- piece material properties, etc.

Grinding: Grinding is a machining process that employs a grinding wheel having abrasive particles at its periphery. The grinding wheel rotates at high speed to remove material from a workpiece comparatively softer than the abrasive particles. Modern grinding machines may have computer-controlled feed drives and slide way motions, allowing complex shapes to be machined through CNC programs without needing any human intervention during operation. Grinding machines equipped with adaptive control would allow the machine to run for most of the time under optimum conditions. Some CNC grinding machines may have algorithms to compensate for wheel wear during the process.

Cooling and lubrication play an important role during the grinding process while aiming at high material removal rate (MRR) and high quality of the ground surfaces. In this direction, many new grinding fluids and methods of delivering grinding fluid have been developed in the past. Minimum quantity lubrication provides an alternative to flood and jet delivery coolant and lubrication, aimed at environment-friendly manufacturing. In practice, four basic grinding processes are in use: (a) surface grinding, (b) peripheral cylindrical grinding, (c) face surface grinding and (d) face cylindrical grinding. However, other categories/classifications also have been mentioned in the literature.

Honing: Honing is an abrasive machining process that produces a precision surface by scrubbing abrasive stone against it along a controlled path on the pre-machined workpiece. It uses a bonded abrasive tool and it is recommended to finish hard materials and hardened surfaces. Honing is normally performed after precision machining such as grinding to achieve the desired surface characteristics. High-precision workpieces are usually first ground and then honed. Grinding determines the size, and honing improves the shape. Honing can give surface finish in the range 130–1250 nm compared to 900–50,000 nm in grinding. Honing is also known as super finishing process. There are many types of honing processes, but all of them consist of one or more abrasive stones that are held under pressure against the surface they are working on. During honing, the stone/stick (abrasive tool) should not leave the work surface any time during finishing and it must cover the entire work length. Some of the process input parameters that affect the process performance are RPM of the honing tool, length and position of the honing stroke, honing stick pressure, etc. Thus, honing is an abrasive finishing process that is used to enhance the dimensional and geometrical accuracy of the functional surfaces of engineering parts. In this process, the abrasive particles apply a comparatively low cutting pressure. Normal machining methods like turning, milling and classical grinding cannot meet these stringent requirements mainly due to process limitations.

Honing is primarily used to improve geometric form of a surface; how- ever, it also changes the surface texture. Typical applications are finishing of cylinders for internal combustion engines, air bearing spindles and gears. The results of the honing process are tight tolerances, high geometrical accuracy and good surface finish. A “cross-hatch” pattern is used to retain oil or grease to ensure proper lubrication. It is possible to correct certain types of errors of the cylindrical components, as shown in Figure 1.3.

The honing process has been combined by other advanced machining process, namely, electrochemical machining (ECM), and developed a new hybrid process known as the ECH process, as discussed later in this book.

Lapping: Lapping is a machining process in which two surfaces are rubbed together with abrasive particles between them, by hand movement or usually by using a machine (Figure 1.4). The other form of lapping involves a softer

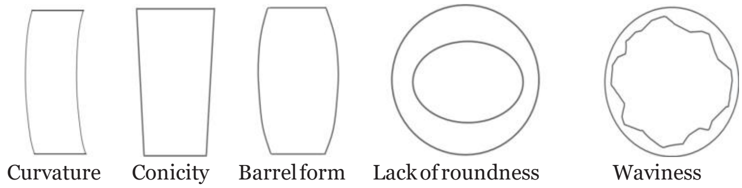


FIGURE 1.3
Errors on the workpieces that can be corrected by the honing process.

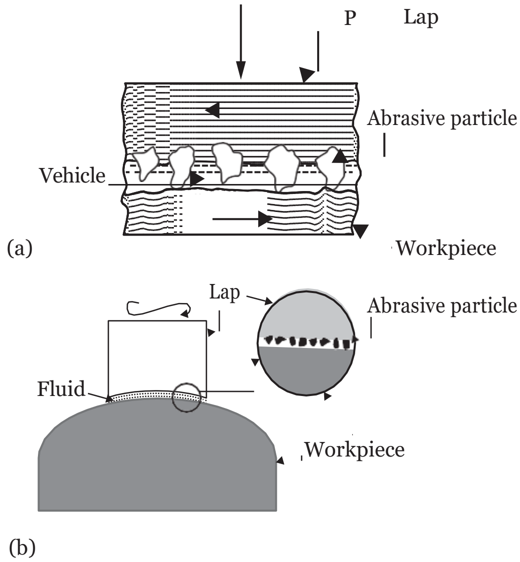


FIGURE 1.4

(a) Lapping using a charged lap. (b) Lapping using free abrasive particles between the lap and workpiece.

material such as pitch, cast iron, or a ceramic for the lap, which is "charged" with abrasive particles. The lap is then used to cut a hard material—the workpiece. The abrasive particles (say, alumina, silicon carbide, etc.) embed within the soft material (Figure 1.4a), which holds it and permits it to score across and cut the hard material (that is workpiece). The carriers used in lap- ping operation are grease, olive oil, kerosene with other oil, etc. Lapping can be used to obtain a specific surface roughness and accurate surfaces, usually very flat surfaces. Surface roughness and surface flatness are two quite different concepts.

The mechanism of lapping on brittle material (brittle fracture) is different from the mechanism for metals that are deformed plastically (shear deformation). Lapping process is found be an ideal option to achieve the highest surface quality requirements.

1.3 General Advanced Nanofinishing Processes

General advanced nanofinishing processes can be divided into different types, as shown in here. The following types of general advanced nanofinishing processes do not need assistance of magnetic field during finishing operation; hence, they have been kept in a category different from the category of magnetic field assisted advanced nanofinishing processes. This category includes the following four different types of nanofinishing processes.

a. AFF
b. EEF
c. EAF
d. FIBF

Abrasive flow finishing (AFF): AFF is a highly versatile finishing process that can finish components irrespective of their complexities, material properties, internal or external surfaces (including concave and convex), free-form sur- faces and size. Starting from a simple to highly complex feature, this process has been able to finish up to a few tens of nanometre Ra value. According to the shape and size of the feature to be finished, one should design the medium viscosity, composition and finishing conditions. This process uses viscoelastic medium (polymer + abrasive particles + plasticizer + additives), which is passed through the passage/feature to be finished. The initial viscosity of the medium and the passage restriction for the medium to flow decide what forces will act on the workpiece surface to be finished. Figure 1.5a shows a complex workpiece (knee joint) that can be comparatively more easily finished by AFF process. Figure 1.5b shows surface roughness plots of one of the faces of a knee joint before and after finishing. Figure 1.5c shows the normal force (Fn) and axial force (Fa) acting on the workpiece to remove material in the form of micro/nano-chips. The size of the chip is governed by the magnitude of the forces acting on the workpiece. In this nanofinishing process, normal force is responsible for the penetration of an abrasive particle into the workpiece surface and axial/shearing force is responsible for removing the material in the form of micro/nano-chips. In this process, the forces acting on the workpiece cannot be varied once the medium com- position and hydraulic pressure (which decides axial force, Fa) are fixed. The viscosity of the medium changes to some extent based on the passage shape and size through which it is extruded. Thus, it can be concluded that on- line control of forces in AFF is not feasible. The details of the different types of setup configurations (one-way AFF, two-way AFF and orbital AFF), force analysis, medium properties and different applications in high-tech industries and biomedical applications have been discussed in different chapters.

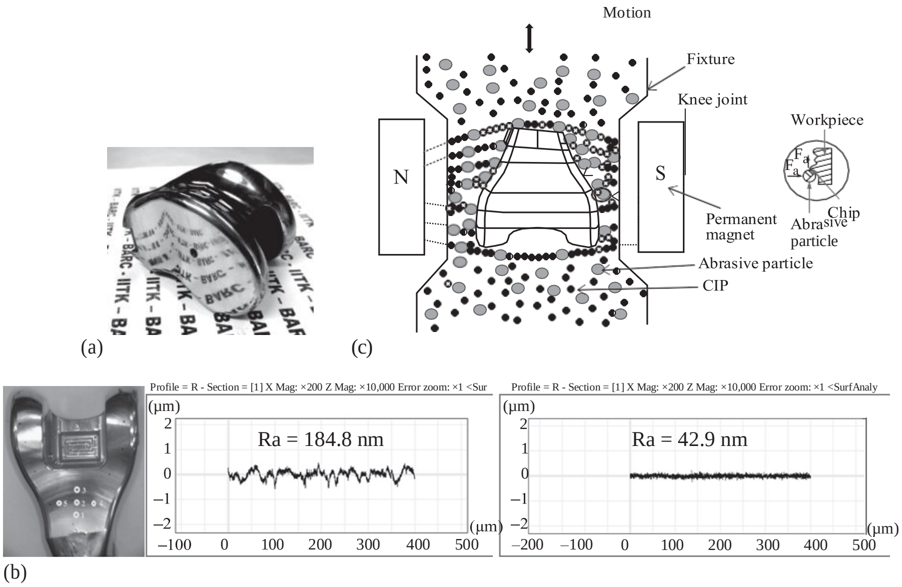
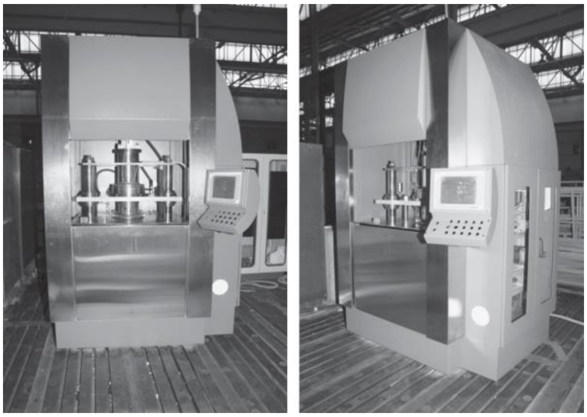


FIGURE 1.5
(a) Finished knee joint having free-form surface. (b) Complex face of a knee joint finished using the AFF process. Initial surface roughness = 184.8 nm; final surface roughness = 42.9 nm; percentage reduction in sur- face roughness value = 72.86%. (From Sarkar, M., Nanofinishing of freeform surfaces by abrasive flow finishing (AFF) process, (c) AFF of a knee joint. Enlarged view on the right side showing normal (Fn) and tangential (Ft) forces acting on the workpiece surface.

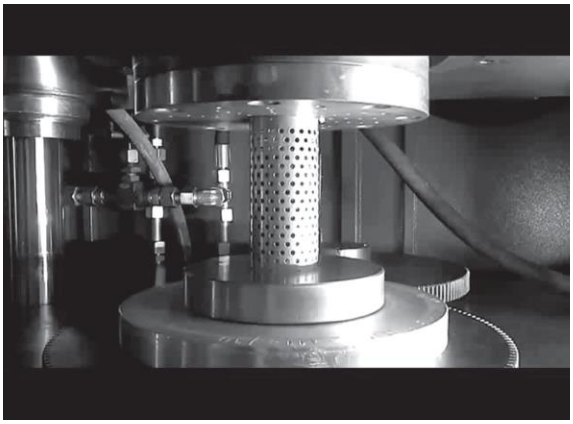
Some researchers have used sintered ferromagnetic abrasive particles in the viscoelastic carrier to control the movement of the ferromagnetic abrasive particles by the magnetic field during the finishing operation. It is claimed that it has improved the finishing rate (FR) of the process.

Figure 1.6a shows an AFF machine developed by CMTI Bangalore in collaboration with IIT Kanpur. Figure 1.6b shows a component that has been finished by this process efficiently in spite of its complexity. In this component, a large number of mini holes have been deburred and finished simultaneously.

This process has been employed for nanofinishing of aerospace components, gas turbine components, automobile components, etc. Lately, this process has been employed for finishing of free-form surfaces efficiently, namely, knee joint in just one fourth time of what was taken by MRF process.



(a)



(b)

FIGURE 1.6
(a) AFF machine developed by CMTI Bangalore and IIT Kanpur (India). (b) A tube having a large number of mini holes deburred and finished simultaneously.

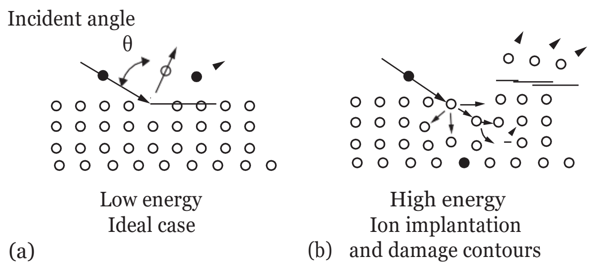
Elastic emission finishing (EEF): In this process, material is removed mechanically but atom by atom. Ideally, each nano-level abrasive particle removes material atom by atom from the top surface of the workpiece. This process is normally called as *elastic emission machining*; however, in this chapter, it is called as EEF because the objective of the process is to improve the surface characteristics, not to create any features on the part as done in case of machining process (Google Scholar: elastic emission machining). This process is truly capable of producing nano or sub-nano level of surface finish but it is definitely a very slow process. Under certain conditions, this is the only mechanical but comparatively simple process that can provide solution to some problems where sub-nano level of surface finish is required.

In this process, abrasive particles are dragged by the flow of liquid over the workpiece surface (not pressed directly by the tool on the workpiece). There is a high probability that the nano-size abrasive particles detach some atoms from the stationary solid material that is the workpiece. If it continues for a long time, atom-by-atom material removal is possible without applying large mechanical force. Workpiece material is one solid body and loose abrasive particle is another solid body in EEM process.

Elastic abrasive finishing (EAF): In this process, abrasive particles are embedded in the elastomeric beads in the form of spherical balls of meso/micro- scale dimensions. When these particle-embedded balls strike the peaks of rough surface of a workpiece, they are able to remove a very small amount of material by shearing the peaks but at the same time the balls are flexible enough not to penetrate too deep to deteriorate the existing surface finish. These elasto-abrasive balls can also be made with magnetic characteristics by adding iron particles along with abrasive particles. By adding ferromagnetic particles, the flexibility of the balls reduces, but on-line control of force acting on the workpiece becomes feasible. In all finishing processes, the objective is to enhance the surface characteristic (including surface integrity) or improve surface roughness value, or both, in place of having higher material removal rate.

Focused ion beam finishing (FIBF): The last process of this class, FIBF is a slightly different process compared to the other three processes discussed earlier. This process cannot be used for finishing a large surface area, say, even in terms of a few millimetre square, because it is comparatively very slow process. This process is mainly suitable for creating nano-features or some time micro-features. Here, a stream of ions (ions beam) hits the work- piece surface. Theoretically, it is assumed that the energy carried by an individual ion while hitting the workpiece surface is slightly higher than the bonding energy of the atoms on the top surface of the workpiece. As a result, when an ion hits an atom, the atom is knocked off (or, sputtered off) from the surface of the workpiece as well as the ion is also knocked off (Figure 1.7a).

FIGURE 1.7
Focused ion beam machining/finishing.



However, if the energy carried by an ion is less than the bonding energy of the atom, then the ion will be knocked off without removing an atom from the workpiece surface. If the energy carried by an ion is much larger than the bonding energy of the atoms, then in place of one atom, it will knock off many atoms from the workpiece surface at a time, and this ion will be implanted inside the workpiece surface (and form a surface defect) (Figure 1.7b). This process, by its nature of material removal, gives surface roughness value in the range of sub-nanometre or nanometre but on a very small area (normally, in the μm^2 or nm^2). This process is also known as ion beam figuring (Google Scholar: ion beam figuring).

1.4 Magnetic Field Assisted Advanced Nanofinishing Processes

There is an important class of nanofinishing processes in which magnetic field is used to control the forces acting on the workpiece to remove material from the workpiece in the form of nano-chips so that a nanometre level finish can be achieved on the targeted surface. This class of processes includes the following:

a. MAF
b. DDMAF
c. MRF
d. MRAFF
e. Nanofinishing of free-form surfaces using ball end magnetorheological tool
f. MFP

Magnetic abrasive finishing (MAF): The previous list is not exhaustive in the sense that there could be other versions of such types of processes that are not listed. These processes can be further classified in two sub-categories: The first category includes first two processes (a and b) in which iron (or ferromagnetic) particles are mixed with the required abrasive particles. This mixture is brought close to the magnet and the workpiece surface to be finished. Due to the magnetic field effect, this mixture forms a flexible magnetic abrasive brush (FMAB), which can change its shape according to the shape of the workpiece, definitely, within certain limits of the size and shape. This brush, when brought in close proximity of the surface to be finished, applies a small normal force that is partly responsible for indentation of abrasive particles of the FMAB, inside the workpiece surface. Usually, direct normal force is also applied to enhance the FR. When there is a relative motion between the FMAB (particularly, abrasive particles) and the workpiece, the abrasive particles shear off the peaks on the workpiece surface and surface finish improves (Figure 1.5c). The shearing force is applied by rotation of the FMAB (or the magnet) using an electric motor. Further, the MAF process can use either sintered ferromagnetic abrasive particles or a mixture of abrasive and ferromagnetic particles. It forms a series of chain-like structure.

However, in many cases, in place of the mixture of ferromagnetic and abrasive particles, researchers and industrial users prefer to use sintered ferromagnetic abrasive particles, which are claimed to give higher MRR or higher FR. Using this process, less than 10 nm surface roughness value on the silicon nitride workpiece has been achieved. In this process and other processes of this category, usually electromagnets are used for producing magnetic field cloud. However, the electromagnets are heavy and their rotation (or rotation of FMAB) becomes a bit difficult. Hence, some researchers have used permanent magnets to create magnetic field cloud. Successful experiments have been carried out by different researchers using permanent magnets in place of electromagnets. However, it is achieved at the cost of reduced flexibility in terms of on-line/real-time changing magnetic flux density, which is possible in electromagnets.

Double-disk MAF (DDMAF): The second process (DDMAF) of this category is a modified version of the MAF process. The modified version of the MAF process was developed so that the productivity of the process could be enhanced. In this case, the disc type of workpiece is finished on both sides (top and bottom surfaces) at the same time by producing FMAB on both sides by using two independent sets of magnets (or, electromagnets) so that the time taken to finish the workpiece is reduced to approximately half.

Magnetorheological finishing (MRF): The second sub-category of the processes encompasses the remaining four processes (c to f) listed earlier. In these processes, magnetorheological fluid (MR fluid) is used as a finishing medium. This fluid consists of carbonyl iron particles (CIPs) or iron particles as magnetic particles, abrasive particles, carrier fluid and some additives (to equip the fluid with specific properties, say, anti-corrosive nature, etc.). In place of mixture of iron and abrasive particles, sintered ferromagnetic abrasive particles can also be tried for getting better performance. Again, when this medium is brought under the magnetic field zone, FMAB (Figure 1.8b) is formed whose strength depends on the composition of the medium and finishing parameters including magnetic field strength.

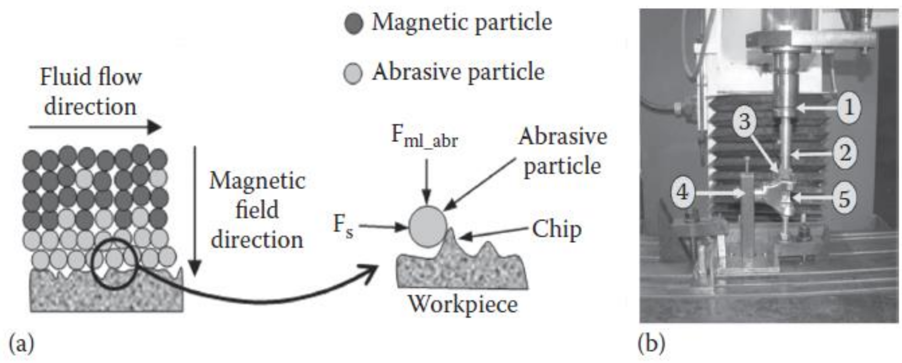


FIGURE 1.8
(a) Close view of MR polishing fluid. (b) Photograph of MR finishing tool for free-form surfaces (1—CNC milling machine head, 2—MR finishing tool, 3—MR polishing fluid [or FMAB], 4—fixture for knee joint implant, 5—knee joint implant).

Magnetorheological AFF (MRAFF): This process is a modified version of the MRF process that has the limitation that it can mainly finish comparatively softer materials and external surfaces. To overcome these limitations of the process, a process was developed in which the setup of the AFF process was used and the MR fluid medium was modified to finish very hard and complex shaped components including 3D and free-form surfaces. This modified process has been used to finish free-form surfaces (knee joint implant) made of titanium alloy. This process can be easily employed for internal as well as external free-form and other complex surfaces made of hard to finish materials by articulating the fixture, the medium constituents and magnetic field.

Nanofinishing of free-form surfaces using ball end magnetorheological tool: This is again a modified version of the MRF process in which a ball-shaped brush is formed by using a straight magnet (or cylindrical or other shape), either permanent magnet or electromagnet. The brush (or FMAB) is given raster motion with reference to the surface of the workpiece to be finished. This process can be quite useful especially in case of micro-sized complex features that are to be finished to a certain acceptable level of surface roughness value.

Magnetic float polishing (MFP): All the nanofinishing processes of class 2 except MFP are applicable for finishing flat, cylindrical and other simple and complex shaped workpieces but they cannot efficiently finish spherical shaped workpieces such as ceramic or stainless steel balls, say, for bearings. MFP is the process that can efficiently finish spherical workpieces. In this process, again, MR fluid is used along with a float, bank of magnets and a rod that pushes the fluid downward and rotates on its own axis. Here, the buoyancy force makes the abrasive particles to rub against the ceramic balls. Shear force removes the material in the form of micro/nano-chips. This is an efficient and deterministic process that has not been exploited to its fullest capabilities.

1.5 Hybrid Nanofinishing Processes

When two or more types of machining/finishing processes (traditional or/ and advanced) are combined together to take the advantage of their merits and to minimize the effect of their weaknesses, this new process is called as a hybrid process. There are many hybrid nanofinishing processes that have been developed over the years as per industries' requirements. Some of them are as follows.

a. ECG
b. ECMAF
c. ECH
d. CMP
e. ELID and grinding
f. CMMRF
g. EDDG

Electrochemical grinding (ECG): When a particular nanofinishing process inde- pendently is not capable to satisfy the job requirements, then two or more processes (traditional or/and advanced processes) can be combined together to get the desired results. For example, grinding as such gives reasonably good surface finish, but it results in thermal defects such as micro/nano cracks, thermal residual stresses, etc. Some researchers combined grinding process with ECM. Here, ECM helps in removing a small layer of material so that thermal defects, if any, due to grinding no longer remain in the workpiece. This process is known as ECG, which gives better quality of the finished component and higher FR as well as higher MRR. However, this also has a problem of corrosion of the finished component. But its potential has not been appropriately exploited by the shop floor engineers as well as researchers working in this field. It is believed that this process has a lot of potential for economic and highly efficient nanofinishing of difficult-to- finish materials. In the ECG process, material is simultaneously removed by grinding process as well as by anodic dissolution process (ECM). Here, the ECG wheel life increases as high as 10 times the life in traditional grinding, and MRR is higher than the individual MRR of grinding as well as ECM. Further, FR is also higher than in grinding process. Figure 1.9 shows the mechanism of material removal by grindings as well as by EC dissolution (or ECM) simultaneously. Figure 1.9 shows electrochemical surface grinding with three zones through which the material removal is taking place. In zone 1 and zone 3 (or stage 1 and stage 3), where the abrasive particles are not in contact with the workpiece, the material removal is taking place due to electrochemical dissolution only. In zone 2, where the abrasive particles are in contact with the workpiece surface, they are forming electrolytic cells between the bonding material (metal) of the grinding wheel and workpiece. The workpiece is the forming anode and the grinding wheel is the forming cathode. The material is removed due to electrolytic dissolution.

Since the abrasive particles are interacting with the workpiece material, the material is being removed by grinding process also. This is shown in Figure 1.9b under "Grinding + EC dissolution." Since the material removal by grinding phenomenon in ECG is very low, grinding wheel life during ECG is very high (say, up to 10 times).

Electrochemical magnetic abrasive finishing (ECMAF): ECM is normally used for shaping and sizing a component made of electrically conducting material but the level of surface finish achieved is not very high. Hence, many times after ECM, a finishing operation is performed on a separate setup. This makes the manufacturing process less efficient and comparatively more expensive and time consuming. However, if an ECM operation is continuously followed by a nanofinishing operation (in the present case, MAF operation), then in one setup and in one operation, one can get the machined as well as finished component. This later combined operation is a hybrid operation (ECM + MAF), which is called as ECMAF operation. This hybrid operation (ECMAF) results in higher productivity. Thus, the material is simultaneously removed by both the mechanisms of electrochemical anodic dissolution and mechanical shearing of the workpiece

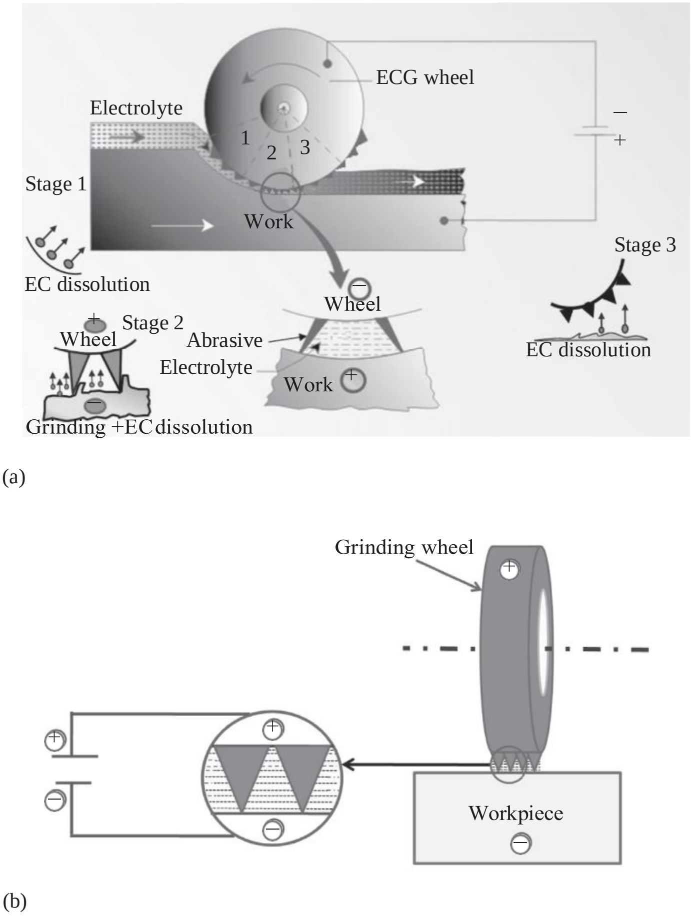


FIGURE 1.9
Mechanism of material removal during ECG. (a) Front view of surface grinding clearly show- ing three different zones and (b) side view of surface grinding showing mainly zone 2.

material in the form of micro/nano-chips by FMAB. It definitely improves productivity by increasing both MRR and FR and by performing both operations (machining and finishing) at the same time. ECMAF is very similar to ECG except that in ECMAF, the finishing operation is performed by MAF (or by a FMAB) process, while in ECG, it is done by grinding operation (or a fixed or a non-flexible tool).

Electrochemical honing (ECH): Gears are extensively used in different mechanical machines, including automobiles, aerospace, heavy industries, machine tools, etc. The finishing of these gears takes a good amount of total production time of gears. For finishing gears, grinding, honing and lapping are used. However, all these conventional processes have their limitations in terms of productivity and cost. AFF is another advanced nanofinishing process that is also used in many industries because it can do three functions (finishing, deburring and radiusing), sometimes at the same time. But in this process, substantial material removal cannot take place to adjust the dimensional inaccuracies. There is another process that has been advantageously explored for finishing gears and for adjusting minor dimensional inaccuracies. This process is known as ECH of gears. In this process, ECM and mechanical honing are combined together, hence the name ECH. This hybrid process simultaneously overcomes the individual process limitations and makes the process more versatile by amalgamating the capabilities of both processes (ECM + honing). This process being practically non-thermal in nature, it is capable of producing nano-level finished surface without any thermal defects.

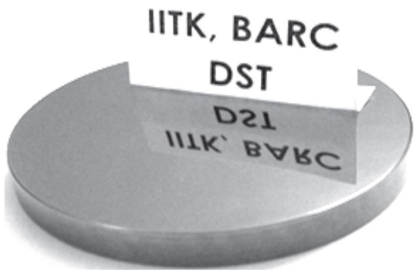
Chemomechanical polishing (CMP): This process is also known as chemo- mechanical planarization. This process uses a medium known as slurry that consists of carrier fluid + abrasive particles + additives. In this process, chemical reaction between the slurry and workpiece takes place, which forms a layer comparatively much softer than the original workpiece material hardness. As a result, this layer of reaction products is easily removed by the comparatively softer abrasive particles in the slurry. This is the most commonly used process for finishing silicon wafers in microelectronics and other related industries.

Electrolytic in process dressing and grinding (ELID grinding): This hybrid process uses a hard-metal-bonded grinding wheel having embedded abrasive particles in it. In this process, two operations are simultaneously performed: grinding of a workpiece along with dressing of the grinding wheel. For the grinding operation, the workpiece can be electrically conductive or non- conductive. In this process, an electrode is used that covers a part of the grinding wheel (say, 15% to 25% of the wheel outer periphery area). An electrolytic cell is formed between the electrode and the grinding wheel. In this electro- lytic cell, the grinding wheel works as an anode and the electrode works as a cathode. As a result of electrolysis, an oxide layer is formed on the grinding wheel, which partially covers the projected abrasive particles. This oxide layer, to some extent, reduces grinding efficiency. Also, due to the oxide layer formation, the bonding of the abrasive particles with the grinding wheel becomes weak, and in due course, the abrasive particles get detached from the grinding wheel. It permits the fresh/new particles to interact with the workpiece material and the grinding efficiency starts going up. Thus, both operations, the grinding and dressing of the grinding wheel, keep going on simultaneously. This process is getting popularity on the shop floor in different types of industries.

Chemomechanical magnetorheological finishing (CMMRF): This process com- bines the essential features of the CMP and MRF processes. In CMP, the forces cannot be controlled on-line or externally, and in MRF, there is no chemical reaction that makes the parent material softer to increase both MRR and FR.

In this process, chemical reactions (used for creating of passivated superficial layer) associated with CMP are used to improve MRR and FR, as well as the final surface finish, whereas MR fluid and magnets of the MRF setup are used to control the magnitude of the abrading forces acting on the workpiece for nano-abrasion as well as to control the flexibility of the FMAB for finishing non-planer surfaces. The CMMRF process is capable to finish a wide variety of materials, say, ductile or brittle, electrically conductive or electrically non- conductive up to a few nanometres and in some cases, even up to sub-nanometre range. This process was used to finish a single crystal silicon blank to the final Ra value as 0.468 nm. Figure 1.10 shows a single crystal silicon wafer mirror finished by this process.

Electric discharge diamond grinding (EDDG): Apart from the earlier stated problems of grinding, it cannot be used for finishing of very hard materials because it imposes the constraint on the hardness of the abrasive particles used in the grinding wheel. To solve this problem, researchers have blended grinding with EDM and named it as electric discharge abrasive grinding (EDAG), or EDDG depending upon whether normal abrasive particles are used or diamond particles are used as abrasive particles in the grinding wheel. In this process, electric discharge/spark removes a very small amount of material, but it softens the hard-to-machine material within and surrounding to the spark area. Thus, the abrasive/diamond particles following the spark are able to easily finish comparatively softer surface (became softer due to heating). Thus, a spark serves two purposes simultaneously: In EDAG, the EDM is able to machine hard to machine material and make it softer, and comparatively, softer abrasive particles are able to finish the converted soft layer of workpiece material. However, the EDM is a thermal process and grinding is a mechanical process producing lot of heat. A probability of the presence of thermal defects in the finished part still persists to some extent if the parameters are not optimized to minimizing the thermal defects.



Mirror image of IITK BARC DST on the finished 'Si' substrate

FIGURE 1.10
Single crystal silicon wafer finished by the CMMRF process.

1.6 Optimization, Simulation, Measurement and Applications

Optimization: It is a well-known fact that the performance of any machining process is controlled by its input process parameters. The optimum value of the input process parameters depends on the objective function in case of single objective optimization and objective functions and weights to different objective functions in case of multi-objective optimization. Researchers have recognized this fact, and many techniques have been developed for single-objective and multi-objective optimization (Jain, 2014), for example, genetic algorithm, teaching-learning-based optimization, goal programming, geometric programming, multivariable regression analysis, artificial neural networks, etc. For achieving the best results out of any machining and finishing process, parameter optimization is highly essential. To study the effects of input process parameters of a finishing processes on its performance measures (say, surface roughness, MRR, cutting forces, etc.), various optimization techniques have been proposed by different researchers working in the field of optimization. With the advancements in machining and finishing machine tools, machine tools are usually equipped with the "adaptive controls" which help in running the machine tool for most of the times under the optimum machining/finishing conditions without any intervention of the operator. The machine tool controlled input parameters are automatically on-line modified periodically depending upon the newly calculated optimum input parameters. However, the cost of such CNC machines with adaptive control is definitely much higher than that of a normal CNC machines.

Simulation: Almost all theories available in the literature related to machining and finishing deal with the material deformation or cutting in the bulk material depending on the mechanical and physical properties of those materials. But it is a well-known fact that as you go to the material removal at a smaller and smaller size, the material properties beyond a particular size keep changing. The properties become completely different when the material is machined/finished at nanometre, in general, and sub-nanometre, in particular. There are certain machining processes that practically remove material atom by atom or a small group of atoms (say, focused ion beam machining and elastic emission machining). The modelling and then simulation of sub-nano-level machining process at this level of material removal (atom by atom) are not available in the existing metal cutting theories. About a couple of decades back, some researchers proposed the molecular dynamics (MD) simulation of nano-cutting process. This process is able to capture very fine details of nano-machining that is not possible otherwise. In fact, MD simulation is virtual computer simulation of nano cutting that is not possible to analyze theoretically as well as experimentally. The same technique has been applied for nanofinishing processes as well. The results are interesting. Different researchers have discussed nano-cutting of copper, polishing of silicon wafers at the atomic scale, etc.

Measurement systems: Metrology has very special place in any manufactur- ing scenario. It will not be exaggeration if I say, "you cannot manufacture a part if you cannot measure it; does not matter whether it is dimension, geometry, or surface integrity." Measurement system's design becomes more important when one talks about micromanufacturing /nanomanufacturing. The measurement systems become more complex when one wants to handle 3D and free-form surfaces in general and at micro level in particular. Hence, advanced-level research in micro- and nano-metrology becomes more important because it will help in understanding the performance of micro/ nanostructured surfaces.

There are two classes of measurement/characterization techniques for microfeatures and nanofeatures. They are contact and non-contact measuring techniques. The real challenge arises when feature size comes down to nanoscale as the contact of measuring instrument will damage the feature. Characterization of free-form surfaces is still more difficult because of varia- tion of x, y and z coordinates from point to point on the surface. To resolve the problem, various techniques have been proposed by different researchers.

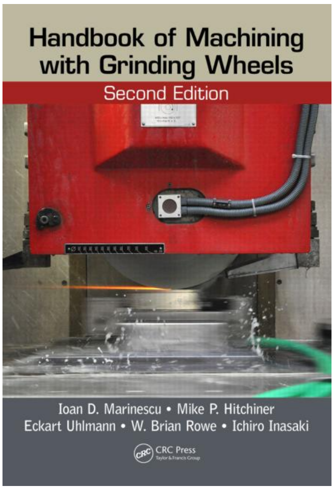
Applications: Nanofinishing techniques have applications in various fields of engineering, biomedical sciences and others. Some human implants (Figure 1.1) require nanometrelevel surface finish. In some cases, differential surface finish is required in different areas of the same part, depending upon the functional requirements of the part. One of the examples requiring differential surface finish is knee joint implant. Different devices in many other areas require nanolevel surface finish, for example, aerospace, automobile, optics, etc.

1.7 Remarks

In view of the brief discussion here about the nanofinishing processes, modelling, simulation, applications and metrology, it can be concluded that this is an important area in manufacturing that should be studied at both the levels of technology and science of these processes, including optimization of the process parameters. Further, it is not the optimization of the process parameters alone, rather, their machine tool design optimization is equally important to extract the best from the existing technologies. With this in view, this book emphasizes on the technology as well as scientific basis of the processes that are discussed in this book. However, the design optimization of their machine tools is out of the scope of this book; hence, they have not been touched upon.

CHAPTER 2

Economics of Grinding



2

Economics of Grinding

12.1 Introduction

Evaluation of grinding costs is key to achieving maximum profitability in grinding and it is important that costs are evaluated in a meaningful way. Old attitudes of treating abrasive cost, or even total perishable tooling costs, as a single measure of a process are completely misleading and unacceptable.

Models for evaluating "total grinding costs" came to the forefront in the early 1990s with the emergence of cubic boron nitride (CBN) for grinding automotive and aero-engine components. Abrasives costs with CBN at that time were often two or three times higher than with conventional abrasives but the reduction in labor costs and scrap produced far higher overall cost savings. Several models are available for costing. A detailed model including comparison for different abrasives and machines is given in Chapter 19 with respect to centerless and cylindrical grinding processes. The following cost analysis gives a clear picture of all the costs involved in a decision involving the comparison of two proposed methods.

12.2 A Comparison Based on an Available Grinding Machine

12.2.1 Introduction

If similar machines are to be employed or the grinding machines are readily available for production, the problem of making cost comparisons between two processes is simplified. presented the items for evaluation of total manufacturing cost which are listed in Table 12.1.

The table shows the main process costs that enter into a comparison between two processes as required by a process engineer in decision-making ignoring the capital cost involved in setting up a grinding facility. It has to be emphasized that these costs depend on the efficiency of the process itself. In other words, it is necessary to carry out grinding trials to determine cycle time, number of parts per dress, and so on before the above costs can be established. An example of the investigation required in order to establish costs per part are given in Chapter 19.

An example of the implications and benefits of the costing approach are given here.

TABLE 12.1

Total Manufacturing Cost Calculation Worksheet

1	Total manpower overhead, cost/part	US$/part
2	Total wheel, cost/part	US$/part
3	Total wheel change, cost/part	US$/part
4	Total dresser roll, cost/part	US$/part
5	Total dresser roll change, cost/part	US$/part
6	Total maintenance labor, cost/part	US$/part
7	Total scrap, cost/part	US$/part
8	Total coolant, cost/part	US$/part
9	Total coolant filter, cost/part	US$/part
10	Total coolant disposal, cost/part	US$/part
11	Total inspection, cost/part	US$/part
	Total grinding cost	US$/part

12.2.2 Aero-Engine Shroud Grinding Example

The application illustrated in Figure 12.1 is the internal grinding of large aero-engine shroud assemblies for aircraft engines. Traditionally, the part was ground using seeded gel (SG) abrasive, but the SG process was replaced by a vitrified CBN wheel that reduced grinding cycle time by 50%. The greatest time saving was achieved by the elimination of the need to dress several times for each component ground. Relevant costs are given in Table 12.2.

Cost items 1–4 are tooling costs and illustrate that the switch to CBN abrasive created a negative impact on grinding costs of US$12.11. However, the increased productivity, items 5–8, had a positive impact on labor cost alone of US$179.44. Also, the quality improvement as a result of the very low wheel wear rate using the superabrasive yielded an even greater cost saving of $399 by the elimination of scrap. Finally, there was also a modest environmental benefit of $0.36 in terms of reduced coolant disposal costs. Converting from

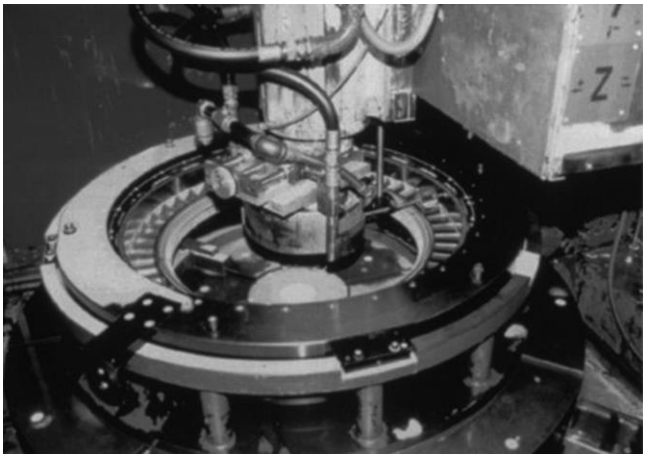


FIGURE 12.1
Internal profile grinding of aero-engine turbine shroud assembly.

TABLE 12.2

Cost Calculation for Internal Profile Grinding of Aero-Engine Shroud Assembly

		Alox	CBN	Impact of CBN
1	Wheel, cost/part	$10.00	$28.74	
2	Dresser roll, cost/part	$7.44	$3.15	
3	Coolant, cost/part	$5.56	$2.46	
4	Filter, cost/part	$2.00	$0.88	−$12.11
5	Labor/part	$247.77	$123.85	
6	Wheel change/part	$30.00	$0.62	
7	Diamond roll change/part	$0.20	$0.19	
8	Maintenance/part	$62.81	$36.75	+$179.44
9	Scrap	$440.48	$48.68	
10	Inspection, cost/part	$22.50	$14.40	+$399.90
11	Coolant disposal, cost/part	$0.65	$0.29	+$0.36
	Total grinding, costs/part	$829.48	$260.01	

a conventional wheel with a *G* ratio of 1 to a CBN wheel with a *G* ratio of 1000 effectively halved the amount of swarf in the coolant stream. Furthermore, the filtered swarf was much cleaner and therefore easier to recycle.

In summary, a change of process from traditional wisdom considering abrasive cost alone would have had a negative impact of $18.74/part. In fact, the change of process reduced total manufacturing cost by $569.47/part.

12.3 A Cost Comparison Including Capital Investment

12.3.1 Introduction

Total in-process costs may be only half the analysis. For new processes, consideration needs to be given to balance capital equipment costs against operating costs.

12.3.2 Automotive Camlobe Grinding Example

An example of this was the introduction in the late 1980s of CBN to grinding camshafts. After the initial installation, which was instigated because it was the only viable method of generating a particular profile on the camlobe, the abrasive cost was found to be 50% higher using CBN. However, the productivity was found to be about 30% higher than a typical alumina wheel-based process. This had a major impact on the number of grinders required on a later new installation even when the profile issues were not present.

An example is shown in Table 12.3. A new installation required six fewer grinders and each machine was actually less expensive. So even taking the most negative view of the process by considering abrasive cost only, for an increase in abrasive cost of $90 K/annum, a capital equipment cost saving of $5.3 M was achieved. Furthermore, since this was a relatively new technology, significant process costs were likely to be recuperated through future process optimization.

TABLE 12.3

Capital Equipment Investment versus Production Abrasive Costs for a High-Production Camshaft Manufacturing Line (Production Requirements: 750,000 Parts/Annum)

	Alox	CBN
Number of machines	22	16
Cost/machine	$750 K	$700 K
Capital equipment cost	$16.5 M	$11.2 M
Capital investment savings	$5.3 M	
Annual abrasive cost	$180 K	$270 K

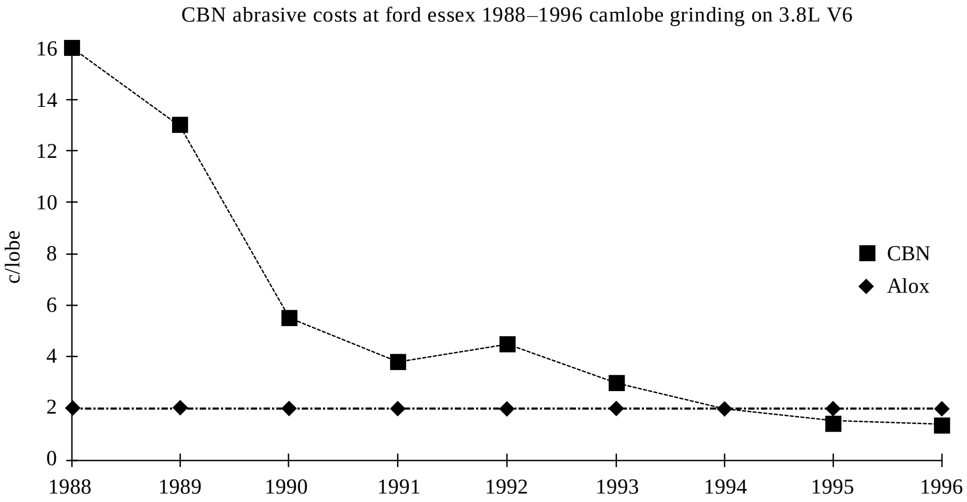


FIGURE 12.2
Abrasive cost improvement in camshaft lobe grinding 1988–1996.

Dramatic process improvement was in fact proven to be the case. Figure 12.2 illustrates the improvement in abrasive cost alone over 8 years at the first CBN installation for grinding camshafts in North America.

12.4 Cost Comparison Including Tooling

12.4.1 Introduction

With better understanding of new technologies such as this it is often possible to push productivity considerably further. The example above based on grinder technology that is now 15 years old had a cycle time of about 6 min limited by burn. On the latest grinders with much more sophisticated computer numerical controls, higher wheel speeds, and faster linear motor technology, it is possible to grind camshafts up to 50% faster, albeit with higher abrasive cost initially. Capital equipment is very expensive and industry is trying

TABLE 12.4

Comparison of Capital Equipment Costs versus Tooling Costs for Various Production Rates

Camlobe Grinding of Automotive Camshafts			
Production requirement = 1,000,000 cams/annum Machine cost with gantry loading, installation, etc. = $1 M			
Production rates	• 10/h @ $0.25/camshaft • 15/h @ $0.40/camshaft • 20/h @ $0.60/camshaft		
Cycle Time	Grinders	Capital Cost	Tooling Cost
6 min	25	$25 M	$250 K/annum
4 min	17	$17 M	$400 K/annum
3 min	13	$13 M	$600 K/annum

to drive up their return on investment by limiting such expenditures. A project engineer must therefore weigh up carefully capital against process costs. The following example shows how more expensive tooling can bring down costs.

12.4.2 Effect of Tooling Costs in Camlobe Grinding

Consider the example of a camlobe grinding operation at a high-production automotive engine plant as shown in Table 12.4.

For an increase in tooling costs of $350 K per annum, a capital cost saving of $12 M can be achieved. Again past history would indicate that processing costs would be further reduced over the expected life of the grinding machines and would be a primary focus for future cost savings from both process optimization and competition between tooling suppliers.

12.5 Grinding as a Replacement for Other Processes

12.5.1 Introduction

With the rapid advances in metalworking technology, it is now necessary when selecting new machines to go back to the basic fundamentals of processing a part. An analysis of capital and processing costs may well indicate that the traditional metal-cutting process for producing a given part may not be the most cost-effective. Grinding has recently successfully replaced such processes as lapping and broaching, while grinding itself has been replaced on many occasions by hard turning. Machine tool builders are combining metal-cutting processes, converting machines from one process to another, or reducing costs by adopting commonality of machine components. At the same time, tighter environmental and quality demands, and the "just-in-time" approach to manufacturing, can make historic processing methods obsolete. Some examples are described below.

12.5.2 Fine Grinding as a Replacement for Lapping

Grinding of flat components by processes such as double disk grinding has traditionally been limited to achievable flatness tolerances of about a micron. To obtain flatnesses of the

TABLE 12.5

Comparative Example of Lapping and Fine-Grinding Costs

Input	Lapping Cost/Part	Grinding Cost/Part
Labor/machine cost	$0.60	$0.25
Abrasive costs	$0.08	$0.25
Plate cost (lapping)	$0.01	$0.00
Cleaning cost	$0.34	$0.00
Total	$1.03	$0.50

order of 0.2–0.6 μm (1–2 light bands) demanded for seals, fuel injection, automotive transmission, and pump components has required lapping. This is a slow, batch process carried out on large cast iron tables up to 3 m in diameter using free abrasive slurries. Lapping is very dirty and requires an expensive postlap cleaning process. However, the kinematics of some lappers is quite sophisticated as described later in this handbook. Machine tool builders have therefore combined lapping kinematics with fixed superabrasive grinding wheels to reduce cycle time by up to a factor of 10.

An example of a comparison of the cost of lapping and fine grinding is shown in Table 12.5 grinding PM steel parts on a Peter Wolters double-sided grinder with vitrified CBN pellet wheels.

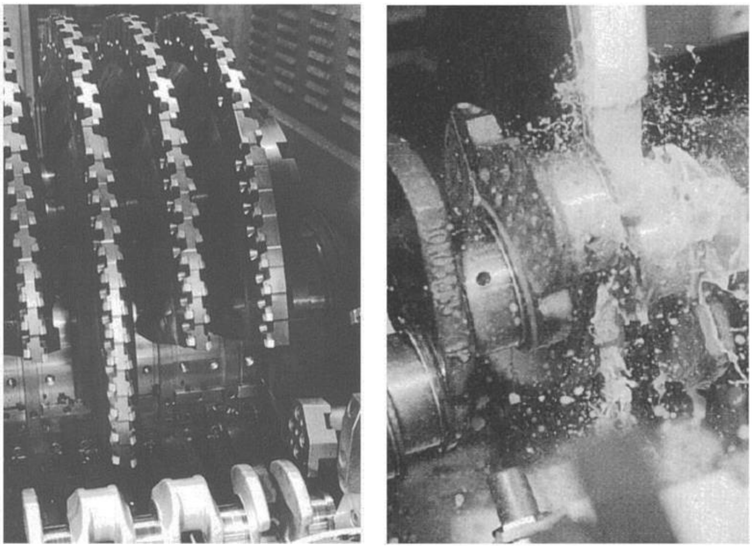
The greater savings come not from the actual grinding process but from the elimination of the subsequent cleaning process required after lapping.

12.5.3 High-Speed Grinding with Electroplated CBN Wheels to Replace Turn Broaching

Traditionally, crankshaft journals are roughed from a forging using turn broaches. The majority of stock is present in the sidewall and undercut at the edges of the journal, where it takes a heavy toll on tool insert life. Insert resetting can take several hours using expensive specialized equipment. Current high-speed grinding technology using electroplated CBN wheels in oil coolant was able to process the part in half the time of a turn broach at comparable or lower tooling costs. A crank grinder costs the same as a turn broach effectively halving the capital equipment costs, while eliminating the labor and capital costs of tool insert resetting. See illustrative examples in Figure 12.3.

12.6 Multitasking Machines for Hard Turning with Grinding

Hard turning can remove stock much faster and with lower forces than regular grinding processes, but it cannot hold quite the tolerances and finishes of grinding. However, when combined in a single machine with a single chucking, the two processes can enhance each other. The photographs (Figure 12.4) show an operation to process two inner diameters and the faces of a hardened steel transmission gear component. The process was originally envisioned as being processed entirely by a single grinding wheel with an estimated cycle time of 4 min. The critical surfaces were the inner diameters. The problem, however, was the grinding of the top face due to quill deflection resulting in a cycle time of 10 min.



Turn broaching High-speed grinding with EPCBN wheels

FIGURE 12.3
Examples of turn broaching and grinding of crank pins.

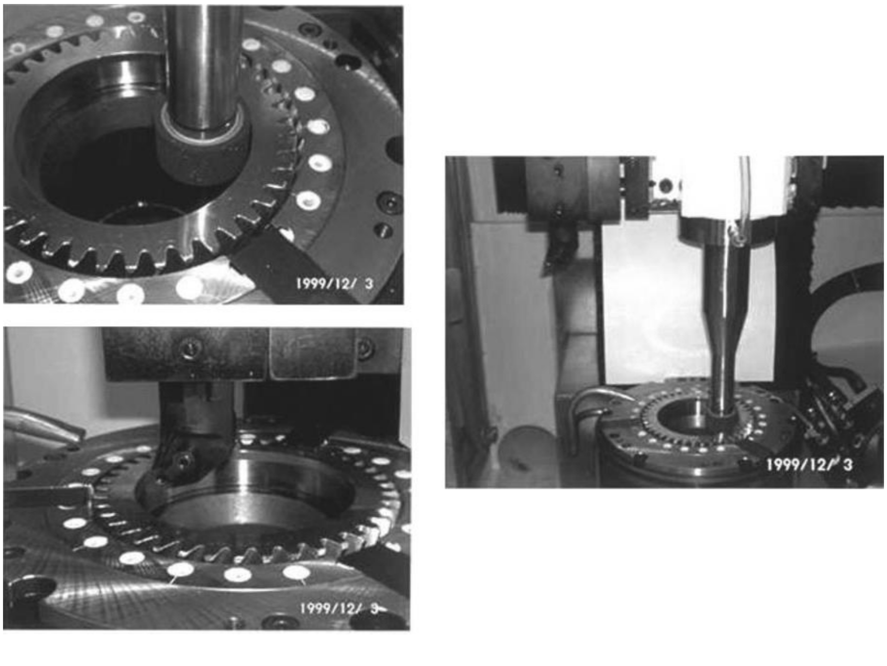


FIGURE 12.4
Multitasking machine for grinding and hard-turning.

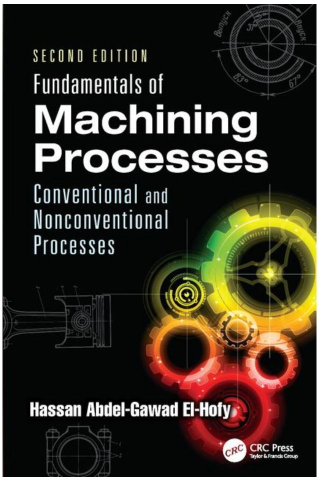
However, the addition of a turning bar for hard turning the top face reduced the cycle time to 3 min to exceed end-user expectations while still maintaining very acceptable quality.

12.7 Summary

Close attention must be paid to the *entire* cost of a given manufacturing process. On very few occasions, does abrasive cost alone for a given operation govern the processing route. Continual advances in machine tool, wheel, and coolant technology together with ever-greater demands for productivity, quality, and environmental considerations demands that the manufacturing engineer review all options available each time an opportunity for new equipment arises. Careful consideration should be given to emerging technologies, global sourcing (if backed up with adequate local technical support), and fundamental university and corporate research.

3

Machining Processes



1

Machining Processes

1.1 Introduction

Many manufactured products require machining at some stage of their production sequence. Machining is the removal of unwanted materials (machining allowance) from the workpiece so as to obtain a finished product of the desired size, shape, and surface quality. Generally, machining ranges from relatively rough cleaning of castings to high-precision micromachining of mechanical components that require narrow tolerances.

The removal of the machining allowance through cutting techniques was first adopted using simple handheld tools made from bone, stick, or stone that were replaced by bronze or iron. The water, the steam, and, later, the electricity were used to drive such tools in the power-driven metal-cutting machines (machine tools). The development of new tool materials opened a new era to the machining industry where machine tool development took place. Nontraditional machining techniques offered alternative methods for machining parts of complex shapes in harder, stronger, and tougher materials that were difficult to cut by the traditional methods.

Machining is characterized by its versatility and capability of achieving the highest accuracy and surface quality in the most economic way. The versatility of machining processes can be attributed to many factors, some of which are

- The process does not require elaborate tooling.
- It can be employed to all engineering materials.
- Tool wear is kept within limits, and the tool is not costly.
- The large number of machining parameters can be suitably con- trolled to overcome technical and economic difficulties.

Machining is generally used as a final finishing operation for parts produced by casting and forming before they are ready for assembly or use (Figure 1.1).

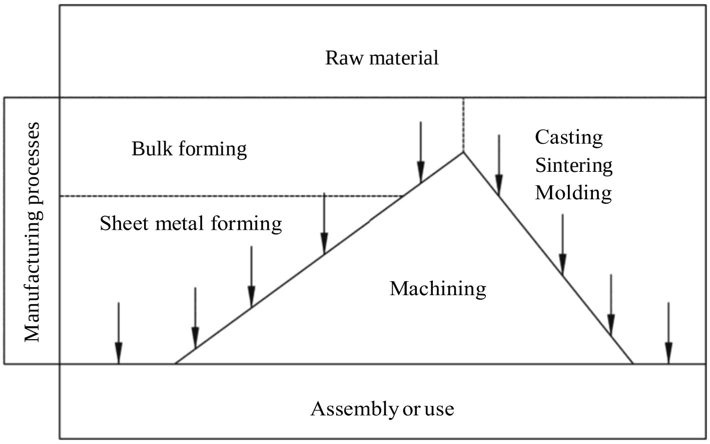


Figure 1.1
Manufacturing processes.

However, there are a number of reasons that make machining processes an obligatory solution as compared with other manufacturing techniques. These are

- If closer dimensional control and tighter tolerances are required than are available by casting and forming
- If special surface quality is required for proper functioning of a part
- If the part has external and internal geometric features that cannot be produced by other manufacturing operations
- If it is more economical to machine the part than to produce it by other manufacturing operations

Micromachining has become an important issue for machining 3D shapes and structures as well as devices with dimensions in the order of micrometers. Furthermore, in nanomachining, atoms or molecules (rather than chips) are removed to produce parts for microelectronics, automobile, and aircraft manufacturing industries.

1.2 Historical Background

The development of metal-cutting machines, usually called machine tools, started from the invention of the cylinder that was changed to a roller guided by a journal. The ancient Egyptians used these rollers for transporting the required stones from quarries to building sites. The use of rollers initiated the introduction of the first wooden drilling machine that dates back to 4000 BC. In such a machine, a pointed flint stone tip acted as a tool. The first deep-hole boring machine was built by Leonardo da Vinci (1452–1519). In 1840, the first turning machine was introduced. Maudslay (1771–1831) added the lead screw, back gears, and the tool post to the previous design. Later, slideways for the tailstock and automatic tool-feeding systems were incorporated. Planers and shapers have evolved and were modified by Sellers (1824–1905). In 1818, Whitney built the first milling machine. The cylindrical grinding machine was built for the first time by Brown and Sharp in 1874.

Fellows' first gear shaper was introduced in 1896. In 1879, Pfauter invented the gear hobbing, while the gear planers of Sunderland were developed in 1908.

Further developments for these conventional machines came by the introduction of the copying techniques, cams, and automatic mechanisms that reduced the labor and work and consequently raised the product accuracy. In 1953, the introduction of the numerical control (NC) technology opened wide doors to the computer numerical control (CNC) and direct numerical control (DNC) machining centers that enhanced the product accuracy and uniformity. Machine tools form around 70% of the operating production machines and are characterized by their high production accuracy com- pared to the metal-forming machine tools.

Machining has been the object of considerable research and experimentation that has led to better understanding of the nature of the machining processes and improvements to the quality of the machined parts. Systematic research began in 1850 and has ever since continued to cover the following topics:

1851—measurements of the cutting forces and power consumption to remove a given volume of metal

1870—mechanics of chip formation 1893—analysis of forces

in the cutting zone

1907—study of tool wear and the introduction of high-speed steel (HSS)

1928—machinability terms and definitions

1935—introduction of the theoretical models of orthogonal and oblique cutting

1950—verification of the metal-cutting models

1960—developments in the field of grinding and nontraditional machining processes

1970—developments in the field of nontraditional and hybrid machining processes, including micromachining and nanomachining

1.3 Classification of Machining Processes

Traditional machining requires a tool that is harder than the workpiece that is to be machined. This tool penetrates into the workpiece for a certain depth of cut. A relative motion between the tool and workpiece is responsible for form and generation cutting to produce the required shapes, dimensions, and surface quality. Such a machining arrangement includes all machining by cutting (C) and mechanical abrasion (MA) processes. The absence of tool hardness or contact with the workpiece makes the process nontraditional, such as the erosion processes (E) by electrochemical and thermal machining methods (see Figure 1.2).

1.3.1 Machining by Cutting

Figure 1.3 shows the main components of a typical metal-cutting process. The machining system includes the tool, the workpiece, and the machine tool that controls the workpiece and tool motions required for the machining process. Table 1.1 shows the different tool and workpiece motions for some important metal-cutting operations. During machining by cutting, the tool is penetrated into the workpiece as far as the depth of cut. Cutting tools

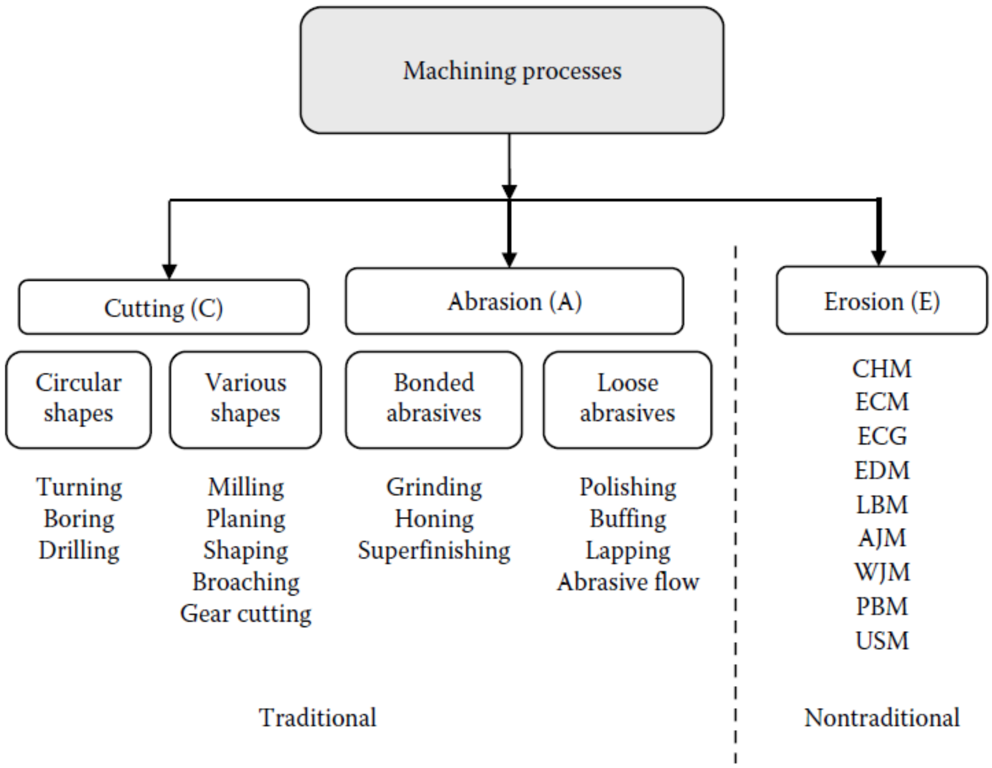


FIGURE 1.2
Classification of machining.

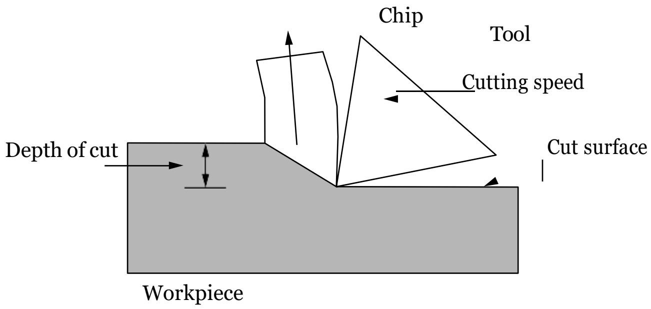


Figure 1.3
Machining by cutting.

Table 1.1
Tool and Workpiece Motions for Metal-Cutting Processes

	Tool Motion			
Workpiece Motion	**Stationary**	**Linear**	**Rotary**	**Spiral**
Stationary		Shaping/broaching		Drilling
Linear	Planning		Milling	
Rotary		Turning		
Spiral (linear + rotary)			Hobbing	

have a definite number of cutting edges of a known geometry. Moreover, the machining allowance is removed in the form of visible chips. The shape of the produced workpiece depends on the relative motions of the tool and workpiece. In this regard, three different cutting arrangements are possible, as depicted in Figure 1.4.

1.3.1.1 Form Cutting

The shape of the workpiece is obtained when the cutting tool possesses the finished contour of the workpiece. The workpiece profile is formed through the main workpiece rotary motion in addition to the tool feed in depth, as shown in Figure 1.5. The quality of the machined surface profile depends on the accuracy of the form-cutting tool. The main drawback of such an arrangement arises from the large cutting forces and the possibility of vibrations when the cutting profile length is long.

1.3.1.2 Generation Cutting

The workpiece is formed by providing the main motion to the workpiece and moving the tool point in the feed motion. In the turning operation, shown in Figure 1.6, the workpiece rotates around its axis, while the tool is set at a feed rate to generate the required profile. During shaping, the cutting tool is responsible for the main cutting motion while the workpiece feeds to generate the profile of the cut surface. During milling of contours, the vertical milling cutter (end mill) rotates (main motion) while the workpiece feeds in accordance to the required profile.

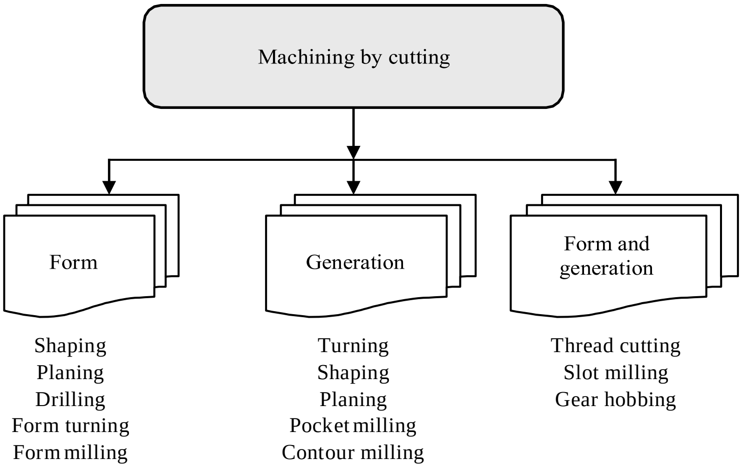


Figure 1.4
Machining by cutting kinematics.

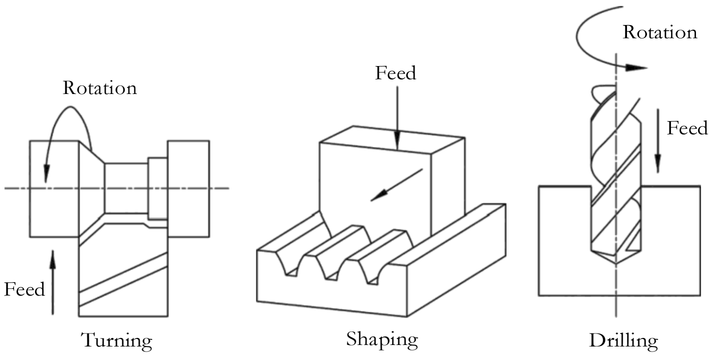


Figure 1.5

Form-cutting processes.

1.3.1.3 Form and Generation Cutting

During thread cutting, the tool having the thread form (form cutting) is allowed to feed (generation cutting) axially at the appropriate rate while the workpiece rotates around its axis (main motion), as in Figure 1.7. Similarly,

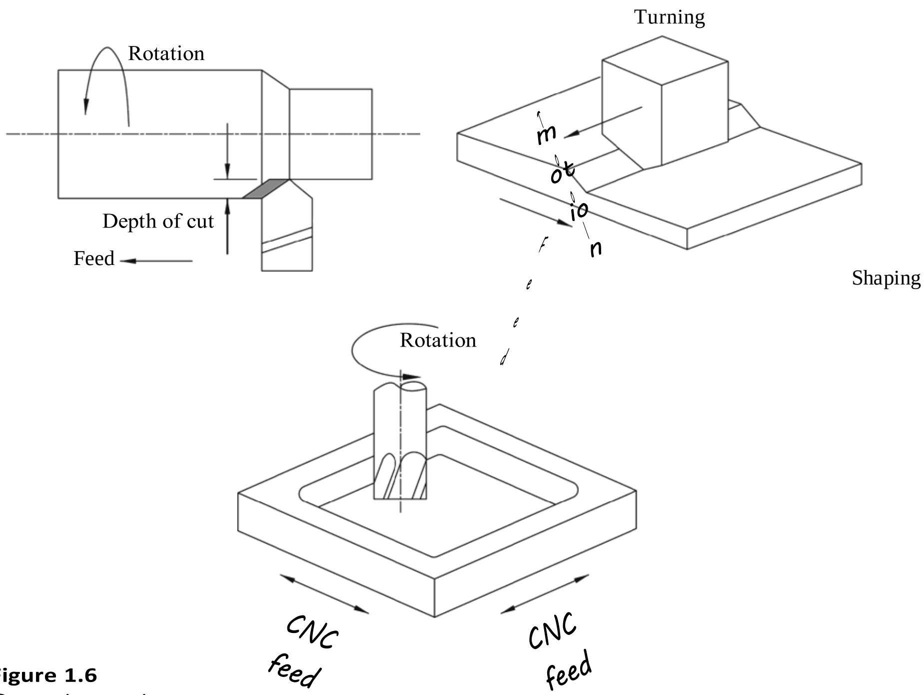


Figure 1.6
Generation cutting processes.

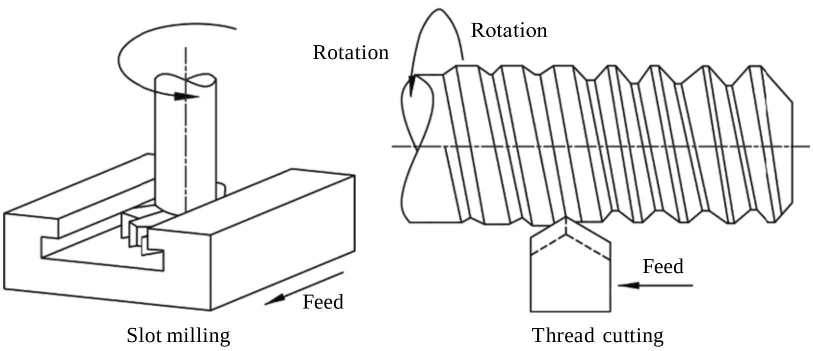


Figure 1.7

Form and generation cutting.

a slot, dovetail, and gear can be milled by feeding the workpiece while rotating the form-milling cutter. Gear hobbing uses a hob that gradually generates the profile of the gear teeth while both the hob and the workpiece rotate. Machining by cutting can also be classified according to the number of cutting edges accommodated in the cutting tool. Single-point machining utilizes tools having a single cutting edge to form or generate the required geometry. Drilling employs a twist drill that has two cutting edges to form cut the required hole. In contrast, reaming, milling, sawing, broaching, filing, and hobbing utilize tools with a definite number of cutting edges to machine a part.

1.3.2 Machining by abrasion

In abrasion machining, a small machining allowance is removed by a multitude of hard, small, angular abrasive grains of indefinite number and shape. These abrasive grains (grit) may be loose or bonded to form a tool of a given shape such as a wheel or a stick. As can be seen in Figure 1.8, the individual cutting grains are randomly oriented and the depth of their penetration is small and not equal for all grains that are in simultaneous contact with the workpiece. Material is removed by the MA effect; the machining allowance is removed in the form of minute chips that are invisible in most cases. Examples of abrasive machining using a bonded abrasive wheel during grinding, is shown in Figure 1.9, or a bonded abrasive stick during honing. In contrast, lapping, which utilizes loose abrasives in a liquid machining media, is shown in Figure 1.10.

During abrasion machining, because only a fraction of the abrasives causes material removal and because there are many sources of friction, the energy required to remove a unit volume may be up to 10 times higher than in machining by cutting processes. Unlike most other machining processes, abrasive machining can tackle materials harder than 400 HV, produce smooth surface finishes, and enable close control of the material removal. It is, therefore, normally adopted for finishing operations. Table 1.2 shows the main and feed motions in some abrasive machining processes. Machining by abrasion is classified in Figure 1.11 into grinding (used for finishing cut parts), superfinishing (for ground and reamed surfaces), and modern abrasive methods that have found many industrial applications. Figure 1.12

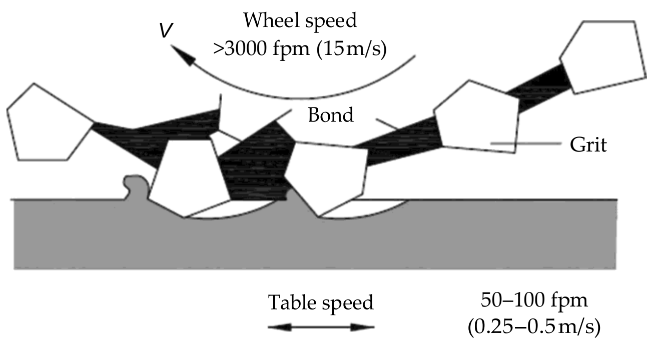


Figure 1.8
Machining by bonded abrasives.

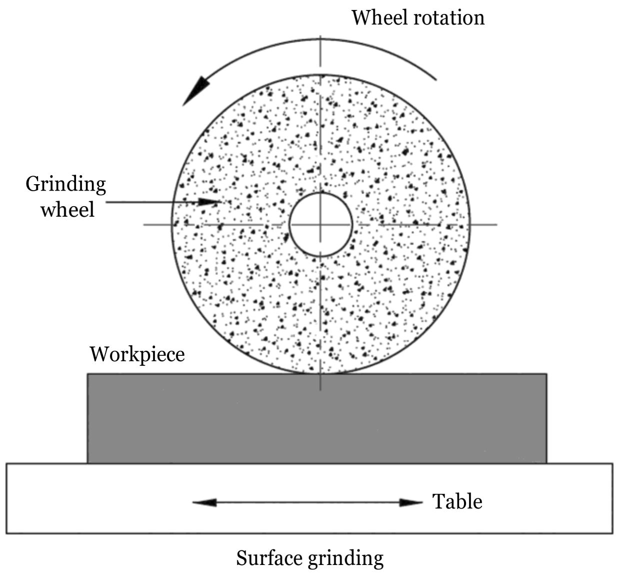


Figure 1.9

Abrasive machining with bonded abrasives.

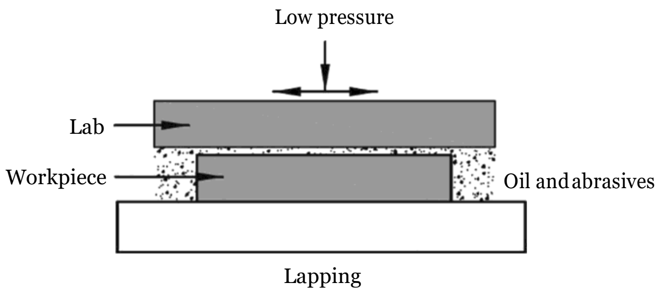


Figure 1.10
Abrasive finishing with loose abrasives.

Table 1.2

Tool and Workpiece Motions for Abrasion Processes

	Tool Motion			
Workpiece Motion	**Stationary**	**Linear**	**Rotary**	**Spiral**
Stationary		Lapping/ polishing		Honing
Linear			Surface grinding	
Rotary		Superfinishing	Centerless grinding	Cylindrical grinding
Spiral (linear + rotary)			Cylindrical grinding	

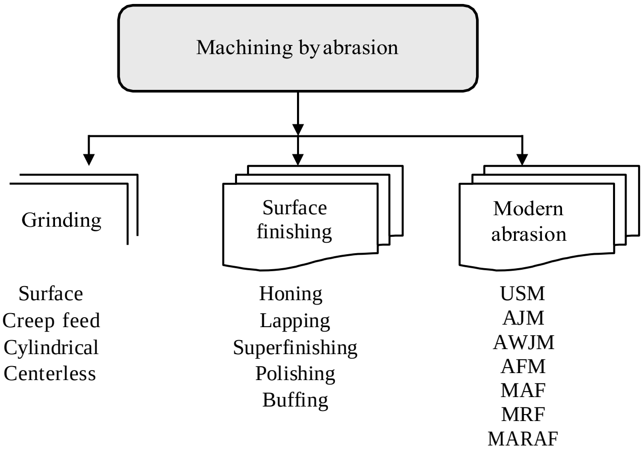


Figure 1.11

Classification of abrasion machining methods.

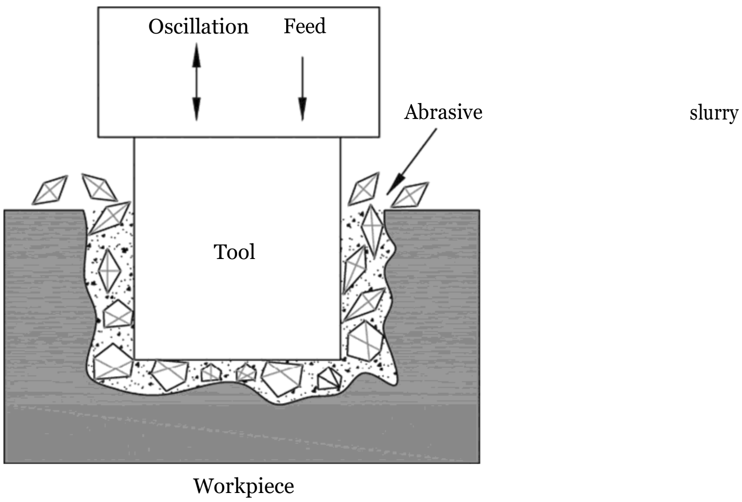


Figure 1.12
Modern abrasive machining (USM).

shows a typical ultrasonic machining (USM) operation where successive layers are removed from the workpiece material by mechanical chipping using the loose abrasives that are hammered against the workpiece surface at 19–20 kHz. Further examples of modern abrasive processes include the high-velocity abrasive jet in abrasive jet machining (AJM), abrasive water jet machining (AWJM), abrasive flow machining (AFM), magnetic abrasive machining (MAF), magnetic float polishing (MFP), magnetorheological finishing (MRF), and magnetorheological abrasive flow finishing (MRAFF).

The development of new engineering materials made machining by cutting and abrasion very difficult because these processes are mainly based on removing materials using cutting or abrasion tools that are harder than the workpiece. Traditional machining proved to be ineffective for machining complex shapes, low-rigidity structures, and micromachined components at high degrees of accuracy and surface quality.

1.3.3 Machining by erosion

Traditional machining includes those processes performed by cutting and abrasion where compression or shear chip formation causes inherent disadvantages, such as

- High cost due to the large energy used to remove a unit volume from the workpiece material.
- Workpiece distortion due to the heat generated during cutting and abrasion.
- Undesirable cold working and the residual stresses, which may require post-processing to remedy their harmful effects.
- Limitations related to the size and complexity of the workpiece shape.
- Highly qualified operators, specialized personnel, and sophisticated measuring equipment are needed.

To avoid such limitations, erosion machining processes are used that do not produce chips or a lay pattern on the machined surface. However, volumetric removal rates are much lower than with machining by cutting and abrasion. Erosion machining removes the machining allowance by the removal of successive surface layers of the material as a result dissolution or melting and vaporization of the material being machined (Figure 1.13).

1.3.3.1 Chemical and Electrochemical Erosion

These processes utilize chemical erosion in case of chemical machining (CHM) or electrochemical erosion during the electrochemical machining (ECM) shown in Figure 1.14a.

1.3.3.2 Thermal Erosion

The thermal erosion of the machining allowance occurs by the melting and vaporization of the workpiece material. Different energy sources can be used, including electric discharges, laser beam, electron beam, ion beam, and plasma jets (Figure 1.14b). Due to the high heat input, microcracks and the formation of heat-affected zones appear in the machined parts.

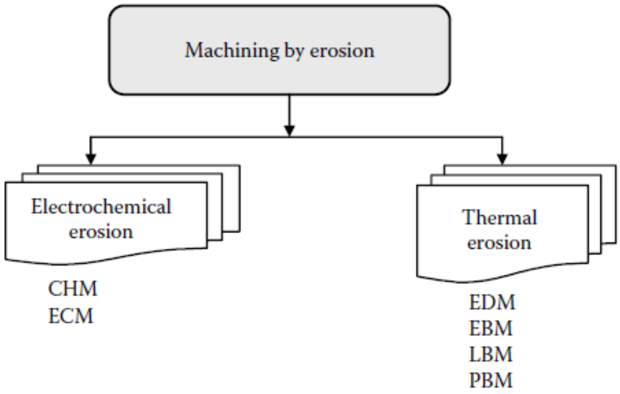


FIGURE 1.13
Erosion machining processes.

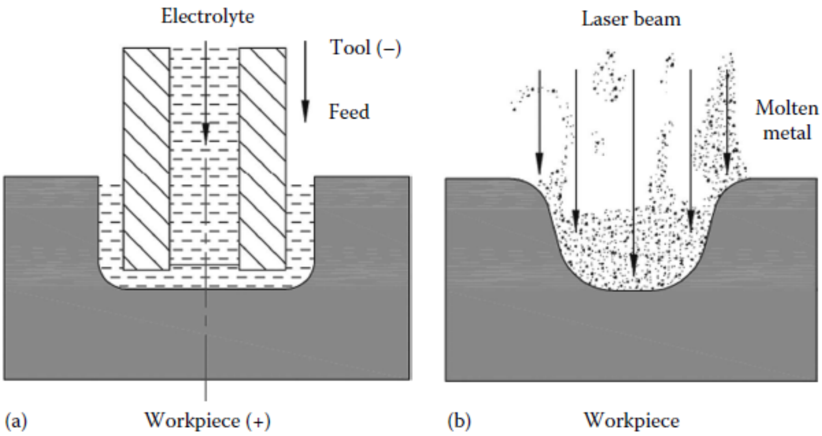


FIGURE 1.14
Typical erosion machining processes. (a) Electrochemical machining and (b) laser beam machining (LBM).

1.3.4 Combined Machining

To enhance the performance of some thermal erosion processes, a secondary erosion process can be added, such as ECM, to form electrochemical dis- charge machining (ECDM) or electroerosion dissolution machining (EEDM). In other situations, the MA is combined to electrodischarge machining (EDM) to form abrasive electrodischarge grinding (AEDG), or EDM is combined to both grinding and ECM to form electrochemical discharge grinding (ECDG). Electrochemical erosion can also be enhanced by combining with MA during electrochemical grinding (ECG) or ultrasonic erosion during ultrasonic-assisted ECM (USMEC) (Table 1.3).

TABLE 1.3

Combined Machining

	Erosion		
Abrasion	ECM	EDM	Abrasion
ECM + abrasion (ECG/ECS/ECH/ECB)		EDM + abrasion (EDG/AEDG/EDMUS)	
	ECM + EDM (EEDM/ECDM)		
	ECM + EDM + abrasion (ECDG)		

Note: ECS, electrochemical superfinishing; ECH, electrochemical honing; ECB, electrochemical buffing; EDMUS, electrodischarge machining with ultrasonic assistance.

1.3.5 Micromachining

Micromachining is the miniaturized shaping of objects by removing excessive materials from a new stock. For such a purpose, both conventional and nonconventional methods of machining are adopted. Micromachining has recently become an important technique for the reduction of workpiece size and dimensions. It refers to the technology and practice of making three dimensional shapes, structures, and devices with dimensions on the order of micrometers. One of the main goals of the development of micromachining is to integrate microelectronic circuitry into micromachined structures and produce completely integrated systems.

Conventional methods of micromachining utilize fixed and controlled tools that can specify the profile of 3D shapes by a well-designed tool surface and path. These methods remove material in amounts as small as tens of nanometers, which is acceptable for many applications of micromachining. The volume or size of the part removed from the workpiece, in mechanical methods, termed as the *unit removal*, consists of the feed pitch, depth of cut, and the length that corresponds to one chip of martial cut. For finer precision levels (atomic level), there are nonconventional methods of machining. The unit removal in this case can be as small as the size of an atom. Turning, drilling, and milling have proven to be applicable to the micromachining of shapes in the range of micrometers through the miniaturization of the required tools. In this regard, the development of wire electrodischarge grinding (WEDG) has significantly advanced the technology of microtool production. Conventional micromachining methods by turning, drilling, and grinding have already been applied to materials including copper and aluminum alloys, gold, silver, nickel, and polymethylmethacrylate (PMMA) plastics.

Micromachining by unconventional methods relies on the removal of microamounts of materials by either mechanical methods (e.g., ultrasonic), anodic dissolution (ECM), or ion impact in ion beam machining. Recent applications of micromachining include silicon micromachining, excimer lasers, and photolithography. Micromachined parts include sensors, parts, and components in existing instruments and office equipment, as well as tiny nozzles in ink jet printer heads; the tip for atomic force microscopes essentially relies on micromachining techniques. Tiny mechanical parts of microscale or microsize can perform in very small spaces, including inside the human body. Machines such as precision grinders may be capable of producing an accuracy level of ±0.01 μm.

The high-precision requirements of nanomachining can be obtained by removing atoms or molecules rather than chips, as in the case of ion beam machining. Nanomachining was introduced by Tanigushi for the miniaturization of components and tolerances from the submicron level down to individual atoms or molecules between 100 and 0.1 nm. Nanomachining techniques can achieve ±nm. The need for such small-scale techniques arose for the high performance and efficiency required in many fields, such as microelectronics, as well as the automobile and aircraft manufacturing industries.

1.4 Variables of Machining Processes

Any machining process has two types of interrelated variables. These are input (independent) and output (dependent) variables (Figure 1.15).

A. Input (independent) variables
- Workpiece material, like composition and metallurgical features
- Starting geometry of the workpiece, including preceding processes

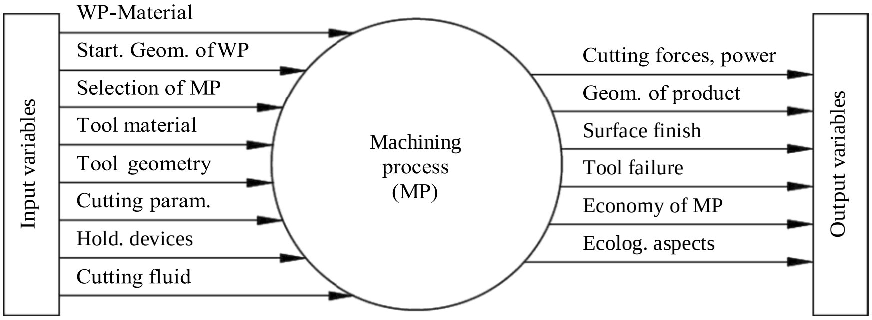


Figure 1.15
Variables of a machining process.

- Selection of process, which may be conventional or nonconventional processes
- Tool material
- Machining parameters
- Work-holding devices ranging from vises to specially designed jigs and fixtures
- Cutting fluids

B. Output (dependent) variables

- Cutting force and power. Cutting force influences deflection and chattering; both affect part size and accuracy. The power influences heat generation and consequently tool wear.
- Geometry of finished product, thus obtaining a machined sur- face of desired shape, tolerance, and mechanical properties.
- Surface finish: it may be necessary to specify multiple cuts to achieve a desired surface finish.
- Tool failure due to the increased power consumption.
- Economy of the machining process is governed by cutting speed and other variables, as well as cost and economic factors. Machining economy represents an important aspect.
- Ecological aspects and health hazards must be considered and eliminated by undertaking necessary measures.

1.5 Machining Process Selection

Selecting a machining process for producing a specific component made from certain material to the required shape, size, degree of accuracy, and surface quality depends on many factors that include the following:

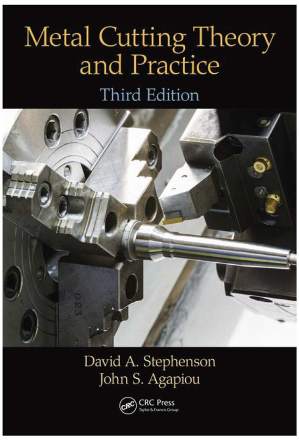
- Part shape
- Part size
- Part material
- Dimensional and geometric features
- Surface texture
- Production quantity
- Production cost
- Environmental impacts

Review Questions

1.1 State the major differences between machining and forming processes.
1.2 What are the main reasons behind using machining technology in industry?
1.3 What are conditions that make machining processes obligatory solutions compared to other manufacturing processes?
1.4 Explain the need for unconventional machining processes compared to conventional ones.
1.5 Show the general classification of the machining processes.
1.6 Using sketches, show the different modes of metal-cutting processes.
1.7 State the main limitations of traditional machining methods.
1.8 What are the advantages offered by nontraditional machining processes?
1.9 Give examples for abrasion machining using loose and bonded abrasives.
1.10 Using diagrams, show the main types of erosion machining.
1.11 Name the important factors that should be considered during the selection of an unconventional machining process for a certain job.
1.12 Explain the following terms: erosion machining, abrasion machining, and combined machining.
1.13 What are the main variables of a machining process?
1.14 What are the main factors that affect the selection of a machining process?

4

Cutting Fluids



14 Cutting Fluids

14.1 INTRODUCTION

The cutting fluid is an important component of the machining system in many applications. Cutting fluids are used in a large proportion of metal cutting operations to improve tool life, surface finish, and dimensional stability, and to help clear chips from the cutting zone. For many materials, cutting fluids are necessary to achieve acceptable part quality and tooling costs. However, cutting fluid acquisition, management, and treatment costs are a significant fraction of the overall operating expense in wet applications, and the fluids may also present an exposure risk to machine operators and require additional investment for enclosures, fire suppression, and air treatment.

Cutting fluids provide lubrication between the tool, chip, and workpiece at low cutting speeds, and cool the part and machine tool and clear chips at higher cutting speeds and in holemaking operations such as drilling and reaming. They also help prevent edge buildup and part rust in most circumstances. When properly applied, they permit the use of increased cutting speeds and feed rates, and improve chip formation, tool life, surface finish, and dimensional accuracy. A cutting fluid's cooling ability depends largely on the base fluid and the coolant volume. Chip flushing capabilities are determined by the operation geometry and the coolant application method. Lubrication is controlled by the chemical composition of the coolant and the application method. In recirculating systems, in which a large volume of coolant is continuously collected in a sump and reused, coolant performance over time is strongly influenced by coolant maintenance practices such as concentration monitoring, stabilization, tramp oil removal, rancidity control, and filtering.

In general, cutting fluids should pose no safety risk to the machine operator, have a long useful life, be waste-treatable, and be chemically inert with respect to the workpiece material to control rust, corrosion, or undesirable residues on machined surfaces. In addition to meeting these requirements, the coolant strategy in a given applications must significantly improve machining performance to justify the investment, infrastructure, and operating costs of the coolant system.

The types of coolants that are effective for broad classes of work materials and operations, for example, for turning aluminum alloys or milling steels, are generally understood. The selection and maintenance of a cutting fluid in a specific application, however, is often determined by experience and limited performance testing, and typically represents one of the more arbitrary decisions in process design. This is unfortunate, since the cutting fluid type, application method, pressure, and flow rate have as strong an influence on tool life and surface quality as parameters such as the tool grade, cutting speed, and feed rate, all of which are normally carefully optimized during process design. As an integral part of the system, the available coolant options should be considered in addition to the tooling and feed and speed variables in process development.

Studies have shown that occupational exposure to cutting fluids can lead to adverse health effects. This has led to increased interest in minimizing coolant usage and other measures to limit workforce exposure. The material safety data sheet (MSDS) describes the characteristics and safe usage practices for a given fluid and should be consulted prior to use. In the United States, the National Institute for Occupational Safety and Health (NIOSH) and Department of Labor provide documentation on the prevalence of hazards, the existence of safety and health risks, and the adequacy of control methods.

This chapter provides a broad overview of common cutting fluids, application methods, filtering, maintenance and waste treatment practices, and health and safety issues. It also provides an overview of recent research on the development of dry and near-dry machining technologies. The most widely used near-dry machining method, minimum quantity lubrication (MQL), is covered in detail in Chapter 15.

14.2 TYPES OF CUTTING FLUIDS

Cutting fluids are commonly classified as neat or cutting oils, water-based fluids, gaseous fluids, air-oil mists, and cryogenic fluids. Water-based fluids include emulsifiable oils, semi-synthetic fluids, and synthetic fluids.

14.2.1 Neat Oils

Neat oils are mineral, animal, vegetable, or synthetic oils used without dilution with water. Petroleum-based mineral oils, including light solvents, neutral oils, and heavy bright and refined oils, have traditionally been most common due to their low cost. Fatty animal oils are used largely as compounding oils as discussed in the following. Vegetable oils used include palm oil, rapeseed (canola) oil, and coconut oil. They are more expensive than mineral oils but are sometimes required in environmentally sensitive applications, especially in Europe, for example, in machining titanium and stainless steel and in applications requiring the German WGK-0 or NWG classification. Synthetic esters or fatty alcohols made from renewable sources are also used as substitutes for mineral oils, especially in MQL applications.

Mineral oils may be classified as straight or compounded, with compounded being the more common. Straight oils are base oils without active additives; compounded oils consist of the base oil mixed with polar or chemically active additives. Common polar additives include fatty animal oils such as lard oil or tallow, and vegetable oils such as palm oil or castor oil derivatives. These additives, which are used in concentrations between 10% and 40%, increase the cutting oil's wetting ability and penetrating properties and thus improve lubricity. Common active additives include chlorine, sulfur, and phosphorous compounds; they are surface reactive and form a metallic film at the tool surface, which acts as a solid lubricant. Additives must be chosen to be chemically compatible with the work material; improper additives can produce staining or corrosion of the part.

Cutting oils are more effective as lubricants than coolants. They are used extensively in grinding and honing operations, where they permit higher metal removal rates with better finish and less surface damage than water-based fluids. Due to their limited cooling capabilities, they are not used in high-speed machining and restricted to relatively low speed operations such as broaching, tapping, gear hobbing, and gun drilling, and in machining nickel alloys and other hard metals.

Cutting oils are stable and provide excellent rust protection. They are relatively costly, however, have limited applicability to high-speed applications, present a potential smoke and fire risk, and have been associated with contact dermatitis and other operator health issues. Due to their high cost and fire risk, they are generally used only on individual machines, and not in large recirculating systems.

Vegetable oils have high flash point temperatures compared to high viscosity mineral oils (typically 230°C versus 165°C), so that smoke formation is less of a concern. They also provide better lubricity (because of the dipolar nature of their molecules) and are often used as a polar additive to enhance the lubricity of mineral oils. Even though vegetable oils are more expensive than mineral oil–based formulations, they may be cost effective in some applications due to reduced consumption (less dragout than mineral oils) and improved tool life and productivity. Natural vegetable oils have limited shelf life due to hydrolization and bacterial degradation and are often treated to produce esters-based or other modified oils to improve stability.

14.2.2 Water-Based Fluids

Water-based fluids are dilute emulsions or solutions of oils in water, which provide less lubrication but better cooling and chip clearing abilities than neat oils. Water cools two to three times faster than mineral oils and can retain more than twice the amount of heat. They are used extensively in higher speed operations and large recirculating systems. There are three basic types: *soluble oils*, *semi-synthetics*, and *synthetics*.

Soluble oils are special types of mineral or other base oils emulsified in water at concentrations typically between 5% and 20%, with lower concentrations (less than 10%) being most common in general-purpose machining. (The term "soluble oil" is in fact incorrect, since oils are not soluble in water, but is in common use.) Soluble oil concentrates contain severely refined base oils (30%–85%), emulsifiers, and performance additives such as extreme pressure (EP) additives, stabilizers, rust inhibitors, defoamers, and bactericides. Base oils have traditionally been primarily naphthenic or paraffinic mineral oils, with naphthenic oils being more common due to their lower cost, although ester-based oils and vegetable oils may also be emulsified. The oil viscosity is typically 100 SUS at 100 F (100/100 oils); higher viscosity oils provide better lubricity but are more difficult to emulsify. Emulsifiers are added to form stable dispersions of oil and water; emulsifier particles are located around the oil droplets to give them a negative charge that will bond them with the water molecules. The size of the emulsified oil droplets is very critical to fluid performance; it is easier for the smaller emulsion sizes to penetrate the interface of the cutting zone. Most emulsions have droplet sizes between 2 and 50 μm and give the fluid a translucent white or blue-white appearance. "Pearlescent" microemulsions have droplet sizes between 0.1 and 2 μm; they provide better lubricity but have a tendency to foam and entail greater waste-treatment difficulties. EP additives have the same function as chemically active additives in neat oils. Stabilizers inhibit the breakdown of the emulsion, which occurs over time as metal particles in the fluid combine with the emulsifiers. Bacteriocides are added to control bacterial growth and rancidity, although there is a trend toward reduced usage due to operator exposure concerns.

There has been increased interest in the development of new environmentally friendly cutting fluids, such as vegetable-oil based coolants, which can be derived from renewable resources. More recently the term "green" metalcutting fluids has been used to include not only vegetable-based soluble oils, but also other fluids that do not contain any chlorine, sulfur, or phosphorus, since these components can present waste disposal concerns. The greenest cutting fluids are vegetable-based neat oils used in MQL applications, since they leave behind very little residue and near-dry chips. Some synthetic and petroleum-based nontoxic and biodegradable oils are also considered green cutting fluids.

The emulsifier may be anionic (negative chemical charge; e.g., carboxylates, sulfonates, phosphates, and phosphonates), cationic (positive chemical charge amine salts, phosphonium compounds), or nonionic (neutral chemical charge; e.g., polymeric ethers, esters, and amides). Light-duty soluble oils use soap-sulfonate emulsifier systems. Moderate to heavy-duty soluble oils contain chlorinated paraffins or sulfurized fat emulsifiers. The percentage of the base oil, emulsifier, EP additives, and other additives by weight in general purpose light duty soluble oils is 83%, 15%, 0%, and 2%, respectively; for medium-duty soluble oils the corresponding percentages are 70%, 15%, 10%, and 5%, respectively, while for heavy-duty soluble oils the percentages are 30%, 20%, 40%, and 10%, respectively.

Soluble oils provide excellent cooling and reasonable lubricity performance at low concentrations, have inherent rust preventive properties, and can incorporate additional performance additives. Their disadvantages include their hard water sensitivity, susceptibility to microbial attack, tendency to foam, potential to cause contact dermatitis, and disposal difficulty.

Semi-synthetic cutting fluids are fine emulsions in which the base concentrate is a mixture of mineral oil and additional chemicals, which may include emulsifiers, couplers, corrosion inhibitors, EP additives, and bacteriocides and fungicides. They combine features of both soluble oils and synthetics. The base concentrate usually contains between 5% and 30% mineral oil and 30%–50% water. The fluid itself typically contains 50%–70% water. Semi-synthetics require higher emulsifier concentrations than soluble oils, especially when oil-soluble chemical additives are used. They produce smaller emulsion particle sizes than soluble oils (from 0.01 to 0.1 μm), which gives them improved lubricity and makes them transparent or translucent. They can be formulated either to emulsify or reject tramp oils. The advantages of semi-synthetics include rapid heat dissipation, excellent wettability, cleanliness, and resistance to rancidity and bacteria; bacterial resistance is enhanced by the small emulsion size and relatively low concentration of mineral oil. Compared to synthetic fluids, they provide better rust prevention, improved flexibility in incorporating additives (since both water- and oil-soluble additives can be used), and fewer waste treatment concerns. Their disadvantages include foaming and residue concerns and susceptibility to contamination by tramp oils.

Synthetic cutting fluids are water-based fluids consisting of chemical lubricating agents, wetting additives, disinfectants, and EP additives. They are true solutions in water and contain no oil. They are used in relatively low concentration (typically 5%) and produce a particle sizes below 0.005 μm. Dilution affects the extreme-pressure lubricity of the fluid, so heavier cuts require a higher concentration. They are generally clear, but are often dyed to indicate their presence in water. Additives are chosen to be low-foaming and stable in water.

Synthetic fluids typically contain rust or corrosion inhibitors, lubricants, and fungicides. Rust inhibitors are necessary since no oil is present. Common inhibitors include borate esters and amine carboxylate derivatives. Both boundary and EP lubricants are added. Typical boundary lubricants include soaps, amides, esters, and glycols. Common EP additives include chlorinated and sulfurized fatty acid soaps and esters. Fungicides are necessary since synthetic fluids are susceptible to yeast and mold growth; bacteria are not a concern since the fluids contain no mineral oils and have a relatively high pH.

Synthetic fluids provide excellent cooling and produce fine surface finishes. Compared to emulsifiable oils, they provide better resistance to bacterial degradation and improved tramp oil rejection, stability, and workpiece visibility. They do not usually cause dermatitis. Their disadvantages include reduced lubricity due to absence of petroleum oils, a tendency to leave hard crystalline residues, high alkalinity, a tendency to foam, and disposal problems.

Figure 14.1 shows historical trends in the usage of cutting oils and water-based fluids. Only straight oils were used prior to 1910. Soluble oils were introduced between 1910 and 1920 to improve cooling properties and fire resistance. Semi-synthetic fluids were introduced in the 1950s to further improve cooling and rust inhibition. Synthetics were first widely used in the 1970s, when the price of petroleum increased dramatically. Over the long term, straight oils have been used less as cutting speeds have increased; of the water-based fluids, soluble oils are still most common due to their low cost.

Water-based fluids commonly fail by loss of emulsion stability or wetting ability (which are affected by the metal machined, the material removal rate in relation to the volume of coolant, the type of water used in the system, the water evaporation rate, tramp oils, the pH level, and the loss of stabilizers such as biocides and odor control agents). In general, the most common causes of failure include heat, hard water, tramp oil, oxidative and reactive agents, and microbial growth. The ASTM Standard E1497-94 and similar NIOSH and OSHA publications should be consulted for safe use guidelines.

14.2.3 Gaseous Fluids

In some operations gases rather than liquids are used as cutting fluids. This is true in particular in applications in which no fluid residue on the workpiece can be tolerated, as is the case in some medical and aerospace applications. Gaseous fluids used include air, helium, CO_2, argon, and nitrogen, with air being the most common due to its low cost. (Freons were used historically but are no longer permitted in the United States.) Air can be compressed or chilled to provide better cooling by forced convection. High pressure air streams can be used to eject chips (though not as effectively as a liquid) assuming the proper shrouding is used. Noise generation is a sig- nificant concern with high velocity or compressed air systems. CO_2 provides evaporative cooling when it is compressed and sprayed into the cutting zone. In Germany CO_2 systems are sometimes called "CO_2 snow" due to the frost frequently left on the tool after their use.

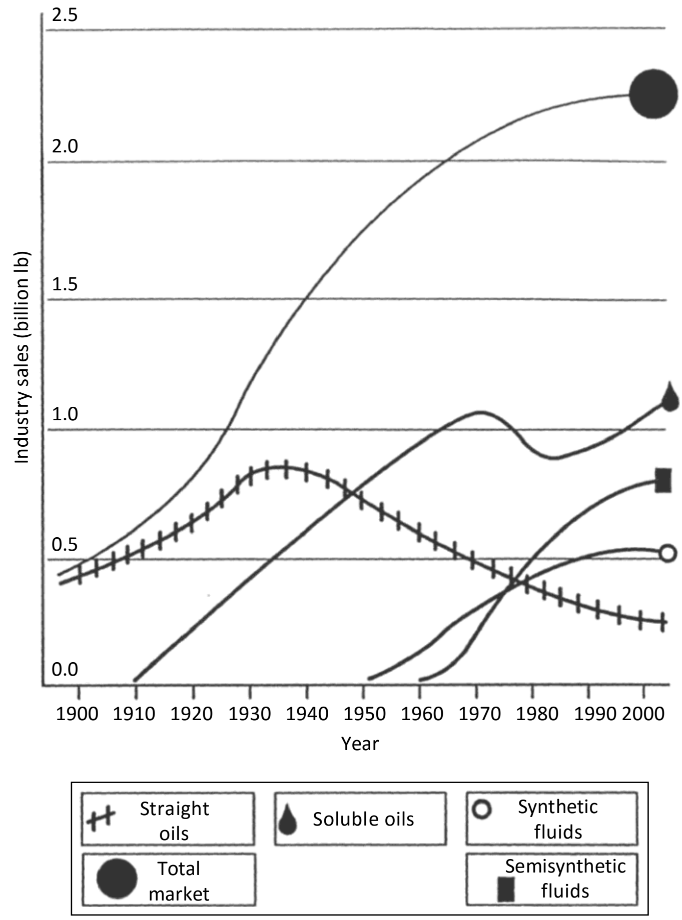


FIGURE 14.1 Historical usage of straight oil and water-based cutting fluids.

14.2.4 Air–Oil Mists (Aerosols)

Air–oil mists, consisting of small droplets of water-based oil mixed with air, have been successfully applied as cutting fluids in many applications. Historically, they were used in high-speed applications with small areas of cut, for example, end-milling applications. With the development of through-spindle coolant systems, they have been increasingly restricted to low-speed cutting applications such as drilling, gear machining, and sawing operations. There are two methods of producing mists: aspirator methods and direct-pressure methods. In aspirator systems, a stream of air is directed past an open tube containing oil, creating a partial vacuum, which draws oil droplets into the air stream. In direct-pressure systems, compressed air is directed through the oil to create a mist. Oil mists are best suited to applications in which flood coolant is impractical, for example, in applications in which the cutting zone is relatively inaccessible, and on large machines. Their major disadvantages are a tendency for the nozzles to clog and exposure of the operator to mist inhalation, which has adverse health consequences as discussed in Section 14.6. Lean air–oil mists are also used in minimum quantity lubrication (MQL) systems as described in Chapter 15.

14.2.5 Cryogenic Fluids

Cryogenic coolants (with boiling points below −150°C) are sometimes used to machine and grind difficult-to-machine materials. Liquid nitrogen (LN_2) is the most common cryogenic cool- ant, although liquid argon and liquid CO_2 are also used. Cryogenic coolant application is especially effective when machining materials for which cutting temperatures are a major concern, for example, titanium alloys, compacted graphite iron, and hard steels. They are also used for stainless steel and nickel alloys, but in these applications an additional oil line may be required to provide lubrication. When properly applied, cryogenic fluids can be used to increase both tool life and metal removal rates compared to conventional and high pressure water-based coolants. Cryogenic fluids are generally used with carbide tooling, and depending on the application method may require pre-cooling of the tool to prevent damage due to thermal shock. Another operational limitation of older systems was the tendency of the nozzles to ice over due to condensation of water vapor from the surrounding atmosphere, but countermeasures have reduced this issue on current systems. Cryogenic fluids are more expensive to apply than air–oil mists, and it may lead to part warping. However, they are vaporized during use and thus do not leave a residue or require treatment, which is a significant benefit in environmentally sensitive applications.

14.3 COOLANT APPLICATION

The effectiveness of cutting fluids depends to a large extent upon the method of their delivery into the cutting zone. There are four basic methods of applying coolant: low pressure flood application, high pressure flood application, through-tool application, and mist application (see Figure 3.61). In *low pressure flood application* systems, coolant is delivered through nozzles over the work zone at line water pressures. Coolant may be applied through either fixed or flexible piping, with fixed systems being common on dedicated systems and flexible tubing being more typical of general purpose machines. In either case coolant nozzles should be directed ahead of the cut, with sufficient additional coolant being supplied to cover the workpiece and back of the cutter, especially in milling operations. Insufficient or intermittent coolant application in milling operations can lead to thermal fatigue wear of the cutter. If the coolant volume is sufficient, low pressure flood application is effective in clearing chips and cooling the part to maintain dimensional tolerance but has limited lubricating effectiveness.

In *high pressure flood application*, coolant is directed through nozzles to impinge ahead of the cutter at higher pressures. The inlet nozzle pressure varies widely with the orifice diameter but is typically between 5 and 100 bar (75 and 1500 psi). Considerably higher pressures are used in some grinding operations and in impingement chip breaking jet systems. Coolant is applied though rigid piping, with nozzles typically being mounted on a ring around the spindle nose in boring, milling, and drilling (Figure 3.61), on the toolholder behind or through the insert in turning, and on a rigid pipe in front of the wheel in grinding. High pressure application provides more effective lubricating and chip clearing capabilities but generates mist, which may present a hazard to the operator if not properly collected and filtered. There is also an increased tendency for the coolant to become aerated and foam.

In *through-tool coolant* systems, coolant is supplied through the spindle or a coolant inducer to coolant passages in the tool under high pressure. Typical application pressures are 35–100 bar (500–1500 psi). Through tool coolant is required to clear chips in many high throughput drilling and deep hole drilling operations and is also used in grinding (through porous wheels). It requires special seals and pumps, which generally must be built into the machine tool. It is very effective in cooling the cutting edge and clearing chips in holemaking operations, and in cooling the wheel in grinding. Effective seals must be installed and maintained to prevent coolant from leaking into the spindle bearings. In drilling, the coolant must be effectively filtered to prevent debris from clogging the tool coolant passages in recirculating systems. Disadvantages of high pressure coolant include increased maintenance to ensure that seals, pumps, and rotary unions do not fail, a tendency to generate mists, and increased foaming.

As discussed in the previous section, mist application is applied using either aspirator or direct pressure systems and is used especially in drilling, gear machining, and sawing operations.

Generally, the coolant pressure should be sufficient to penetrate the vapor barrier pocket generated around the cutting edge. The force with which the fluid penetrates the cutting zone (through the vapor barrier) is somewhat proportional to the coolant velocity and a critical factor for the design of the process. However, the velocity is proportional to the square root of the pressure. Therefore, doubling the coolant pressure results in a roughly 40% increase of the coolant force as explained in Chapter 4. Hence, it is preferable to increase the coolant volume rather than the pressure to optimize coolant performance in most applications. However, for some difficult-to-machine materials, coolant pressures of 20–30 bar (2000–3000 psi) have been found to be effective. Some machines are equipped with a standard coolant pump and a high-pressure pump for flexibility for various applications.

During machining, airborne mist is generated from cutting fluids. Many factors including the machining conditions, cutting tool design, and fluid application method influence mist generation. Mist generation is usually controlled through mechanical means (i.e., enclosures, ventilation), chemical means (i.e., anti-mist polymer additives, mist suppression at the source, foam reduction, formulations with low oil concentrations, avoiding contamination with tramp oil, etc.), minimizing fluid delivery pressure and flow rate, the proper design and operation of the cutting fluid delivery system, or the use of dry or near-dry machining methods. Once generated, mists are normally controlled or abated through ventilation and filtering as discussed in the next section.

Regardless of the method used to apply coolant, sufficient volume must be supplied to provide adequate cooling and chip clearing capability. Coolant volume is measured by the flow rate in gallons or liters per minute. As a reasonable rule of thumb, the coolant volume should be 1–2 gal/min for each HP of cutting energy (or 5–10 L/min for each kW) for general machining, and 2–4 gal/min per HP (10–20 L/min/kW) for grinding [4]. As will be discussed in the next section, an adequate sump capacity is required to ensure proper filtering and minimize foaming; as a general rule of thumb, the sump capacity should be 3–10 times the flow rate per minute. More detailed recommendations of the sump capacity are 5 times the flow rate for steel machining, 7 times the flow rate for cast iron and aluminum machining, 10 times the flow rate for grinding, and 10–20 times the flow rate for high stock removal machining and grinding.

14.4 FILTERING

Coolants in recirculating systems entrain and transport a number of impurities, including chips, airborne contaminants, hydraulic and machine way oils, residues left on the part from previous operations, etc. These impurities must be removed to maintain coolant performance. A variety of methods and systems are used to remove contaminants from cutting fluids, which can be broadly classified as either separation methods or filtration methods. Often two or more methods are used in sequence to increase effectiveness.

Common separation methods include settling tanks, centrifuges, cyclones, and magnetic separators. A *settling tank* is a large tank with two or more baffles (Figure 14.2); as the fluid moves under and over successive baffles, tramp oils and lighter impurities rise to the surface, where they can be skimmed off, and chips and other heavy debris settle on the bottom, where they can be similarly removed. The effectiveness of the tank depends on the settling time or the volume of the tank divided by the inlet flow rate; if the settling time is too short, not all impurities will settle out, there will be an increased tendency to foam since coolant bubbles will not have time to burst, and coolant temperature will be more difficult to control. Settling times should be 5 min for small systems, 7–10 min for general purpose systems, and 10–15 min for large systems. Centrifuges and cyclones separate debris from the coolant through centrifugal action.

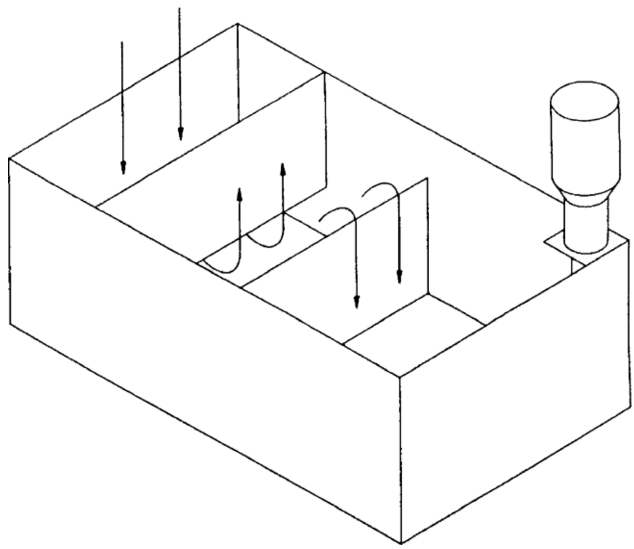


FIGURE 14.2 Settling tank.

In a *centrifuge,* dirty coolant is introduced between rotating bowls or cone-shaped disks. Chips and other heavy debris are forced toward the center of the bowls or disks, and tramp oils with low specific gravity are forced outward. The bowls or disks eventually fill with debris and require periodic cleaning. In a *cyclone* (Figure 14.3), dirty coolant is directed into a cone-shaped vessel; the resulting rotary motion of the fluid forces chips and debris outward, so that relatively clean fluid emerges from the center of the device. In a *magnetic separator* the coolant is directed past a rotating magnetic drum. Chips and fines stick to the drum and are removed by a blade on the opposite side of the drum, generally out of the coolant bath. Magnetic cyclones and belt systems are also used. These systems are obviously effective mainly for ferrous chips, although they will also remove abrasive grains adhering to ferrous fines in grinding systems.

Since separators are not effective in removing impurities with specific gravities near that of the coolant, they are normally used in conjunction with filtering systems. These systems may use either disposable or permanent porous media; the degree of filtering achieved is determined by the pore size of the medium. Common *disposable medium filtering systems* include bag, cartridge, and roll systems (Figure 14.4). The filter medium in these systems may be made of paper, cotton, wool, synthetic fibers, or felted materials; they are often pre-coated with fine particles such as cellulose fibers or diatomaceous earth. In a bag system, coolant is passed through two or more fabric bags with successively smaller mesh sizes. The bags fill with chips and must be changed periodically. Cartridge systems are similar but use cylindrical cartridges, similar to an automotive oil filter, rather than bags. Flat-bed roll filters are common in large recirculating systems. In this approach, coolant is passed through a sheet of filter media. As filtering progresses and the filter becomes clogged, the fluid level in the tank rises, eventually triggering a float, which indexes the roll to expose fresh media. Disposable media filters may be driven by gravity, a vacuum, or pressure. In a gravity system, fluid flow is maintained by gravity. In a vacuum system (Figure 14.5), a negative pressure is applied to the back of the medium to accelerate flow. In a pressurized system positive pressure is applied to the fluid to force it through the medium. Pressurized systems operate at higher pressures and can produce the largest flow rates. Both gravity and pressurized systems are used with flat-bed roll filters. Pressurized systems are also commonly used with cartridge filters.

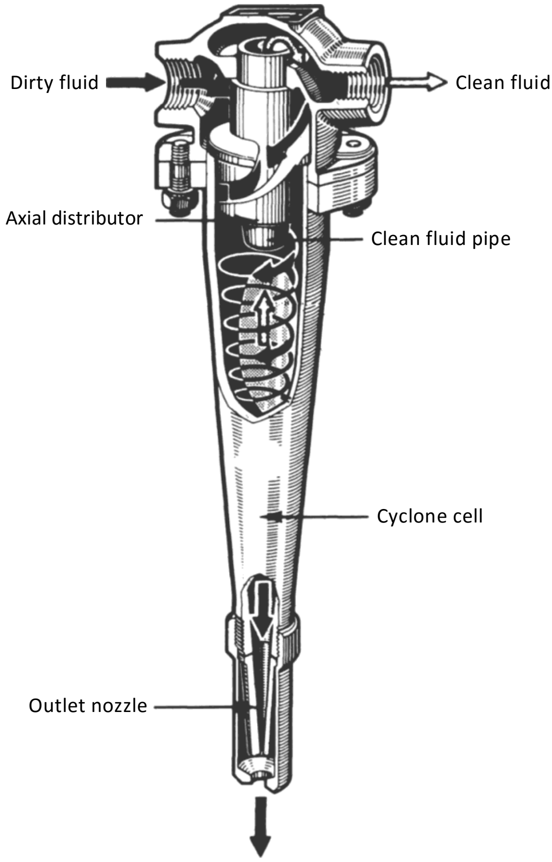


FIGURE 14.3 Chip cyclone.

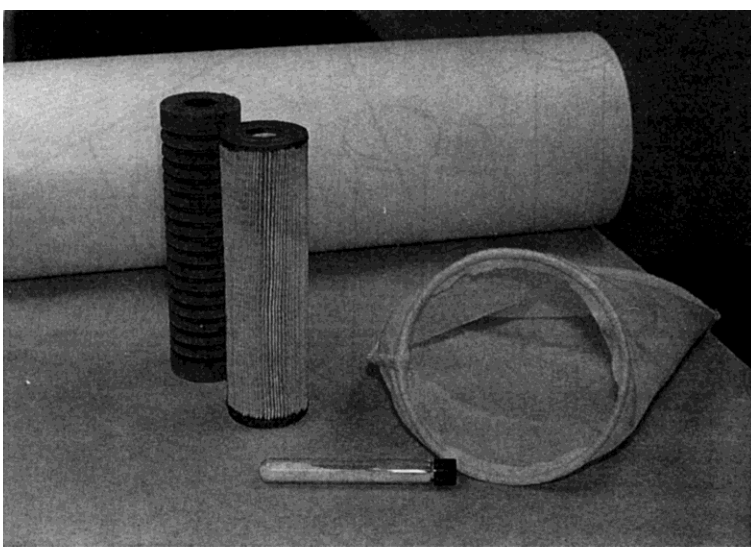


FIGURE 14.4 Disposable filtering media.

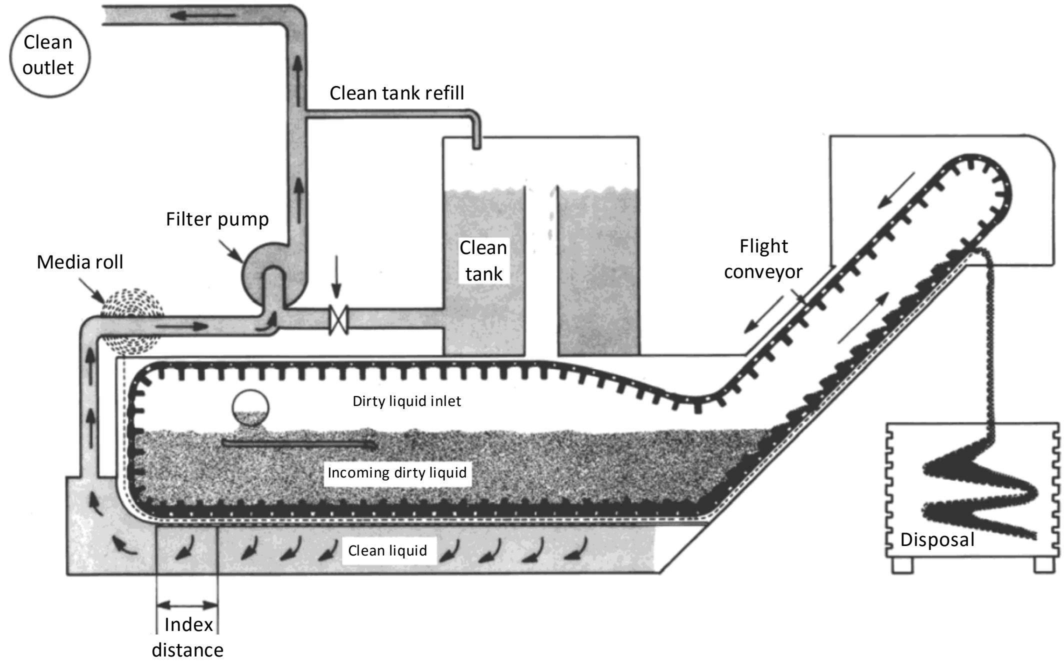


FIGURE 14.5 Vacuum media flat-bed roll filtering system.

In *permanent media filtering systems*, a wire mesh or permanent fabric is used as the filtering medium. As in disposable media systems, a porous pre-coating material is often used to increase effectiveness. Chips and other debris are periodically removed by a cleaning unit; cleaning may be controlled by a timer or activated by a float trigger. Common system configurations include those employing circular meshes, flat belts or screens, and stacked disks separated by spacers. Figure 14.6 shows one especially common approach, in which a wedge-wire mesh belt is used in a flat-bed configuration. Permanent media filters require higher initial investment but may be more economical over time, since disposable media costs are avoided; they also generate waste in cake form, which may be more economically disposed of than the contaminated fabrics produced by disposable media systems. Large sand or diatomaceous earth filter systems are sometimes used for neat oil applications, especially grinding. In these systems oil seeps through a bed of fine earth, which traps entrained particles. Periodic back-flushing is required to remove accumulated debris.

Aside from cost, factors to be considered in choosing a filtering strategy are the level of filtration necessary, required system capacity, and the effect of the filter medium on the coolant. The level of filtration is generally expressed as the largest dimension of contaminant, which can be tolerated. Generally, standard chip removal and cutting fluid filtration systems remove debris over 50 μm in size fairly easily. Greater care and additional filtering stages are required to remove finer debris. A common rule of thumb for general purpose machining is that coolant should be filtered to 1/10th the tolerance band. This can lead to very stringent requirements for precision operations. In large systems employing through-tool coolant, it is common to filter to between 5 and 10 μm. The required system capacity depends on the coolant flow rate. Minimum capacities can also be computed from the sump volume; large systems typically pump at least three times the sump capacity in 24 h. Bag filters generally have capacities between 25 and 50 gal/min/ft^2 of filter area (1000–2000 L/min/m^2).

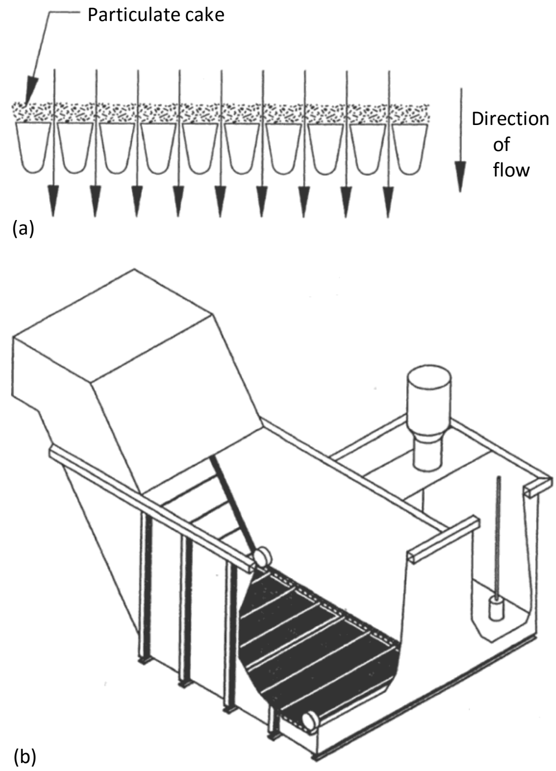


FIGURE 14.6 (a) Wedge-wire permanent media filtering principle. (b) Flat-bed wedge wire filtering system.

Cartridge filters typically have a capacity of approximated 1 gal/min/ft of cartridge length (1 L/min for 6 cm). Flat-bed systems have much higher capacities and are most common for large installations. Permanent media systems have the same flow capacity as disposable media systems of comparable pore size. Some types of filters can reduce fluid effectiveness by removing oxidization inhibitors, detergents, and other additives as well as contaminants. Filter system manufacturers provide information on flow rates, filtering levels, and application ranges for specific systems.

Another frequently important component of the fluid filtration system is the *Ventilation System* to control mist and airborne contaminants. Of major concern are atomized mists with particle diameters of tenths of a micron, which are most common in high-speed machining and grinding operations with high pressure coolant. When mist generation cannot be reduced, effective building ventilation and source isolation through machine enclosures ventilated to appropriate mist collectors must be implemented. The ANSI B-11 Technical Report 2 and ACGIH provide guidelines for proper ventilation system consisting of physical barriers or ductwork. The key points discussed in the ANSI B-11 Report are summarized in Figure 14.7. Similar guidelines for isolation, ventilation, and filtration in recirculating air systems are provided by the U.S. Occupational Safety & Health Administration (OSHA). Systems that recirculate air (rather than venting it outside) normally require submicron mist filtering using high-efficiency particulate air (HEPA) filters. HEPA filters combined with spark arrest systems are required for aluminum MQL machining systems to remove fine mists and mitigate fire and explosion risks.

- Metalworking fluid delivery system
  - Proper fluid selection
  - Proper fluid maintenance
  - Proper fluid application
- Machine tool design
  - Efficient chip disposal and control
  - Properly arrange the coolant nozzles
  - Coolant should be kept on only during actual cutting cycle
- Machine enclosure design
  - Enclose the cutting process
  - Prevent mist release around the people
  - Employ effective exhaust methods
- Duct work design
  - Employ heavy-duty industrial construction
  - Employ drains with traps
  - Design for mist collection, not chip transportation
- Collector design
  - Employ high particulate removal efficiencies
  - Multistage collectors are cost effective
- System testing
  - Evaluate the collection systems to verify the proper airflow and static pressures
  - Use test standards to select system components

FIGURE 14.7 Key points discussed in the ANSI B-11 Report.

14.5 CONDITION MONITORING AND WASTETREATMENT

The chemical composition and other properties of the cutting fluid should be monitored regularly to maintain acceptable performance. Common parameters monitored include concentration, percent solid and tramp oil, bacteria and fungi count, water quality, and temperature.

In water-based systems, the *concentration* of the base oil or synthetic concentrate should be monitored to ensure that it is within acceptable limits. If the concentration is too low, the fluid will not perform properly and corrosion of the workpiece may be a concern; if it is too high, the system is being run uneconomically, and the fluid will have an increased tendency to foam. In mineral oil–based fluids, excessive concentration may also promote bacterial growth. Concentration is most often measured using a refractometer, a device that correlates the diffraction of a beam of light by a drop of sample fluid to concentration. Laboratory tests such as oil split methods and chemical titration are also used. Concentration can be difficult to measure accurately if tramp oil contamination is not controlled, since refractometers do not distinguish tramp oils from base oils well. The *percent solid* and *tramp oil* are indications of the effectiveness of filtering and of maintenance issues. Excessive solid entrainment, which often produces poor surface finish, indicates that filtering is not effective and should be corrected. Similarly, excessive tramp oil may indicate the presence of a broken hydraulic line, bad seal, malfunctioning way lubrication unit, or other component failure. Excessive tramp oil contamination results in pumping problems, poor filter performance and life, and destabilization of the cutting fluid emulsion. Regular machine maintenance minimizes contamination of the cutting fluid with free debris and tramp oils leaking from spindles, slides, and gearboxes. Both percent solid and tramp oil are measured by allowing a fluid sample to stand in a graduated cylinder; over a period of hours, the tramp oil will rise to the top, and solids will settle in the bottom. Centrifuges and filters can also be used for this purpose.

Bacteria and fungi in the coolant should be monitored and controlled. Standard tests for microbial content include plate count and dipslide tests; other methods, including enzyme catalase and dissolved oxygen monitoring, are less commonly used. Excessive microbial content generates objectionable odors and may cause corrosion, changes in fluid chemistry, and filter blockage. In rare instances there may also be adverse health effects as discussed in the next section. In addition, bacteria consume cutting fluid components, and the by-products of this activity can lower the mix pH. Typically, well-maintained coolant systems have bacterial counts below one million per milliliter. Methods of controlling microbial growth include filtration, the use of chemical biocides, and a variety of less common pasteurization, radiation, and microwave treatments. The best method to control bacteria and fungi is to maintain a clean system and limit oil and water contamination. Excessive use of biocides should be avoided to limit occupational exposure to toxic concentrates.

Important factors in *water quality* are hardness, pH, and chemical content. Fluid effectiveness can be compromised if its hardness exceeds 200 ppm dissolved minerals and organics, or if it contains excessive levels of chloride, sulfate, or phosphate ions. Hard water increases concentrate usage and may lead to corrosion and residue problems. Hardness is a particular concern if wetting agent additives are used. Conversely, when the water is too soft (total hardness less than 80 ppm) the fluid will have an increased tendency to foam. The ideal water hardness range for metalworking fluid mixes is between 80 and 125 ppm. Treatment of incoming water or an alternative water source is required for excessively hard or soft water. The fluid's pH can be measured using a pH meter or pH paper. New coolants generally have a pH between 8 and 9. In this range the fluid is alkaline, which discourages microbial growth. The spoilage range of most coolants is between 7 and 8. Low pH may result in increased corrosion, objectionable odors, and destabilization of the coolant. If the pH is above 9.5, it may irritate the skin of operators.

Corrosion is a problem not only of water-diluted cutting fluids but also in dry machining. Corrosion results from chemical reactions and increases with increasing temperature in the presence of moisture and oxygen in the atmosphere. Moisture condenses on a workpiece and acts as an electrolyte to form a galvanic cell. The concentration and type of additives used to provide protection against corrosion depend upon the type of metal(s) involved (including ferrous and nonferrous), the cutting fluid, and the anticipated chemical reactions. Some of the factors affecting corrosion are the pH of cutting fluid (>9 protects ferrous metals, although this level can adversely affect nonferrous metals such as aluminum and brass), impurities in the water (e.g., high concentration of ions, >100 ppm chloride, >100 ppm sulfate, or >50 ppm nitrate and conductivities > 4 mS/cm are considered aggressive waters), high bacteria counts, and unstable emulsions and fluid concentrations.

The cutting fluid *temperature* should be controlled in operations, which generate large amounts of heat, and in precision operations in which thermal expansion may produce significant dimensional errors. Temperature control to within 1°C–2°C is normally sufficient [39]. Temperature control can be accomplished using natural convection currents or forced air circulation, or circulating the coolant through a chiller integrated into the tank or sump. Fluids cooled to 10°C are effective in difficult operations.

Waste treatment is an important consideration in selecting a coolant. The manner and degree to which used coolants must be treated are governed by local regulations. Generally, straight oils are reprocessed by distillation or vacuum distillation prior to reuse or burning. Soluble oils are treated by adding chemicals such as sulfuric acid, polyelectrolytes, or salts to deactivate the emulsifier to separate the concentrate. Chemical separation is not effective for semisynthetics and synthetics, which must generally be treated using special filtration methods. A more thorough discussion of this subject is given in Refs.

14.6 HEALTH AND SAFETY CONCERNS

Occupational exposure to cutting fluids in liquid or mist form can have a number of adverse health effects. The common exposure mechanisms are dermal (skin) contact and inhalation; less common mechanisms include ingestion either orally or through an open cut. The resulting health effects may include toxicity, dermatitis, respiratory disorders, microbial infections, and cancer.

14.6.1 Toxicity

Short- or long-term exposure to cutting fluids and fluid additives, especially biocides and fungicides, may induce toxic reactions. Acute toxicity may occur through accidental ingestion through splashes or handling food with dirty hands, absorption through cuts, or inhalation of mists; chronic toxicity may result from long-term exposure to mists. Coolants and additives are regulated by local laws; in the United States, coolant suppliers must provide a material safety data sheet (MSDS), and biocides are regulated as pesticides by the EPA. The documentation required by regulation provides information on permissible exposure levels, necessary protective equipment, and countermeasures in case of ingestion. Coolants used in recirculating systems may leach heavy metals or lead from the work material; if this is a possibility, coolants should be monitored for metal content and changed as needed to avoid unacceptable exposure levels.

14.6.2 Dermatitis

Dermal contact with cutting fluids can cause contact or allergic dermatitis. Dermatitis is the most common health problem associated with cutting fluids; estimates are that it afflicts between 0.3% and 1% of machinists in the United States. There are two common mechanisms for skin irritation: blocking of hair follicles by fines or other debris in used fluid, and removal of protective oils from the skin, particularly when the coolant pH is high (over 9). The first mechanism leads to condition called oil acne, an old ailment first reported in the United States in 1861. The second mechanism has become common in recent years with the increased use of water-based fluids and is also associated with some types of additives, notable biocides. Dermatitis is more easily prevented than treated; common prevention methods include ensuring that fluid concentration levels are not too high, providing gloves, hand creams, and low pH soaps to operating personnel, transferring operators who show particular sensitivity to dermatitis, substituting alternative additives for those suspected of causing a problem, improved filtering, and education on the workforce on proper hygiene and methods of minimizing exposure.

14.6.3 Respiratory Disorders

Exposure to cutting fluid mists has often been reported to cause acute respiratory difficulties including coughs, increased airway secretions, asthma, bronchitis, and airway constriction, which can result in shortness of breath. When these symptoms persist, or get worse over time, the condition is sometimes called occupational asthma. Since these difficulties result from mist exposure, they occur primarily in water-based fluid applications. As discussed in detail in Ref., a number of cutting fluid components or additives may act as sensitizing agents. Machine enclosures and proper mist filtering can reduce workforce exposure to this risk.

Another respiratory disorder associated with cutting fluid mists is hypersensitive pneumonitis (HP), which may ultimately result in pulmonary fibrosis or similar build-up in the lungs of sensitive individuals. Bacteria have been proposed as sensitizing agent, although other causes have also been suggested. Switching biocides to alter the bacterial makeup of the fluid may help, but the safest course appears to be to transfer affected operators to a job that does not entail mist exposure.

14.6.4 Microbial Infections

Coolant sumps often sustain populations of bacteria, yeasts, and fungus. Most microbes feed off mineral oils, so microbial growth is a particular problem for coolants with high mineral oil content, either through high concentration or free oil contamination, and less of a problem for synthetic fluids, which contain no mineral oil. Vegetable oils are also subject to microbial attack and spoilage. Other factors contributing to bacterial growth are a bacteria-rich water supply, poor housekeeping, and low fluid pH.

Excessive microbial growth in the sump is regarded as a problem mainly because it produces objectionable odors and leads to fluid breakdown. It has traditionally been felt that microbial infection is unlikely. Most coolant systems are comparatively nutrient-poor and unlikely to support true human pathogens, which generally require a nutrient-rich environment. Isolated exceptions are reported, however. Microbial infections may be a problem for operators whose immune systems are compromised. There have also been reports of flu-like outbreaks associated with the bacteria that causes Legionnaire's disease. Control measures recommended in these cases included diligent microbial monitoring and avoiding allowing sumps to stagnate for long periods of time.

14.6.5 Cancer

Long-term exposure to cutting fluids has been associated with increased incidence of several types of cancer, including skin, scrotal, laryngeal, rectal, pancreatic, and bladder, and digestive cancers. Exposure routes include both dermal contact and inhalation. Details of specific correlations are given in Ref. Broadly, risks are increased when cutting with neat mineral oils rather than water-based fluids, and in grinding operations, which generate more mists.

There is some indication that greater risk is associated with exposure to older oils. Prior to the 1950s, the mineral oils used were primarily raw or mildly refined petroleum and shale oils, which contained significant concentrations of substances now known to be carcinogenic; in addition, work practices at that time resulted in more severe dermal exposure. Since the mid-1970s, and especially after 1985, substantial changes have been made in fluid composition, which reduce concentrations of harmful substances, and work practices have been modified to reduce exposure. As noted in the OSHA best practices manual, the substantial changes in industry practice over the last decades have likely reduced cancer risks from metalworking fluid exposure, but more data is required for a more definite conclusion.

14.7 DRY AND NEAR-DRY MACHINING METHODS

There has been increasing interest in reducing or eliminating the use of cutting fluids in machining. This would be of benefit for three reasons. First, it would reduce or eliminate exposure of operators to health risks as discussed in the previous section. Second, it would reduce machining costs. One frequently cited study by an automotive company indicates that 16% of the cost of machined parts is directly attributable to cutting fluids (including fluid management, disposal, and equipment) [82]. While this percentage varies for different applications, there is no question that the costs associated with the purchase, maintenance, and disposal of cutting fluids are invariably significant. Third, large central coolant systems require in-ground trenches and sumps, which greatly limit equipment flexibility.

Some processes are readily carried out without a cutting fluid for some workpiece materials; for example, cast iron parts can be machined dry under conventional cutting conditions if the tool is oriented properly for chip ejection; aluminum parts can be milled and turned without coolants at high cutting speeds using PCD tooling, and low carbon and hardened steels are also often machined dry. As discussed in Chapter 17, high-speed gear milling and hobbing are performed dry. Titanium medical implants are also often machined dry to avoid contamination. As some of these applications illustrate, dry machining is often advantageous in interrupted cutting operations such as milling or hobbing at high speeds, due to reduced thermal fatigue of the tool (especially for insufficient coolant volume). For most materials, however, dry machining is more difficult to perform effectively, especially at higher cutting speeds. This is especially true for harder materials such as stainless steels and nickel alloys. Without coolant, it becomes difficult to effectively clear chips (especially in holemaking operations), control dimensional distortion due to part heating, and prevent build-up on the tool. Special machine architectures that shed chips passively and low-friction tool coatings help address some of these problems. It is unlikely, however, that coolants will be completely eliminated in the near future, especially in holemaking and grinding processes. Significant reduction in coolant use, however, is achievable in many operations. Strategies include reducing cycle times to reduce the amount of coolant used per part, extending coolant life to reduce waste disposal volumes per unit time, and reducing coolant flow rates. When true dry machining is not practical, significant benefits can still be achieved using these methods or by using minimum quantity lubrication (MQL), a near-dry machining method discussed in detail in the Chapter 15. MQL has many of the advantages of the dry machining but also some of the disadvantages of wet machining. MQL implementation has led to tooling innovations and chip removal practices that are generally applicable to dry machining.

14.8 TEST PROCEDURE FOR CUTTING FLUID EVALUATION

The availability of new coolant types, and increased interest in reducing coolant use per part, has increased the need for a common procedure for evaluating or comparing cutting fluids. The current practice has been to evaluate two or more cutting fluids in the same machine, under the same operating and cutting conditions, and to measure cutting forces, spindle power, part quality (surface finish, dimensional control, etc.), or tool wear as the main criteria for performance comparison. Recommended procedures for cutting fluid performance testing or Machinability Test Guidelines are available for turning (plunging), drilling, milling, and grinding processes. Such tests require the specification of the cutting tool, cutting conditions, cutting fluid, criteria for ending the test (e.g., tool wear considering uniform flank wear along the cutting edge or grinding ratio G).

Some of the critical areas to be evaluated for longer-term tests are tool life, odor, foam, rust, residue, stability, filterability, dermatitis, biological control, pH, machine cleanliness, and overall usage rate as a function of the condition of the coolant. Information about solving cutting fluid problems and extending the life of the cutting fluids is summarized in the Refs.

As noted before, cutting fluid costs often account for 10%–15% of the total machining cost, while cutting tool costs typically account for a smaller component (on the order of 5% in high volume machining). In many operations, reducing or eliminating cutting fluid use if possible and accepting somewhat lower tool life may lead to lower overall machining costs.