面向21世纪 机械工程及自动化 机电一体化 专业规划教材

MODERN MACHINING TECHNOLOGY

现代加工技术

（英文版）

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内 容 简 介

《MODERN MACHINING TECHNOLOGY 现代加工技术（英文版）》是从近年出版的数十本英文著作及论文中摘录、筛选后编写而成。全书共分6章。第Ⅰ章介绍了以机械能为基础的加工工艺，包括磨粒射流加工、水射流加工、超声波加工及喷丸加工等工艺。第Ⅱ章介绍了以电能为基础的加工工艺，包括电化学加工、电化学磨削、电化学放电磨削、电流毛细钻孔等工艺。第Ⅲ章介绍了以热能为基础的加工工艺，包括电火花加工、电火花磨削、电子束、离子束及激光束加工、热能加工、等离子体弧加工等工艺。第Ⅳ章介绍了以化学能为基础的加工工艺，包括化学加工、光化学加工等工艺。第Ⅴ章介绍了复合交叉的加工工艺，包括脉冲式电化学和激光辅助电化学加工、WJM/USM/ECM/EDM/MAP 等交叉工艺、激光/等离子体辅助加工、激光冲击加工和水下激光加工等工艺。第Ⅵ章介绍了基于特种加工工艺的新技术，包括微制造、物理气相沉积、化学气相沉积和快速原型制造等加工工艺。

本书可以作为机械制造及自动化专业的高年级本科生和研究生的双语教材，以及专业英语教材，也可作为本专业技术人员的参考书。

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AN OVERVIEW

Nontraditional Machining Processes have evolved out of the increasingly complex needs of modern society. Inventions have been created to meet these needs, and new tools have been devised to enable the creation of increasingly sophisticated inventions.

One invention that has created new manufacturing challenges is the airplane. In the effort to increase performance, slow-flying aircraft have evolved into transatmospheric vehicles, and this has required continual improvements in materials to meet the demands for improved engine and aircraft-skin operating temperatures. Over the last 60 years, engine operating temperatures have been increased by more than 1100% and aircraft-skin operating temperature requirements have been increased by 2500% to withstand the increased friction resulting from extremely high airspeeds.

Technological developments of this type have prompted the creation of new, difficult-to-machine materials, such as racial-matrix composites, monolithic and composite ceramics, aluminides, and high-performance polymers. The difficulty in machining these and other new materials results from their high hardness and brittleness, high refractoriness, poor thermal properties, chemical reactivity with the cutting tool, and inhomogeneous micro-structures. In many cases, the only effective way to machine such materials is by nontraditional methods.

A concise definition of nontraditional machining processes is difficult to establish because of the widely differing processes that fall into this category. Generally, non-traditional processes are considered to be manufacturing processes adopted in the last 50 years that use common energy forms in new ways or that apply forms of energy never used before. Nontraditional processes are subdivided according to the form of energy being harnessed. The generally accepted categories are mechanical, electrical, thermal, and chemical. Table 1 lists the processes that fall within each of these areas.

Mechanical Methods: Mechanical nontraditional processes harness direct mechanical abrasive action to remove material. Mechanical processes are usually applied to workpiece materials that are difficult to machine by traditional techniques because of material hardness, toughness, or brittleness, Ceramics, composites, and organic materials are particularly good candidates for mechanical machining because most of them are not electrically conductive (a requirement for processing by electrical methods) and because they are damaged by burning, charring, or cracking when thermal processes are applied.

Electrical Methods: The electrical nontraditional processes are limited in application to electrically conductive workpiece materials. Workpiece materials that are difficult to machine by conventional means constitute a large percentage of the applications in this category; however, numerous applications are selected because of the ability of the electrical processes to produce complex shapes in a single pass of the tool and (with the exception of the electrical grinding variations) to process parts without tool wear.

Thermal Methods: Primarily because of rapid increases in the sales of wire electrical discharge machining and laser equipment, thermal processes have become the fastest-growing segment of the nontraditional market. Given the diversity of energy sources used in this category (electrons, photons, electrical sparks, and so forth), generalizations are difficult to make concerning the application of these processes. Thermal processes are generally unaffected by the physical properties of the materials being processed and are therefore often applied to extremely hard or low-machinability workpiece materials. Because the mechanism for material removal is thermal, workpieces that will be used for critical applications may require the removal of thermally affected zones.

Chemical Methods: High-volume, high-production manufacturing is often performed by chemical nontraditional processes. Although sometimes applied to low-quantity or even one-of-a-kind parts because of low initial tooling costs, chemical machining has gained wide acceptance for the economical manufacture of high-volume products such as springs, electric motor laminations, and television picture tube masks. Because material is removed by means of chemical action, there are no farces acting on the workpiece. This enables parts to be machined without concern for distortion or damage. In addition, because the machining action occurs on all surfaces of the workpiece simultaneously, effective throughput can be extremely high, even compared to high production rate processes such as punching and stamping.

The future of nontraditional machining processes will no doubt be characterized by steady growth. Although nontraditional processes will probably never replace the conventional tools currently used by industry, the newer methods are ensured an increasingly important role because of the beneficial effects of computer control, adaptive control, and education.

Compared to conventional processes, nontraditional processes possess almost unlimited capabilities, with one exception—volumetric material removal rates. Currently, conventional processes excel in rapid bulk material removal rates. However, many improvements in nontraditional process removal rates have been made in recent years, and there is every reason to believe that this trend will continue. This will enhance the competitiveness of nontraditional processes and will increase the range of applications.

Most nontraditional machining processes are computer controlled with respect to process parameters. Computer control simplifies processes that might otherwise intimidate potential users and, in the long term, accelerates acceptance of the process. In addition, the computer control of process parameters ensures process reliability and repeatability, and this further accelerates acceptance and implementation.

Unlike many conventional processes, most nontraditional processes can easily be adaptively controlled through the use of a broad range of in-process inspection sensors. For example, if a sensor detects that the holes being produced in a product are decreasing in diameter, the hole size can be modified without changing the hard tools by simply changing the process parameters or the offset values in the computer. In contrast, hard tools such as drills or punch and die inserts must be changed when conventional techniques are used. This ability to monitor, respond to, and correct undesirable situations automatically ensures the increasing importance of nontraditional processes in unattended machining cells and automated factories.

Every year more attention is directed toward nontraditional processes, as evidenced by the increasing number of technical papers, conferences, college courses, hooks, and technical symposia on the subject. These activities not only educate the manufacturing and product design communities about the unique capabilities of these processes, but also ensure a successful future for nontraditional machining processes.

Table 0-1 Categories of nontraditional machining processes

Mechanical Methods	Abrasive Jet Machining (AJM)	1.1
	Abrasive Flow Machining (AFM)	1.2
	Water Jet Machining (WJM)	1.3
	Abrasive Water Jet Machining (AWJM)	1.4
	Ultrasonic Machining (USM)	1.5
	Burnishing	1.6
Electrical Methods	Electrochemical Machining (ECM)	2.1
	Electrochemical Grinding (ECG)	2.2
	Electrochemical Discharge Grinding (ECDG)	2.3
	Electrostream Drilling (ES) and Capillary Drilling (CD)	2.4
	Shaped Tube Electrolytic Machining (STEM)	2.5
Thermal Methods	Electrical Discharge Machining (EDM)	3.1
	Electrical Discharge Grinding (EDG)	3.2
	Electron Beam Machining (EBM)	3.3
	Ion Beam Machining (IBM)	3.4
	Laser Beam Machining (LBM)	3.5
	Thermal Energy Method (TEM)	3.6
	Plasma Arc Machining (PAM)	3.7
Chemical Methods	Chemical Milling (CM)	4.1
	Photochemical Machining (PCM)	4.2

continued

Cross Machining Processes Innovations	Introduction of Cross Process Innovations	5.1
	General Issues in Cross Process Study	5.2
	Pulsed ECM and Laser Assisted ECM	5.3
	Cross Abrasive Processes — WJM / USM / ECM / EDM / MAP	5.4
	Laser / Plasma Assisted Machining	5.5
	Laser Shock Processing and Underwater Laser Machining	5.6
New Technology Based on Nontraditional Machining Processes	Microfabrication	6.1
	Physical Vapor Deposition (PVD)	6.2
	Chemical Vapor Deposition (CVD)	6.3
	Rapid Manufacturing — Rapid Prototyping (RP)	6.4

Contents

CHAPTER I

Machining Processes with Mechanical Methods

1.1 Abrasive Jet Machining (AJM)

Abrasive Jet Machining (AJM) removes material by the impingement on the workpiece of fine, abrasive particles entrained in a high-velocity gas stream. Abrasive jet machining differs from conventional sand blasting in that the abrasive is much finer, and process parameters and cutting action are carefully controlled. Material removal occurs through a chipping action, which is especially effective on hard brittle materials such as glass, silicon, tungsten and ceramics soft, resilient materials, such as rubber and some plastics resist the chipping action and thus are not effectively processed by AJM. The process is inherently free from chatter and vibration problems because the tool is not in contact with the workpiece enabling AJM to produce fine, intricate detail in extremely sensitive objects. In addition, the cutting action is cool since the carrier gas serves as a coolant, and workpieces experience no thermal damage.

Principle of AJM

As the particle impacts the surface, it causes a small fracture, and the gas stream carries both the abrasive particles and the fractured (wear) particles away.

(i) Fine particles (0.025 mm) are accelerated in a gas stream (commonly air at a few times atmospheric pressure).

(ii) The particles are directed towards the focus of machining (less than 1 mm from the tip).

(iii) As the particles impact the surface, they fracture off other particles, as shown in Fig. 1-1.

AJM System

Fig. 1-1 schematically depicts the main elements of an AJM system, which includes tooling, media, workpiece etc. The tooling confines and directs the media jet to the appropriate areas, and controls the media jet pressure, volume and if desired, the media determines the pattern and aggressiveness of the abrasive action that occurs.

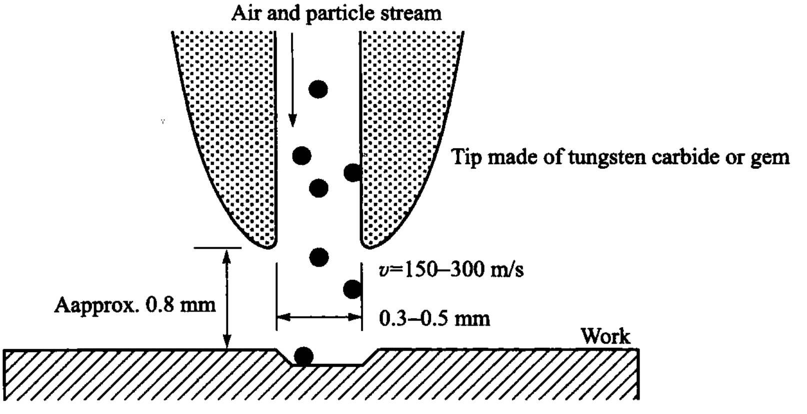

Fig. 1-1 Schematic of AJM process

The Abrasive:

- materials: aluminum oxide (preferred); silicon carbide;
- the grains should have sharp edges;
- material diameters of 10–50 μm, 15–20 μm is optimal;
- should not be reused as the sharp edges are worn down and smaller particles can clog nozzle.

Gas Jet:

- mass flow rate of abrasive is proportional to gas pressure and gas flow;
- pressure is typically 0.2–1 N/mm^2;
- gas composition effects pressure flow relationship.

Machines (as shown in Fig. 1-2):

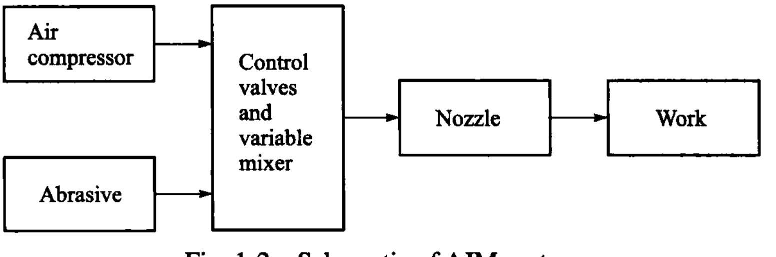

Fig. 1-2 Schematic of AJM system

Nozzle:

- must be hard material to reduce wear by abrasives: WC (lasts 12–30 h); sapphire (lasts 300 h);
- cross sectional area of orifice is 0.05–0.2 mm^2;
- orifice can be round or rectangular;

- head can be straight, or at a right angle (as shown in Fig. 1-3).

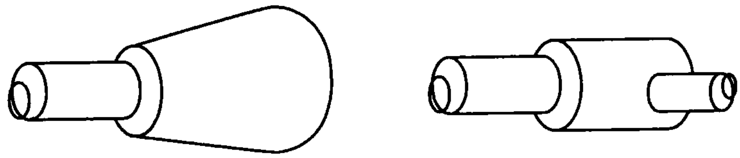

Fig. 1-3 Different nozzle

Process Parameters of AJM

Major process variables that affect the removal rate are nozzle tip distance abrasive type, abrasive flow rate, and gas pressure. Each of these variables is treated briefly in the following discussion.

Various nozzle tip distances (NTD) are used depending upon the application. When exacting definition is required as in cutting, the nozzle is positioned very close to the workpiece, typically 0.8 mm. At this close distance, cutting rates are sacrificed for the sake of increased accuracy. As the NTD is increased, the particles are accelerated to much higher speeds increasing the cutting speed until an optimum is reached. At even larger distances about 7–13 mm, the expanding gas accelerates radially as well as axially and energy is lost, resulting in decreasing cutting speeds for a glass workpiece. In addition, as the nozzle is moved away from the work, the diameter of the hole or width of the cut increases. At the same time, the walls of the cut assume a tapered shape. The relationship between head and nozzle tip distance is shown in Fig. 1-4.

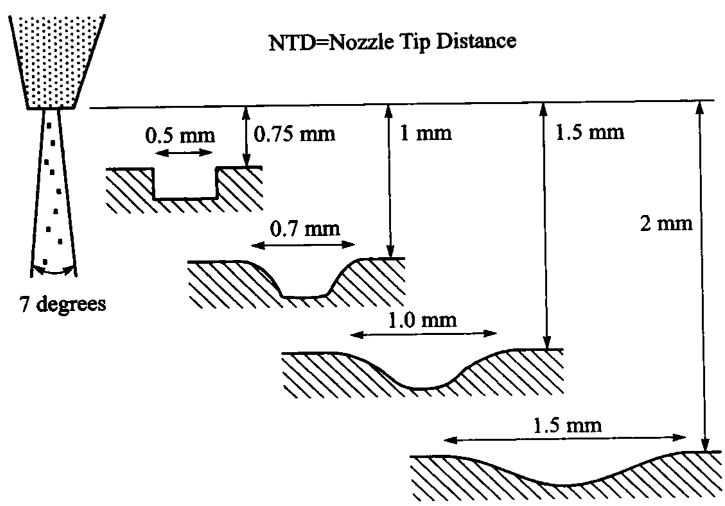

Fig. 1-4 Kerf width is a function of nozzle tip distance

The various abrasives used in AJM are selected by application. Aluminum oxide or silicon carbide is commonly used for cleaning, cutting, and deburring, while polishing or peening often is accomplished with glass beads. For very soft materials, sodium bicarbonate may be used. A summary of abrasives for AJM and their applications is given in Table 1-1. Particle size is important. Best cutting results are obtained when the bulk of particles vary between 15 μm and 45 μm. Abrasive powder should not be reused because its cutting and abrading action decreases and because it becomes contaminated with foreign material.

Table 1-1 The AJM abrasives and their application

Abrasives	Applications
Aluminum oxide	Cleaning, cutting, deburring
Silicon carbide	As above, but for harder materials
Glass beads	Matte polishing cleaning
Crushed glass	Peening cleaning
Sodium bicarbonate	Cleaning, cutting-soft materials

The flow rate of the abrasive particles is directly related to the metal removal rate, as shown in Fig. 1-5 and Fig. 1-6. The curve shows a maximum because in the beginning increasing the flow rate means more abrasive particles available for cutting. However, as the powder flow is further increased, the abrasive velocity decreases, reducing the removal rate. This effect becomes apparent with flow rates greater than about 15 g/min and consequently most operations are performed at 10 g/min, which also helps to conserve nozzle life.

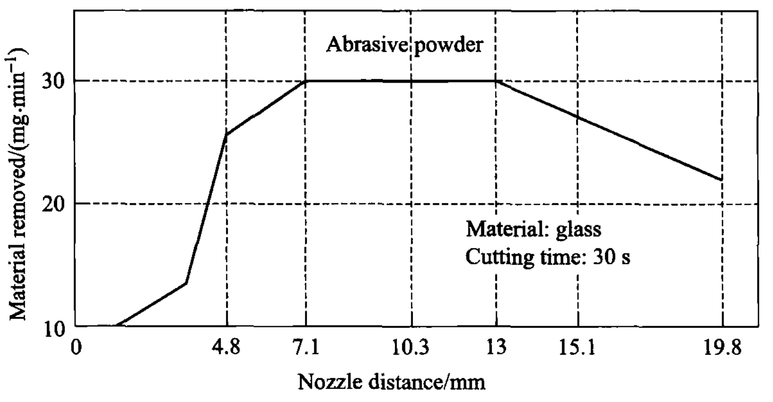

Fig. 1-5 Influence of nozzle tip distance on cutting speed in glass

Increasing the nozzle pressure results in a small increase in removal rate, but the effect is modest compared with the other process variables? However, these small increases are offset by decreased nozzle life, and pressures higher than 20–100 N/cm^2 are, therefore, seldom used.

The mass rate of removal is low, usually about 50–100 mg/min, but this is more than compensated for by the ability to produce intricate detail in very hard materials. Tolerances better than 0.1 μm are easily obtained while surface finishes range from 0.3 μm to 1.5 μm with the finer abrasives achieving the best finishes. Steel as thick as 1.5 mm and glass 6.3 mm thick have been cut, but at very slow rates and with large amounts of taper.

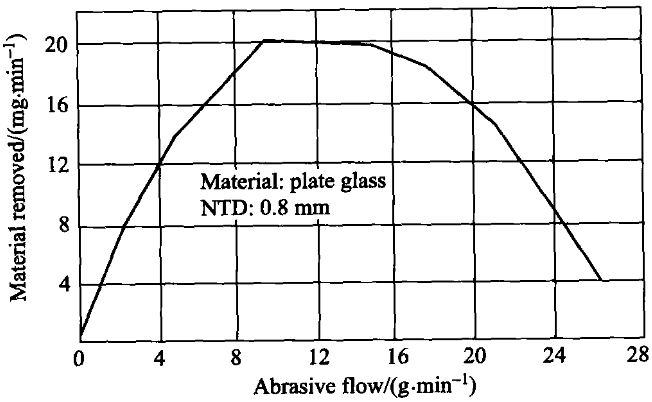

Fig. 1-6 Effect of powder flow rate on material removal

Material Removal Rate (*MRR*) is:

$$Q = \chi Z d^3 v^{\frac{3}{2}} \left(\frac{\rho}{12 H_w} \right)^{\frac{3}{4}}$$

where Z—# of abrasive particles impacting per unit time;
d—mean diameter of abrasive grains;
v—velocity of abrasive grains;
ρ—density of abrasive grains;
H—the hardness of the workpiece—the flow stress;
χ—a constant.

Factors that affect the process are

- Material removal rate (*MRR*)
- Geometry of cut
- Roughness of surface produced
- The rate of nozzle wear

The factors are in turn effected by

- The abrasive: composition; strength; size; mass flow rate
- The gas: composition, pressure and velocity
- The nozzle: geometry; material; distance to work; inclination to work

Applications of AJM

AJM has been successfully employed in the electronics industry to shape ceramic elements and for resistor adjustment through accurate and controlled removal of conductive material. Semiconductor materials such as germanium, silicon, and gallium are cut, cleaned, drilled, and beveled, and so on.

It is possible to make small adjustments in steel molds and dies after they have been given a final hardening treatment. Precision deburring is another area for AJM applications since high quality standards are required in such technologies as aerospace, medical equipment and computers.

It is also worth mentioning that abrasive jet machining can be used for safe removal of metallic smears on ceramics, oxides on metals, resistive coatings etc, especially from parts too delicate to withstand manual scraping or conventional grinding. The process is not practical for removing heavy burrs or large amounts of material. Also, it should not be used for large parts or surfaces or low value components.

Summary of AJM Characteristics

(i) Mechanics of material removal—brittle fracture by impinging abrasive grains at high speed

(ii) media—Air, CO_2

(iii) abrasives—Al_2O_3, SiC, 0.025 mm diameter, 2–20 g/min, non-recirculation

(iv) velocity—150–300 m/s

(v) pressure—2–10 atm*

(vi) nozzle—WC, sapphire, orifice area 0.05–0.2 mm^2, life 12–300 h, nozzle tip distance 0.25–75 mm

(vii) critical parameters—abrasive flow rate and velocity, nozzle tip distance from work surface, abrasive grain size and jet inclination

(viii) materials application—hard and brittle metals, alloys, and nonmetallic materials (e.g., germanium, silicon, glass, ceramics, and mica) specially suitable for thin sections

(ix) shape (job) application—drilling, cutting, deburring, etching, cleaning

(x) limitations—low metal removal rate (40 mg/min, 15 mm^3/min), embedding of abrasive in workpiece, tapering of drilled holes, possibility of stray abrasive action.

1.2 Abrasive Flow Machining (AFM)

Abrasive Flow Machining (AFM) finishes surfaces and edges by extruding viscous abrasive media through or across the workpiece. Abrasion occurs only where the flow of the media is restricted; other areas remain unaffected. Abrasive flow machining can process many inaccessible passages on a workpiece simultaneously, and it can accommodate several dozen parts in one fixture. Tooling can also be designed so that tooling changes can be performed in minutes in production applications.

Abrasive flow machining is used to deburr, polish, or radius surfaces and edges. A

* 1 atm = 10^5 Pa

variety of finishing results can be achieved by altering the process parameters. The process embraces a wide range of applications—from critical aerospace and medical components to high-production volumes of parts. The process can yield production rates of up to hundreds, or even thousands of parts per hour.

Process Characteristics of AFM

The AFM process uses two opposed cylinders to extrude semisolid abrasive media back and forth through the passages formed by the workpiece and the tooling (Fig. 1-7). By repeatedly extruding the media from one cylinder to the other, an abrasive action is produced as the media enter a restrictive passage and travel through or across the workpiece. The machining action is similar to a grinding or lapping operation as the abrasive media gently polish the surfaces or edges.

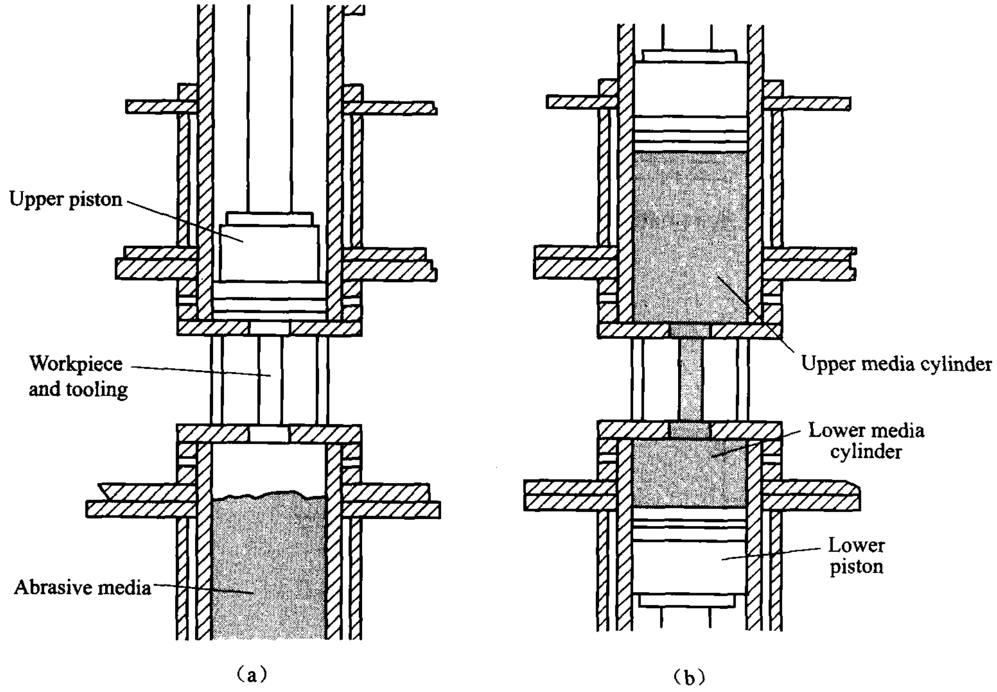

Fig. 1-7 Schematic of AFM process

(a) Abrasive media in the lower cylinder; (b) Abrasive media being extruded through the workpiece and tooling

The process is abrasive only in the extrusion area, where the flow is restricted. When forced into a restrictive passage, the polymer carrier in the media temporarily increases in viscosity; this holds the abrasive grains rigidly in place. They abrade the passages only when the matrix is in this thicker viscous state. The viscosity returns to normal when the thickened portion of media exits the restrictive passage.

The viscosity and the flow rate of the media affect the uniformity of stock removal and the edge radius size. If the objective of abrasive flow machining involves the uniform polishing of walls within the restricted passages, as in die polishing, for example, the media chosen should maintain a uniform flow rate as it travels through the passage (Fig. 1-8). Low flow rates are best for uniform material removal. For deburring or radiusing the edges of a passage, the higher flow rate of lower viscosity media within the passage causes the edges to be abraded more than the passage wails (Fig. 1-9). The flow rate depends on the machine settings, the formulation of the media, and the workpiece and tooling configuration.

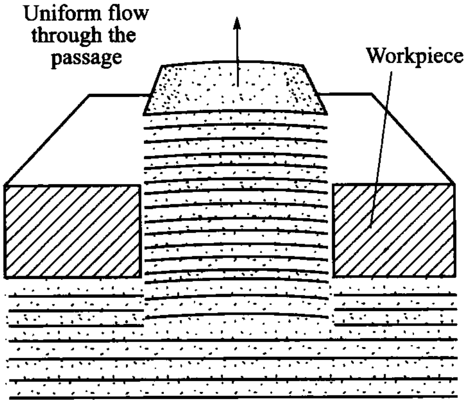

Fig. 1-8 Schematic showing uniform flow through the passage

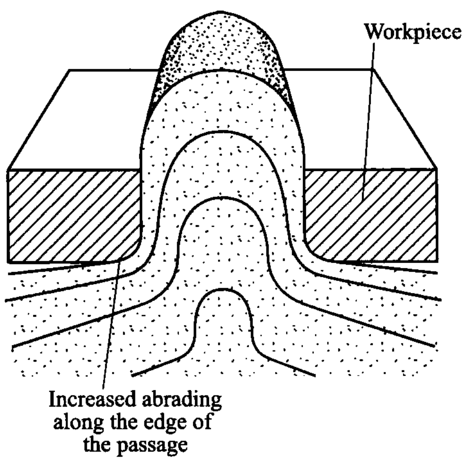

Fig. 1-9 Schematic showing the flow pattern of media entering a passage

Equipment of AFM

The major elements of an AFM system include the machine, the tooling, and the abrasive media. Each is discussed below.

Machines for abrasive flow machining are available with extrusion pressures ranging from 700 to 22000 kPa, with flow rates up to 380 L/min (Typical flow rates range from 1 to 50 L/min). The flow rate of the media depends on the extrusion pressure, the viscosity of the media, and the workpiece and tooling configuration. Extrusion pressure and flow volume (the displacement of each cylinder of media multiplied by the total number of stroke cycles) are both preset at the machine.

Control systems can be added to monitor and control additional process parameters, such as the temperature, viscosity, wear, and flow speed of the media. Abrasive how machining systems designed for production applications often include part-cleaning and unload/reload stations as well as media maintenance and cooling units. Automated systems can process thousands of parts per day, with processing times typically ranging between 1 mm and 3 mm for each pallet loaded with workpieces.

Tooling holds the workpiece in position and directs the abrasive media to the appropriate areas. Many AFM applications require only simple fixturing. Dies, for example, typically need no special tooling, because the die passage itself provides the restriction for the flow path.

For external edges or surfaces, tooling is used to restrict the flow between the outside of the part and the inside of the fixture (Fig. 1-10). The tooling restricts flow at areas where abrasion is desired. The tooling can also block flow from areas that are to remain unaffected.

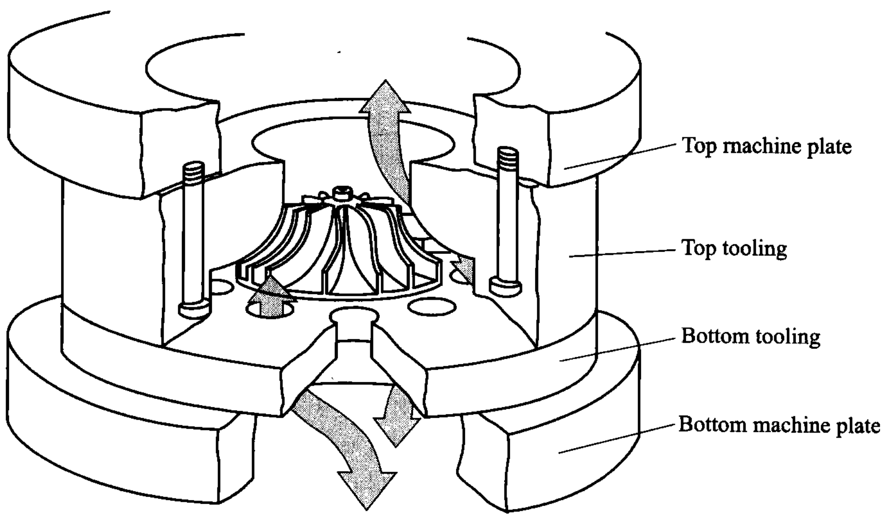

Fig. 1-10 Tooling for restricting the flow of the media

High-production fixtures are designed to facilitate part loading, unloading, and cleaning. Often mounted to indexing tables, these fixtures can hold multiple parts for processing in one operation.

The media consist of a pliable polymer carrier and a concentration of abrasive grains. The viscosity of the carrier and the type, concentration, and size of the abrasive grains can be varied to achieve specific results. Higher-viscosity media (Fig. 1-11) are nearly solid and are used for uniform polishing or for abrading the walls of large