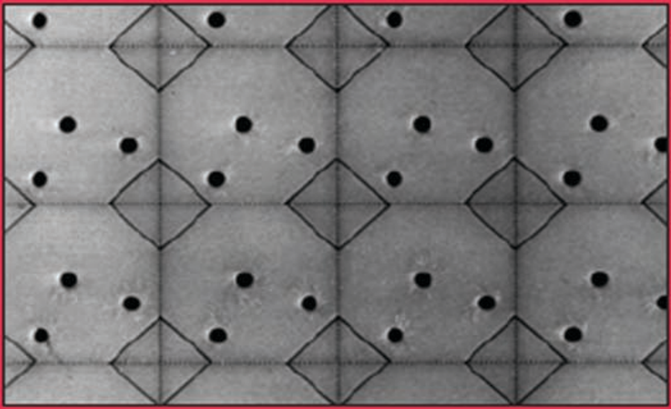
Manufacturing Engineering and Materials Processing/19

NONTRADITIONAL MANUFACTURING PROCESSES



GARY F. BENEDICT

Nontraditional Manufacturing Processes

MANUFACTURING ENGINEERING AND MATERIALS PROCESSING

A Series of Reference Books and Textbooks

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To Marilyn, for
her patience and support

Preface

The manner in which manufacturing tools are used has changed significantly over the past 40 years, as evidenced by such innovations as computer controls, flexible manufacturing systems, and robotics. These innovations became necessary due to rising labor costs, decreasing lead times, and the increasing demand for product quality. Not only has there been a change in the way tools are used for manufacturing, but due to the rapid development of new, difficult-to-machine materials and increasingly complex part configurations, it has become necessary to change to more sophisticated tools as well.

This need for more sophisticated tools has resulted in the creation of a new, unique family of manufacturing processes known as nontraditional manufacturing processes. Generally speaking, nontraditional processes differ from conventional processes (e.g., drilling, turning, and stamping) either by utilizing energy in novel ways or by applying forms of energy heretofore unused for the purpose of manufacturing. High-velocity material jets, pulsed magnetic fields, light beams, and electrochemical reactions are but a few of these new tools currently used to perform operations such as cutting, welding, deburring, and forming.

Nontraditional manufacturing processes are currently employed by many diverse industries, yet many manufacturers are unaware of these processes and the benefits that can be realized by implementing them. In addition, those people who believe that they are already familiar with nontraditional processes are often unaware of all of the process options available to them or are lacking information on the most recent advances which drastically increase the cost-effectiveness and capabilities of these processes.

Numerous articles, technical papers, and reports have addressed various nontraditional manufacturing processes in recent years. It is nearly impossible, however, for those who are interested to be aware of all the available information sources as well as to find the time to stay abreast of all the developments concerning this very broad and rapidly changing subject. The few books written on this subject present information that is either now out-of-date or incomplete in scope.

In addition to presenting information from hundreds of sources, this book represents the writer's seven years of experience in both teaching the subject at a major university and implementing these processes in industry. The volume was written to provide industry and academia with the most up-to-date and comprehensive book on nontraditional manufacturing processes available today. To assure that the reader is exposed to the full spectrum of these processes, the book does not stop with just nontraditional machining processes, but includes the nontraditional forming and joining processes as well. Specifically, this book was prepared to provide engineers, designers, students, and instructors with a single source of information explaining what these nontraditional processes are, what they are capable of doing, and how they benefit manufacturers.

To accomplish this objective, one chapter is dedicated to each of the 21 most commonly used nontraditional manufacturing processes. Each chapter begins by first introducing a process through the discussion of its principles and equipment. Next, the reader is familiarized with the capabilities and operating parameters of the process. Finally, each chapter concludes with a discussion of applications and a brief summary. Additionally, a large number of references has been provided at the end of each chapter to facilitate further investigation by the reader.

Conceptually, the nontraditional processes in this book are grouped into four sections according to the type of energy source they utilize: mechanical, electrochemical, chemical, or thermal. An extensive list of companies offering nontraditional equipment and services is included in Appendix A to assist the reader with implementation.

Gary F. Benedict

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1

Introduction: Why Nontraditional Manufacturing Processes?

The human race has distinguished itself from all other forms of life by using tools and intelligence to create items that serve to make life easier and more enjoyable. Through the centuries, both the tools and the energy sources to power these tools have evolved to meet the increasing sophistication and complexity of mankind's ideas.

In their earliest forms, tools primarily consisted of stone instruments. Considering the relative simplicity of the items being made and the materials that were being shaped, stone was adequate. When iron tools were invented, durable metals and more sophisticated articles could be produced. The twentieth century has seen the creation of products made from the most durable and, consequently, the most unmachinable materials in history. In an effort to meet the manufacturing challenges created by these materials, tools have now evolved to include materials such as alloy steel, carbide, diamond, and ceramics.

A similar evolution has taken place with the methods used to power our tools. Initially, tools were powered by muscles; either human or animal. However as the powers of water, wind, steam, and electricity were harnessed, mankind was able to further extend manufacturing capabilities with new machines, greater accuracy, and faster machining rates.

Every time new tools, tool materials, and power sources are utilized, the efficiency and capabilities of manufacturers are greatly enhanced. However as old problems are solved, new problems and challenges arise so that the manufacturers of today are faced with tough questions such as the following: How do you drill a 2-mm (0.079-in.) diameter hole 610-mm (24-in.) deep without experiencing taper or runout? Is there a way to efficiently deburr passageways inside complex castings and guarantee 100% that no burrs were missed? To be able to compete with the cheap labor of my foreign competition I would need to cut shapes in my product at 250 m/min (10,000 ipm). Is it possible? Is there a welding process that can eliminate the thermal damage now occurring to my product?

Since the 1940s, a revolution in manufacturing has been taking place that once again allows manufacturers to meet the demands imposed by increasingly sophisticated designs and durable, but in many cases nearly unmachinable, materials. This manufacturing revolution is now, as it has been in the past, centered on the use of new tools and new forms of energy. The result has been the introduction of new manufacturing processes used for material removal, forming, and joining, known today as nontraditional manufacturing processes.

The conventional manufacturing processes in use today for material removal primarily rely on electric motors and hard tool materials to perform tasks such as sawing, drilling, and broaching. Conventional forming operations are performed with the energy from electric motors, hydraulics, and gravity. Likewise, material joining is conventionally accomplished with thermal energy sources such as burning gasses and electric arcs.

In contrast, nontraditional manufacturing processes harness energy sources considered unconventional by yesterday's standards. Material removal can now be accomplished with electrochemical reactions, high-temperature plasmas, and high-velocity jets of liquids and abrasives. Materials that in the past have been extremely difficult to form, are now formed with magnetic fields, explosives, and the shock waves from powerful electric sparks. Material-joining capabilities have been expanded with the use of high-frequency sound waves and beams of electrons and coherent light.

In the past 40 years, over 20 different nontraditional manufacturing processes have been invented and successfully implemented into production. The reason there are such a large number of nontraditional processes is the same reason there are such a large number of conventional processes; each process has its own characteristic attributes and limitations, hence no one process is best for all manufacturing situations.

For example, nontraditional processes are sometimes applied to increase productivity either by reducing the number of overall manufacturing operations required to produce a product or by performing operations faster than the previously used method.

In other cases, nontraditional processes are used to reduce the number of rejects experienced by the old manufacturing method by increasing repeatability, reducing in-process breakage of fragile workpieces, or by minimizing detrimental effects on workpiece properties.

Quite often, nontraditonal processes are able to provide a capability that simply cannot be met with conventional techniques. Drilling small holes with aspect ratios of 150:1, forming titanium sheet metal without experiencing springback, or metallurgically joining two materials without the use of heat are just a few examples.

Because of the aforementioned attributes, nontraditional manufacturing processes have experienced steady growth since their introduction. An increasing growth rate for these processes in the future is assured for the following reasons:

Currently, nontraditional processes possess virtually unlimited capabilities when compared with conventional processes, except for volumetric material removal rates. Great advances have been made in the past few years in increasing the removal rates of some of these processes, and there is no reason to believe that this trend will not continue into the future. As removal rates increase, the cost effectiveness of operations such as bulk material removal will also increase, stimulating even greater usage of nontraditional processes.

Approximately one-half of the nontraditional manufacturing processes presented in this book are available with computer control of the process parameters. The use of computers lends simplicity to processes that people may be unfamiliar with, and thereby accelerates acceptance. Additionally, computer control assures reliability and repeatability, which also accelerates acceptance and implementation.

Most nontraditional processes are capable of being adaptively-controlled through the use of vision systems, laser gages, and other in-process inspection techniques. If, for example, the in-process inspection system determines that the size of holes being produced in a product are becoming smaller, the size can be modified without changing hard tools, such as drills. Most nontraditional processes used for generating holes or cavities are capable of automatically changing sizes by changing the radius offset value in the machine's computer program. This ability assures the increased use of nontraditional processes as unmanned machining modules and automated factories become more common.

The implementation of nontraditional manufacturing processes will continue to increase as manufacturing engineers, product designers, and metallurgical engineers become increasingly aware of the unique capabilities and benefits that nontraditional manufacturing processes provide.

2
Abrasive Jet Machining (AJM)

2.1 PROCESS PRINCIPLES

Abrasive jet machining (AJM) removes material through the action of a focused stream of abrasive-laden gas. Micro-abrasive particles are propelled by inert gas at velocities of up to 300 m/sec (1000 ft/sec). When directed at a workpiece, the resulting erosion can be used for cutting, etching, cleaning, deburring, polishing, and drilling.

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 (*Manufacturing Engineering,* 1982). No workpiece chatter or vibration occurs with this process because the large quantity and small mass of the abrasives result in uniform loading of the part. This further enables AJM to produce fine, intricate detail in extremely brittle objects. The AJM-processed eggshell shown in Fig. 2.1 pro-

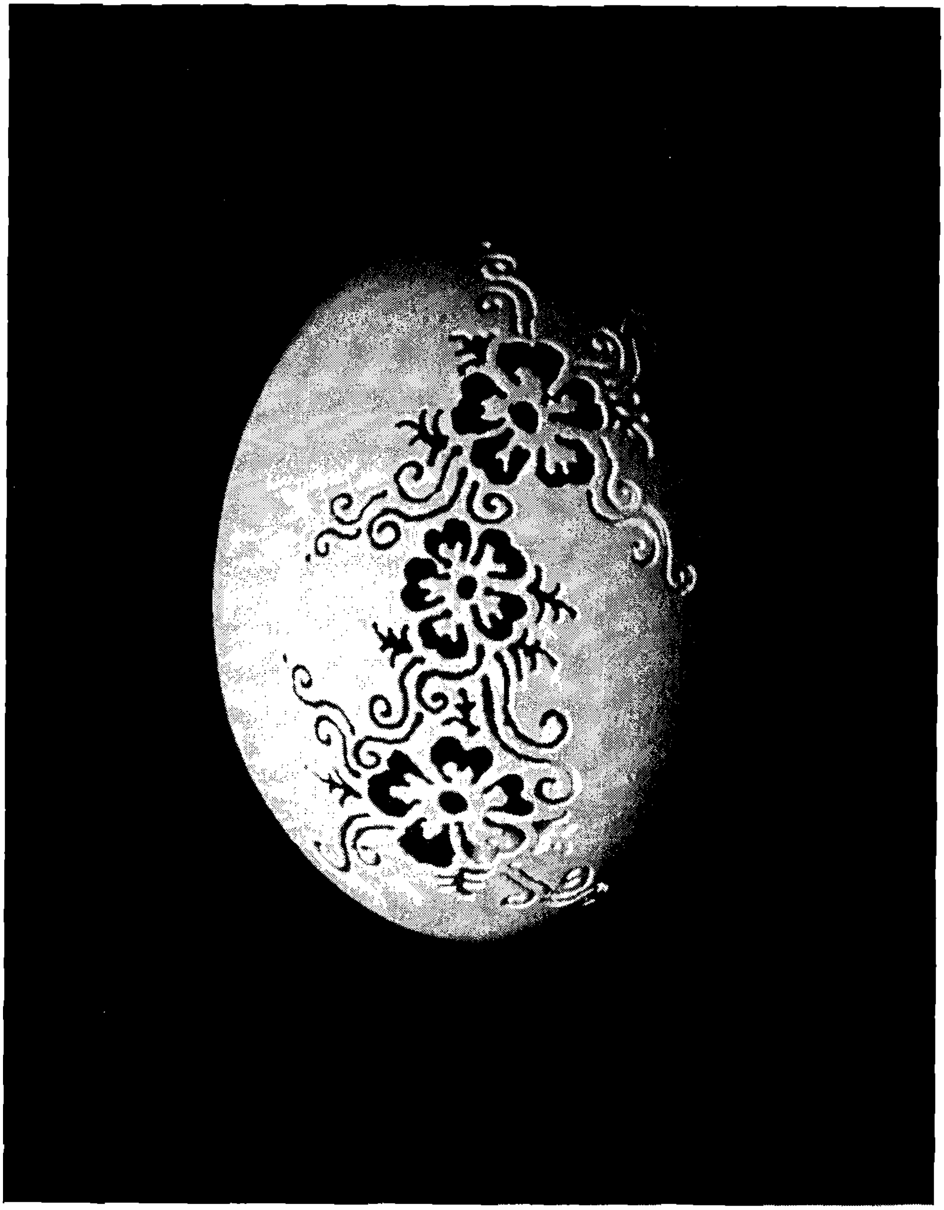

Figure 2.1 An AJM-machined egg shell showing the ability of the process to machine intricate shapes into brittle workpieces (Source: S. S. White Industrial Products, Pennwalt Corporation, Piscataway, NJ).

vides a graphic example of the delicate nature of the process. In addition, because heat is carried away by the abrasive propellant gas, workpieces experience no thermal damage.

2.2 EQUIPMENT

One of the least expensive nontraditional processes to incorporate is AJM; a typical AJM system can be purchased for under 5000 dollars. An AJM system, schematically depicted in Fig. 2.2, consists of four major subsystems: (1) gas propulsion system, (2) metering system, (3) delivery system, and (4) abrasive collection system. An actual AJM system is shown in Fig. 2.3.

The gas propulsion system provides the steady supply of clean, dry gas used to propel the abrasive particles. Depending upon the demands of the installation, either an air compressor or bottled gas may be used. If an air compressor is used, proper line filters must be installed to avoid water or oil contamination of the abrasive powders. Most users decide on bottled gas systems because consumption rates are only 9.5 L/hr (1/3 ft^3/hr), and the gas is guaranteed to be dry and clean. The least expensive, and thus the most common gasses to use, are nitrogen and carbon dioxide. Oxygen should never be used as it presents a fire hazard.

The metering system must inject a uniform, adjustable flow of abrasive particles into the gas stream. Generally, this is accomplished by a powder hopper that feeds into a vibrating chamber, which in turn causes the powder to be metered uniformly into the jet stream. The powder flow rate is directly adjustable by varying the amplitude of the vibration.

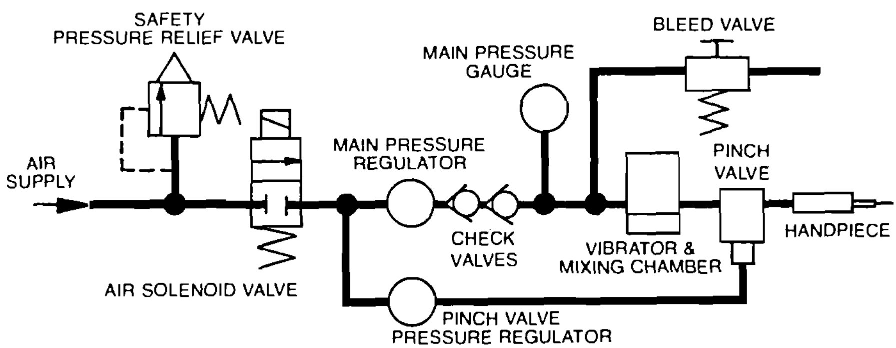

Figure 2.2 Schematic diagram of an AJM system showing how gas propellant and abrasive powder are combined and delivered to the handpiece (Source: S. S. White Industrial Products, Pennwalt Corporation, Piscataway, NJ).

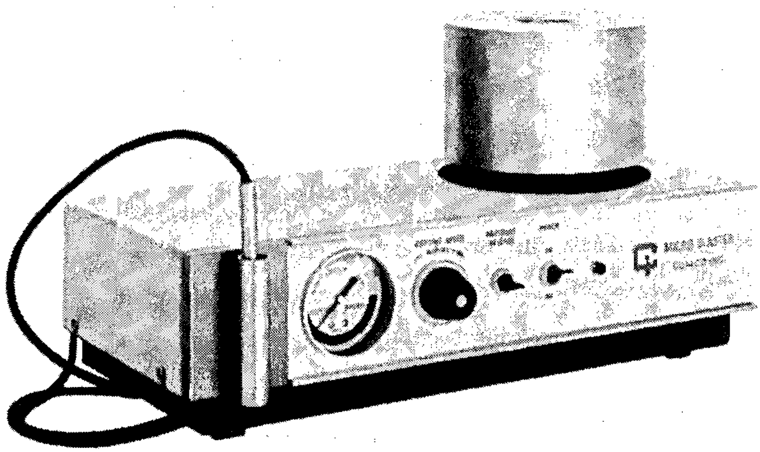

Figure 2.3 An AJM system showing main unit, powder hopper, and hand-piece (Source: Comco, Inc. Burbank, Calif).

A dust collection system is incorporated into AJM systems, when found necessary, to maintain the operator's exposure to dusts within permissable limits. Figure 2.4 illustrates a work chamber of the type used to confine these dusts. A vacuum dust collector is sometimes used to draw the dust particles from the exhaust chamber and keep the operator's viewing clear. Special considerations must be given to the dust collection system if toxic materials such as beryllium are being abraded.

2.2.1 Nozzles

The AJM nozzles are typically made of either tungsten carbide or sapphire. Tungsten carbide nozzles with either round or rectangular holes are available for approximately 10 dollars each and last for an average of 30 hr. Sapphire nozzles, available only in round configurations, last an average of 300 hr but are three to eight times more expensive. Round nozzles are available with diameters ranging from 0.12 to 1.25 mm (0.005 to 0.050 in.), with 0.5 mm (0.018 in.) being the most common. Rectangular nozzles range from 0.07 x 0.5 mm to 0.17 x 3.8 mm (0.003 x 0.020 in. to 0.007 x 0.150 in.).

The life of a nozzle must be partly defined by its application. Exacting operations, such as cutting, require that nozzles be changed more often than

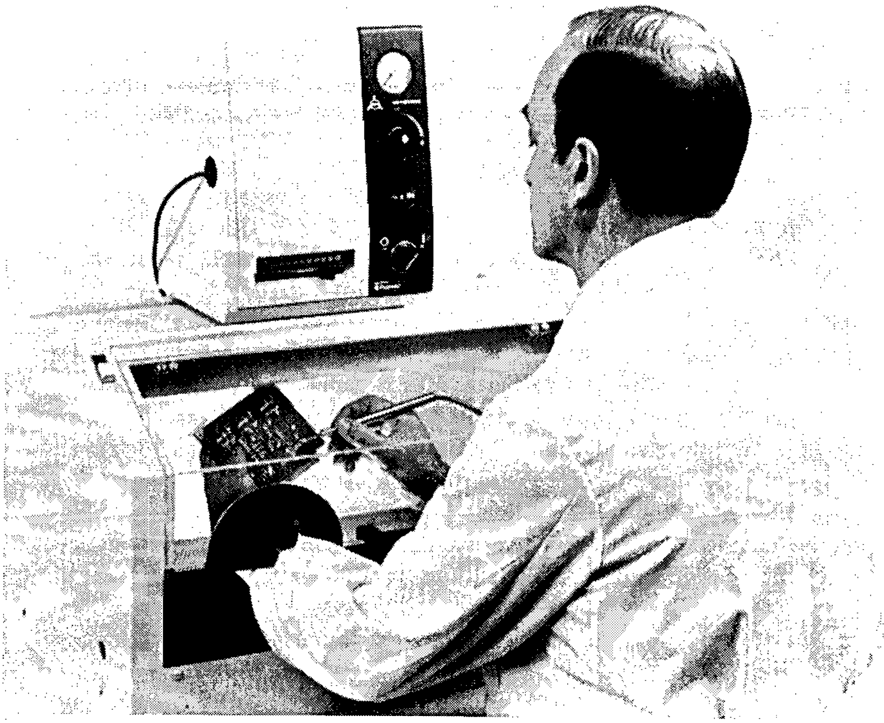

Figure 2.4 An AJM system being used inside a dust-collecting work chamber (Source: S. S. White Industrial Products, Pennwalt Corporation, Piscataway, NJ).

when etching or cleaning. As nozzles wear, the jet stream tends to diffuse faster, resulting in material damage outside the intended line of cut. This is known as stray cutting or overspray. Rectangular nozzles create less overspray compared with round ones.

2.2.2 Masks

Masks are used to control overspray or to produce large holes and intricate detail without having to move the nozzle and trace the shape. First, the mask is produced with open areas where material removal is desired, and then it is placed on the part. When the AJM stream is passed over the exposed areas, cutting or etching takes place on a selective basis. This is how the egg in Fig. 2.1

was cut and how numbers and intricate patterns can be permanently etched into a workpiece.

Masks can be fabricated from rubber or metal, each having its advantage and disadvantage. While the rubber masks are easy to fabricate, they give poor edge definition. The metal masks give much better definition but erode faster.

2.2.3 Abrasives

The various abrasives used in AJM are selected by application. Aluminum oxide, one of the most commonly used materials, is used to clean, cut, and deburr. Silicon carbide, a harder abrasive, is effective for the same applications as aluminum oxide but is usually applied only when the workpiece material is very hard. Polishing surfaces to a matt finish or peening surfaces is accomplished with glass beads. Crushed glass provides sharper edges than glass beads and can therefore be used for heavier cleaning and peening operations.

The lightest duty applications, such as the cleaning, cutting, and deburring of soft materials, are performed with sodium bicarbonate (baking soda) which is a soft powder and can leave surfaces free of scratches. It is important to note that sodium bicarbonate is hygroscopic and will absorb moisture if heated above 49°C (120°F), thus rendering it useless if allowed to become moist, and therefore must be kept completely dry at all times.

A summary of all the AJM abrasives and their applications is presented in Table 2.1.

Because abrasive particle size is important, abrasives are available in many sizes ranging from 10 to 50 μ (0.0005 to 0.002 in.) The smaller sizes are most useful for polishing and cleaning, while the larger sizes are best for cutting and peening.

Abrasives are not reused because "chips" from the workpiece material clog the nozzle and also because the cutting action of used particles is degraded. In

Table 2.1 The AJM Abrasives and Their Application

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

addition, very little savings would result from reusing powders because prices range from 3.00-20.00 dollars/kg, and the consumption rate is typically only 300 g/hr.

2.3 PROCESS PARAMETERS

Major AJM process variables that affect the removal rate are nozzle tip distance, abrasive flow rate, gas pressure, and abrasive type.

Figure 2.5 illustrates the effect of the nozzle tip distance (NTD) on the material removal rate when cutting glass for 30 sec with 27 μ aluminum oxide abrasive. Note that the removal rate is maximized when the NTD is between 7 and 13 mm (0.27 and 0.50 in.).

Various NTDs 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 (0.032 in.). At this close distance, cutting rates are compromised for the sake of increased accuracy. Maintaining a close NTD also eliminates taper and minimizes the kerfwidth. Figure 2.6 illustrates these changes as the function of NTD. The typical divergence angle for an abrasive jet is 7°.

By increasing the NTD to a distance of 5-12.5 mm (3/16-1/2 in.), the abrasive jet stream is widened, thereby lending itself to abrading operations such as cleaning and peening. Light-duty operations, such as glass frosting, are accomplished with an NTD of 25-75 mm (1-3 in.).

Powder flow rate is directly related to the material removal rate, as shown in Fig. 2.7. Increasing the flow rate increases the removal rate because more abrasive particles are available for cutting. However as the powder flow rate is increasing, the mass fraction of abrasive in the jet is also increasing. As the mass fraction increases, the abrasive velocity decreases, thus reducing the removal rate. This effect becomes apparent with flow rates greater than 14 g/min, thus to conserve nozzle life and abrasives, most operations are performed at 10 g/min.

Large changes in nozzle pressure have very little effect on removal rate when compared with the other process variables. As shown in Fig. 2.8, increasing the nozzle pressure slowly, increases the removal rate. However because these increases are offset by decreased nozzle life, pressures higher than 560 or 630 kPa (80 or 90 psi) are seldom used.

The final major process variable is the abrasive size. Figure 2.9 illustrates the effect that various powder sizes have on the removal rate. Note that larger particle sizes remove the material fastest. Notice also that the optimum flow rate for all powders was approximately 10 g/min, a figure that is in agreement with the data presented earlier in Fig. 2.7.

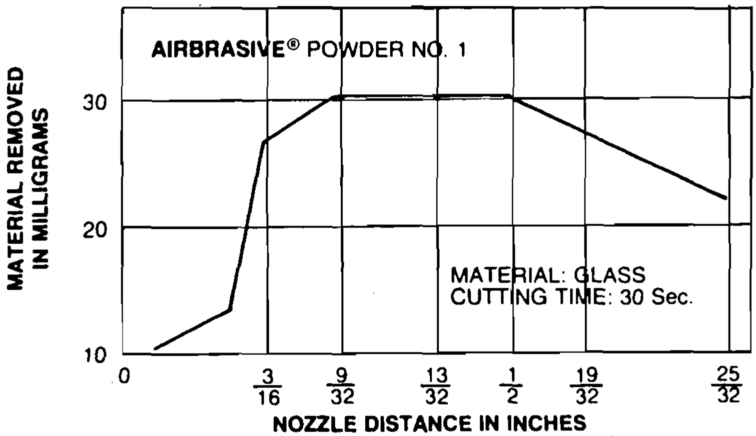

Figure 2.5 Effect of nozzle tip distance on removal rate (Source: S. S. White Industrial Products, Pennwalt Corporation, Piscataway, NJ).

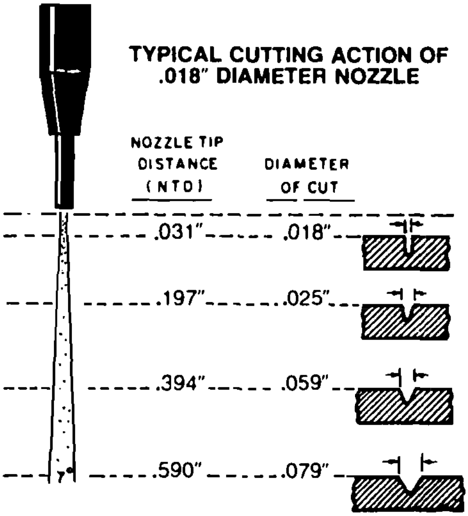

Figure 2.6 Kerfwidth is a function of nozzle tip distance (Source: S. S. White Industrial Products, Pennwalt Corporation, Piscataway, NJ).

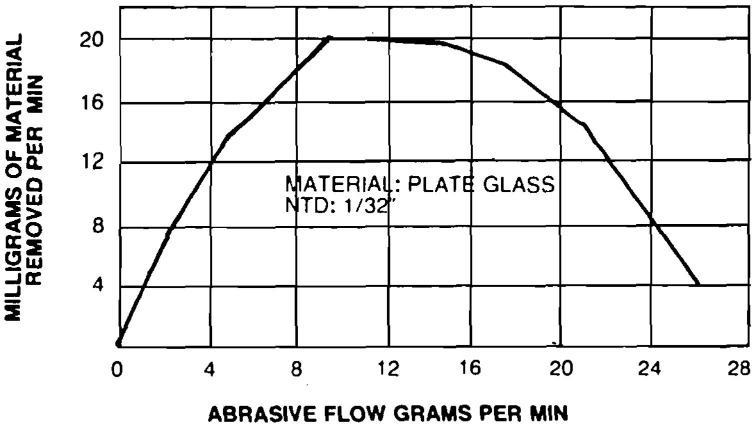

Figure 2.7 Effect of powder flow rate on material removal (Source: S. S. White Industrial Products, Pennwalt Corporation, Piscataway, NJ).

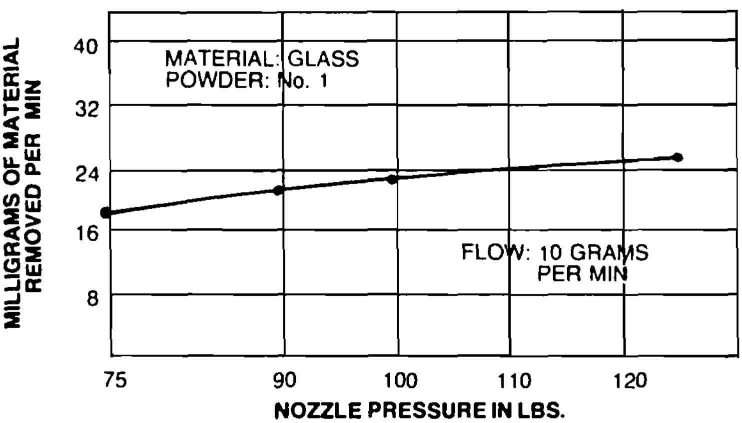

Figure 2.8 Effect of nozzle pressure on material removal rates (Source: S. S. White Industrial Products, Pennwalt Corporation, Piscataway, NJ).

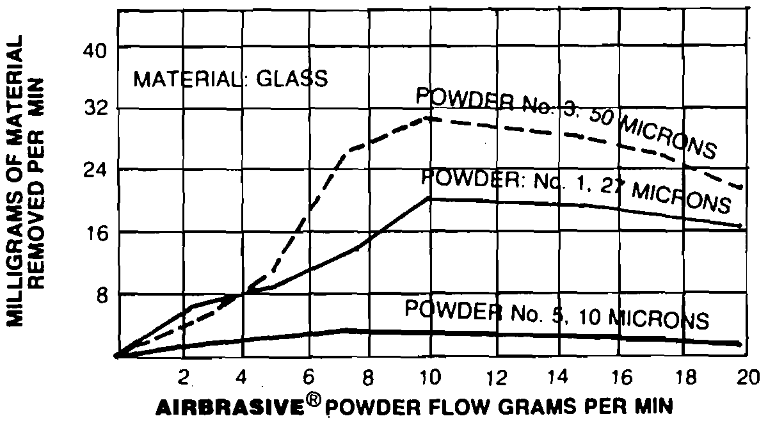

Figure 2.9 Effect of powder size on material removal rate (Source: S. S. White Industrial Products, Pennwalt Corporation, Piscataway, NJ).

2.4 PROCESS CAPABILITIES

Material removal rates with AJM are considered low, typically only 0.016 cm^3/min (0.001 $in.^3$/min). This equates to cutting with a 0.45-mm (0.018-in.) kerf-width in 0.5-mm (0.020 in.) thick material at a linear rate of less than 76 mm/min (3 ipm). However the ability to produce intricate detail in hard, brittle materials makes up for the low removal rates. Slots as narrow as 0.12-0.25 mm (0.005-0.010 in.) can be produced when stray cutting is minimized with rectangular nozzles. Tolerances of ±0.12 mm (±0.005 in.) are easily obtained, and ±0.05 mm (±0.002 in.) can be achieved with proper techniques. The minimum radius that can be produced is 0.2 mm (0.008 in.). Surface finishes range from 10 to 50 μin., with the finer abrasives achieving the best finishes.

Steel as thick as 1.5 mm (0.060 in.) and glass 6.3-mm (0.25-in.) thick have been cut by AJM but at very slow rates and with large amounts of taper. In thinner materials, taper is present at the rate of 0.12 mm (0.005 in./in. of material thickness. If no taper can be tolerated on the cut edge, the nozzle or the workpiece can sometimes be tilted to compensate. This has the effect of negating taper on the part and doubling the taper on the scrap.

2.5 APPLICATION EXAMPLES

As reported by Butler (1980) and Dombrowski (1983), AJM has been successfully employed to manufacture small electronic devices consisting of a 0.38-mm (0.015-in.) thick wafer of silicon brazed to a 0.75-mm (0.030-in.) thick

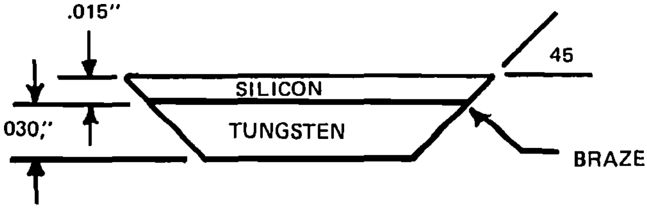

Figure 2.10 Final part configuration requirements for AJM-trimmed electronic components.

tungsten disk (Fig. 2.10). After the two materials are brazed together, the silicon wafer must be trimmed and beveled without harming the tungsten disk. To accomplish this task, an AJM nozzle is mounted at the desired angle and directed at the slowly rotating part (Fig. 2.11). With this technique, the unwanted silicon is trimmed off each part in less than 1 min.

An example of deburring plastic parts with AJM is cited by LaCourte (1979) in an application involving the manufacture of small biomedical analysis packages. Small plastic cubes are cross-drilled with two 0.34-mm (0.013-in.)

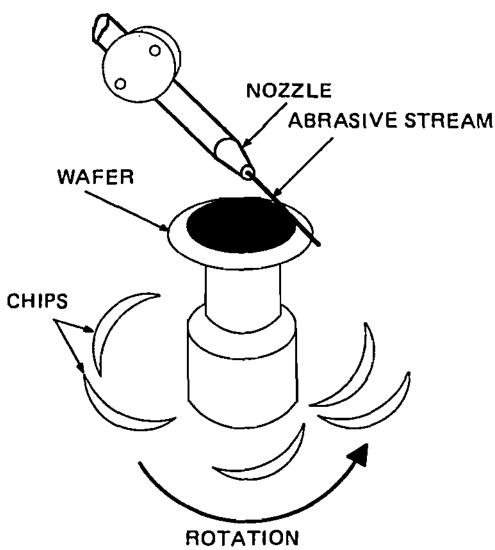

Figure 2.11 Technique used for AJM-trimming of silicon/tungsten disks.

diameter holes. Tiny burrs are created internally at the intersection of the two holes and must be removed without producing scratches. Not only was AJM able to meet this difficult quality requirement, but it also was able to reduce deburring time by 80% when compared with the old method of hand deburring.

Figure 2.12 shows an example of the excellent results achieved when using AJM to deburr plastic parts. In this example, AJM is used to remove the mold flash from electronic connectors without degrading the smooth surface finish.

An example of the savings that can be realized by incorporating AJM etching for permanent product marking is reported by Butler (1980). A manufacturer that produces many different models of electronic power supplies found that it was uneconomical to order and stock the hundreds of different printed panel labels required for his products. As an alternative, the manufacturer switched to AJM as a method of producing markings directly on the product.

In application, the manufacturer prepares a reusable, rubber stencil for each model of panel. The rubber stencil is then placed on the surface of the panel and the abrasive jet is used to etch the exposed areas providing permanent marking. In this particular case, the AJM process costs 3 cents/mark while the label method costs 30 cents/mark. In addition to the outright cost differential associated with this approach, a substantial reduction in panel label inventory costs are also realized.

A variety of other diverse jobs have been successfully performed by AJM. These include cutting threads into glass rods, deflashing small castings, die and mold touch up, cutting titanium foil, and drilling glass wafers (Coleman, 1981).

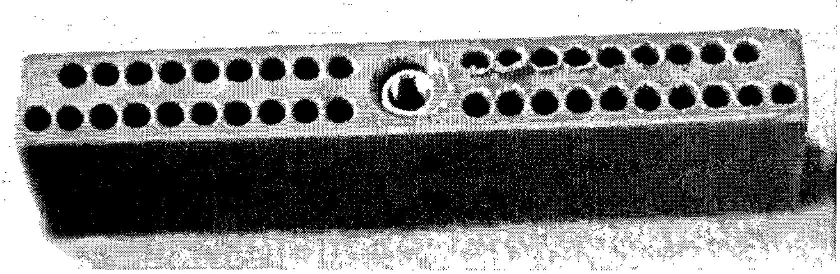

Figure 2.12 Plastic connector body showing condition before and after flash removal by AJM (Source: Comco, Inc., Burbank, Calif).

2.6 PROCESS SUMMARY

Advantages

Machines heat sensitive and fragile materials
Very low capital cost
No part chatter or vibration
Good for difficult-to-reach areas
Machines very hard materials

Disadvantages

Stray cutting
Low removal rate
Taper
Short nozzle standoff when used for cutting
Particles can imbed into workpiece

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3
Water Jet Machining (WJM)

3.1 PROCESS PRINCIPLES

Water jet machining (WJM) is a process used primarily to cut and slit porous nonmetals such as wood, paper, leather, and foam. Two WJM process variations are also available for performing wire stripping and deburring.

Water jet machining removes material through the erosion effects of a high-velocity, small-diameter jet of water. The principle behind this method of cutting was first observed in the early 1900s by workers in steam plants. When a pinhold leak developed in a high-pressure steam line, workers discovered that the resulting steam jet had sufficient power to quickly and cleanly cut through objects such as a wooden broomstick. Although this demonstrated the potential usefulness of high-velocity jets as a cutting tool, no significant effort was made to apply this technology until the 1960s when Norman Franz patented the technique for producing a coherent, high-velocity stream of water. This

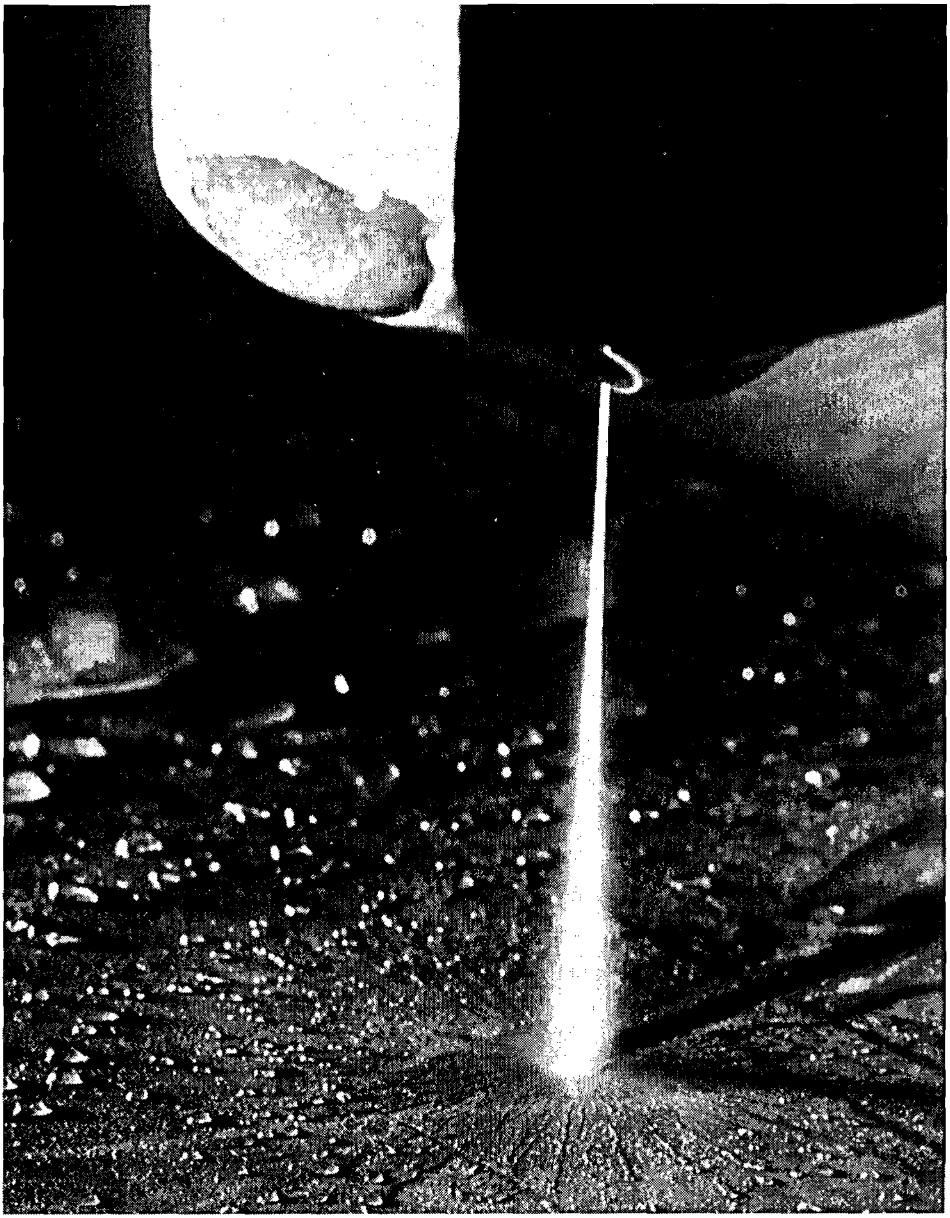

Figure 3.1 A close-up view of a high-velocity water jet showing the mist shroud and the width of the cut resulting from the core jet (Source: courtesy, Lockheed-Georgia Company, Marietta, Ga.).

invention, which became the basis for today's WJM technology, was refined during the 1960s and was first introduced to industry as a new cutting tool in the early 1970s.

Water jet machining provides omnidirectional cutting capabilities at very high speeds with a resulting edge quality that is usually superior to other conventional cutting processes. Unlike conventional mechanical cutting processes, downtime for the replacement of worn or broken cutting tools is virtually nonexistent with WJM because the "tool" never dulls or breaks. Additionally, the health hazards associated with cutting materials such as asbestos and fiberglass are minimized because almost no airborne dust is generated by this process.

The exact equations governing the interaction of a high-velocity water jet and the workpiece material are complex and detailed. A thorough discussion of these specifics can be found in Hashish and Reichman (1980).

In general, the WJM process is performed with a collimated jet of water that exits a specially shaped nozzle at velocities of 900 m/sec (3000 ft/sec, over 2000 mph). Approximately 25 mm (1 in.) from the nozzle, a shroud of mist begins forming around the tight water jet core. As shown in Fig. 3.1, the shroud of mist rapidly diverges because of interactions with air, but the tight water jet core continues to provide the cutting action. This cutting action can be maintained through soft solids that are up to 250-mm (10-in.) thick.

3.2 EQUIPMENT

Figure 3.2 shows the schematic of a typical WJM pumping unit. At the heart of the unit is a 15-37 kw (20-50 HP) electric motor that drives an oil pump. Special systems may utilize motors as large as 75 kw (100 HP).

In operation, oil is drawn from a reservoir and pumped to a device known as an intensifier. An intensifier uses the relatively low-pressure oil to generate extremely high-pressure water.

As illustrated in Fig. 3.3, oil pressure is applied on one side of the large piston in the center of the intensifier, causing a displacement of the small pistons. During this motion, one small piston compresses the water in its cylinder as the other small piston sucks water into its cylinder. When the piston reaches the end of the stroke, a valve reverses the direction of the oil flow, and the functions of the two small pistons are exchanged, thus allowing pumping action during both directions of the stroke. One-way valves assure that the liquids flow in the proper directions.

The intensifier, acting as a very high-pressure pump, increases the pressure ratio between the low-pressure oil and the high-pressure water by up to 40 times. The magnitude of this pressure ratio increase is determined by the relationship between the oil piston/water piston areas. The resulting water pressure on the small area of the water piston is high to balance the oil pressure acting