Workshop technology-3

Gear Manufacturing Process

The concept of gears has been around for a while as they are among the oldest mechanical components that are still relevant today. Be it the automobile industry, the aerospace sector, any industrial machinery, or something simple like a clock. Gears are required everywhere and perhaps you would like to learn about gear manufacturing.So, the question is about how gears are manufactured.

Preface: Gear Manufacturing Process :

There is no single process to gear manufacturing as they require different processes depending on the type and application.

Generally, gears operate in very strenuous conditions because transmission of power (the actual purpose of the gear) has several requirements. Firstly, the gears need to be in absolutely perfect condition. Then, they must always be reliable, have minimal residual stresses, and a little to no chance of crack propagation.

Naturally, all these requirements are extremely difficult to fulfill. However, no one can deny their importance. That’s why gear production is a highly specialized field with limited tolerances and room for error.

This article will take you back to the basics of gear manufacturing concerning the common materials for industrial gears, the processes that prepare gears, and how gears can sustain all that load without failing.

Common Types of Gears and Their Applications

Before moving on to the details about gear cutting and manufacturing processes, it’s important to take a look at the basics. They are **different types of gears** and their application and advantages.

Your application, performance parameter, and numerous other factors play an important role in the kind of gears you use. There are several ways to characterize the type of gear, but the best and most relevant from a gear manufacturing perspective is through their teeth profile.

Here are the 5 kinds of gears you'll encounter.

Spur gears

Draw a rough picture of what gear looks like in your mind. There are high chances that you are thinking of gear with straight teeth. That's exactly what a spur gear looks like.

The spur gear is the most common type of gear and has multiple applications in powerplants, **aerospace components**, industrial machines, and much more. Straight teeth are the simplest to manufacture and sustain high speeds and high loads. However, they produce a lot of noise and are not suitable for applications where you need smooth operations as well.

Furthermore, spur gears can mate with other gears of the same type and internal/external gears. You’ll find spur gears in many gearing mechanisms like a simple rack/pinion setup or a planetary gear system.

Their simplicity means that it’s easier for you to make. Therefore, you’ll find it easier to maintain precision during gear production. Spur gears also have little to no axial load, so they are quite efficient for a gear train where you want to minimize mechanical losses.

Helical gears

Helical gears are quite similar to spur gears but they come with teeth that are twisted around a cylindrical body. This quality allows them to work with both parallel and non-parallel shafts easily. Their mating, however, only works with other helical gears of the same helix angle (the angle of twist from the original cylinder).

Most of the applications of helical gears are the same as spur gears. However, the angled teeth play a huge role in reducing the impact load and making the operations smoother. This means less noise as well but at the cost of efficiency. Relative to spur gears, a helical gear train will have more losses and will also need thrust bearings because of the shape.

From a manufacturing perspective, helical gears are tougher than spur gears. The helix angles are quite hard to replicate with a low acceptable tolerance range. Furthermore, the costs of manufacturing and then the addition of other axial elements make them suitable for limited operations.

Bevel gears

Bevel gears are not your standard cylindrical gears. They come on a conical surface that allows you to change the direction of the transmission on intersecting shafts. Generally, bevel gears work with 90^0 angles. However, you can use them on other configurations as well.

Here are some common types of bevel gears you can find in a variety of applications.

- Straight bevel gears
- Spiral bevel gears
- Miter gears
- Crown gears
- Hypoid gears

Worm gears

The worm gear system is a combination of two components. A worm wheel and a screw-shaped gear. They are predominantly used in aerospace, industrial machines, elevator, and automobile steering.

The worm wheel setup doesn't offer much speed or efficiency. However, it offers a unique characteristic required for self-locking mechanisms. In many cases, the worm may turn the wheel, but vice versa can't happen because of the gear angles. Furthermore, another important thing to note is that worm-wheel gears have a lot of friction and may require continuous friction to operate properly.

Rack and pinion

The rack and pinion system is another combination that primarily works to transfer rotational motion to linear and vice versa. The gear teeth can mate with both spur and helical type teeth, so you can work on both parallel axis and at an angle. Some of the most common applications of this system are in automobile systems, weighing scales, and other similar systems.

Materials Used to Produce Gears

There is no material restriction when it comes to gears. The earliest ones were wooden, and you can find different material gears throughout the industry. From large industrial scale gears of steel or iron to small plastic gears in toys. The material combinations are endless.

Nevertheless, the following items are most commonly used in gear manufacturing and gear forming processes:

- Cast iron
- Steel
- Bronze
- Plastics

Gears have very specific criteria for material selection. Depending on the application, whatever material you choose should have the appropriate tensile strength and endurance.

Additionally, the coefficient of friction is another consideration because gears need constant contact. Finally, you should also select materials that are easy to process. A strong material with low manufacturability will be harder to deal with because gears manufacturing requires extreme precision and accuracy.

The aforementioned materials come with the perfect balance of these properties for their applications. That’s why you’ll commonly see them in most gears you come across.

RapidDirect can offer all these materials used in the gear manufacturing process. Upload your design file to get a quotation for your gear project.

Common Gear Manufacturing Processes

Gear production is quite complicated because of the precision it demands. Today, gear manufacturing is an industry in itself that relies on multiple processes, both traditional and modern, to ensure the right balance between cost, quality, and operations.

Here's a list of common gear cutting and manufacturing processes along with their apparent advantages and disadvantages.

1 – Casting

Casting is a simpler process that is predominantly used to prepare blanks or cylinders for gears, while the teeth are prepared through machining. However, it's a viable gear manufacturing process for the whole thing for many applications because of its mass production capability and relative ease.

There is, however, one area where casting is the most preferred manufacturing method in the industry. That is the production of very large gears. Machining methods and other gear forming methods are not that viable in cases of large diameters. Generally, larger gears are almost always of spur gear type. So, their relative simplicity makes casting a very good option.

Among the most common types of casting methods, shell casting, **die casting**, sand casting and permanent mold casting are the most common for gear production. Other methods have limited use in some applications. However, the aforementioned are the most common in the industry.

2 – Forging

This is another forming process that can give you both blanks and prepared gears depending on your requirements. Forging is quite viable in cases where you have relatively simple gears.

Theoretically, forging is an excellent gear manufacturing process for heavy-duty applications because of a simple reason. Forging requires heat treatment, which means that the resulting gear would have better fatigue properties. However, the tremendous force required for the forging process limits the size and thinness of this process.

Generally, forging works well for gears within 6 – 10 ft diameter gears. Depending on the type of forging for example precision forging, you may or may not need to machine the gears in the end.

3 – Extrusion and cold-drawing

This is another gear-forming process that's both versatile and simpler. In fact, extrusion has a lower tool expenditure but it doesn't mean that it's the most economical process.

Extrusion, as its name suggests, is the process of passing a heated metal profile through a smaller pre-determined shape. Resultingly, you get a bar of your desired shape with a hardened and smooth outer surface.

The cold drawing process is very similar to extrusion. There are two differences. Extrusion pushes the blank through a die drawing pulls it. The other difference is the temperature. Cold drawing doesn't heat the billet. Thereby increasing the mechanical properties at the expense of cost.

4 – Powder metallurgy

Powder metallurgy is an advanced process that made significant advancements in recent years. Today, it's used for multiple manufacturing processes including gear production.

So, how does powder metallurgy works? From the outlook, it's quite simple. However, there are many intricacies involved.

It all starts with metal powder. The first step is to take all the powder is give it a finalized form that you desire. Once you are done, the next step ensures that the entire setup is quite compact as it will result in better mechanical properties. Heat the entire setup carefully and you are done.

Powder metallurgy is extremely efficient, simple, and viable for large quantities. You don't have to worry about any post-processing as well as the product will be ready to use. However, the resulting gears can't bear too much load and there are size limitations as well.

Moreover, the initial cost for any powder metallurgy setup is quite high, which makes it unviable for any low-volume production.

5 – Blanking

Blanking is a very similar process to extrusion but has limited 3-dimensional capabilities. This gear forming process uses sheet metal to create the desired shape with the help of multiple dies. You can produce different types of gears with the blanking process. However, spur gears give you the best results.

Today, the blanking process of gear production is used by multiple industries for lightweight applications. For example, office equipment, hydraulics, small medical devices, and other applications with low load requirements.

6 – Gear Machining

Machining is among the most common gear manufacturing processes because of its versatility. Traditional machining was quite common for gear cutting and manufacturing but the advancements of **CNC machining** have propelled its popularity.

The following 4 gear cutting methods are the most common across the industry.

Hobbing

Hobbing utilizes a conical cutting device called a hob. Both the hob and the workpiece turn as the hob rotates around the gear blank. So far, external spur and helical gears are the only products you can create from hobbing.

The process is quite versatile and quick. You can also increase your production rates by processing multiple stacks together. However, it requires more skills and precision.

Shaping

Shaping is an advanced gear cutting and manufacturing process that develops gears that Hobbing can't handle. The cutter can be of any shape like a pinion, rack-shape, or single-point shape. It looks quite similar to gears and works by cutting into the blank at your required shape. You can create internal or cluster gears with the shaping process.

Broaching

Broaching is perhaps the quickest method of gear form-cutting. It relies on a multi-teeth tool with embedded cutters that go deeper than their predecessor. This results in smaller, incremental cuts that are easier to make and quickly give you the required shape without compromising the precision.

This gear manufacturing process is typical for internal gears but you can use it to make external teeth as well. For that, you'll need a specialized tool for pot broaching that allows you to replicate the same precision and efficiency.

Milling

This is a basic gear cutting method where you produce individual gear teeth sequentially. It is however quite versatile, especially when you involve a **CNC milling** machine. While you can make any type of gear on a milling machine, the precision of this method leaves a lot to be desired. That's why milling is not as common as it was before.

However, the recent developments in the CNC domain and multi-axis have changed things. Gear manufacturing on milling machines is becoming more and more common. So, things will get even better with time.

Gear Manufacturing Post-processing

Depending on the gear manufacturing method you used, your gears will need some post-processing before they are 100% ready. That post-processing can range from **heat treatment** for improved fatigue characteristics to dimensional correction and surface finishing.

Here are the 5 most common surface finishing processes that are common in gear production.

- **Grinding:** Just as its name suggests, grinding is a common surface finishing process that gives you a smooth finish throughout the surface. You can perform it intermittently or continuously, and it won't affect the results.
- **Lapping:** This process is for sensitive gears where you need extreme precision. Lapping uses small abrasive particles to smooth out a surface at low or medium speeds.
- **Honing:** This is another common process that polishes the surface and makes it smooth. Moreover, you can also correct some minor errors in your tooth geometry.
- **Shaving:** This process removes extremely thin layers from the surface to achieve a smooth profile. Shaving is generally expensive, so it's rarely used in gear production.
- **Burnishing:** In its essence, burnishing is the process of using compression to smooth out the surface.

Approach RapidDirect for the Best Gear Manufacturing Services

Gear manufacturing is a highly specialized field that requires extreme precision and accuracy. Gears are an essential component for any mechanical system and even the smallest manufacturing flaw can have a lot of disastrous consequences. Therefore, you need to be careful about the service you select.

Grinding

Grinding is an abrasive machining process that uses a grinding wheel or abrasive belt as the cutting tool.

It is commonly used to remove material from a workpiece, to produce a smooth finish on the surface of the workpiece, or to remove burrs from the surface.

Grinding can be performed wet or dry, and can be performed on a variety of materials, including metals, plastics, and ceramics.

The grinding process is a material removal and surface generation process used to shape and finish components made of metals and other materials.

The precision and surface finish obtained through grinding can be up to ten times better than with either turning or milling.
Grinding employs an abrasive product, usually a rotating wheel brought into controlled contact with a work surface.

The grinding wheel is composed of abrasive grains held together in a binder. These abrasive grains act as cutting tools, removing tiny chips of material from the workpiece. As these abrasive grains wear and become dull, the amount of material removed per wheel revolution decreases.

The grinding wheel is then dressed, which is a process of removing the abrasive grains from the wheel's surface so that it will again cut cleanly. The wheel is then reconditioned, which is a process of vitrifying the bonding material to make it harder and stronger.

The workpiece is moved past the grinding wheel in a table-fed or centerless grinding operation. The workpiece is moved past the grinding wheel either manually or by power feed. The grinding wheel is composed of abrasive grains held together in a binder. These abrasive grains act as cutting tools, removing tiny chips of material from the workpiece.

Working Principle of Grinding Machines

Most grinding machines work by using an abrasive wheel to remove material from the workpiece. The abrasive wheel is typically made of diamond or aluminum oxide and is rotated at high speeds. The abrasive particles on the wheel are what actually remove the material from the workpiece.

There are different types of grinding machines, each with its own unique set of wheels and abrasives. The most common type of grinding machine is the surface grinder, which is used to remove material from flat surfaces.

Another common type of grinding machine is the cylindrical grinder, which is used to remove material from cylindrical surfaces.

The grinding process can be very precise and produce very smooth finishes. However, it can also be very time-consuming and expensive, depending on the type of grinding machine and the materials being used.

Conditions of Use of Abrasive

Abrasive conditions of use are determined by the type of material being worked on, the type of abrasive being used, the speed of the abrasive, and the amount of pressure being applied.

The correct abrasive condition for each application must be determined experimentally, and the following general rules apply:

- Abrasive materials harder than the workpiece material are used for grinding. -Abrasive materials softer than the workpiece material are used for polishing.
- Abrasive materials with a Mohs hardness of 9 or 10 are used for lapping.
- The coarser the abrasive, the higher the speed and the lower the pressure.
- The finer the abrasive, the lower the speed and the higher the pressure.
- Abrasive materials with a low friability are used for grinding, and those with a high friability are used for polishing.
  If the wrong abrasive condition is used, the result will be poor quality work, excess wear on the abrasive, and excessive heat generation.

The Benefits of Grinding: Why It's a Key Process in Manufacturing and Metalworking

Grinding is a highly effective process that offers numerous advantages for a wide range of industries. Some of the key benefits of grinding include:

- **Improved surface finish**: Grinding is an excellent way to achieve a smooth and uniform surface finish, which is essential for many applications. The process removes rough patches, burrs, and other imperfections, resulting in a more polished and professional appearance.

- **Enhanced dimensional accuracy**: Grinding is a precise and controlled process that can help improve dimensional accuracy and consistency. This is particularly important for applications where tight tolerances are required, such as in the aerospace, medical, and automotive industries.
- **Increased productivity**: Grinding can be a highly efficient process, allowing for high volumes of material to be removed quickly and accurately. This can help boost productivity and reduce manufacturing costs, making it a popular choice for many industrial applications.
- **Versatility**: Grinding can be performed on a wide range of materials, including metals, plastics, ceramics, and composites. This versatility makes it a valuable process for a variety of industries, from aerospace and automotive to electronics and medical devices.
- **Environmental benefits**: Grinding generates less waste than many other manufacturing processes, making it a more environmentally friendly choice. It also requires less energy than some other methods, reducing carbon emissions and energy costs.

Grinding a highly effective process for many industrial applications. By removing material quickly and accurately, improving surface finish and dimensional accuracy, and reducing waste and energy use, grinding offers a range of advantages that can help improve productivity, quality, and efficiency.

Grinding Technology Applications

Grinding technology can be applied in a number of ways to improve manufacturing processes. For example,

- It can be used to improve the surface finish of machined parts
- To improve dimensional accuracy
- Increase productivity
- It can also be used to prepare surfaces for further finishing processes, such as polishing or plating.
- In addition, grinding technology can be used to repair damaged surfaces or to create new surfaces with desired characteristics.

Industries or Applications Where Grinding is Commonly Used

Real-world examples of industries and applications where grinding is commonly used to understand the importance of the process. Here are a few examples:

1. Automotive Industry: Grinding is commonly used in the automotive industry for various applications such as grinding crankshafts, camshafts, and other engine parts. It is also used for finishing and polishing the surface of car body panels.
2. Aerospace Industry: Grinding is an essential process in the aerospace industry for producing precision parts such as turbine blades, fuel nozzles, and landing gear components. The industry requires parts with high dimensional accuracy and surface finish, which can be achieved through the grinding process.
3. Medical Industry: Grinding is also used in the medical industry for producing precision parts such as surgical instruments, dental tools, and orthopedic implants. These parts require high accuracy and surface finish, which can be achieved through grinding.
4. Tool and Die Industry: The tool and die industry extensively uses grinding for sharpening and shaping cutting tools, punches, and dies. The process is essential for producing high-precision components that require tight tolerances and surface finish.
5. Construction Industry: Grinding is also used in the construction industry for finishing concrete surfaces and removing excess materials such as paint, adhesives, and coatings.

ULTRASONIC MACHINING

Ultrasonic machining is a subtractive manufacturing process that removes material from the surface of a part through high frequency, low amplitude vibrations of a tool against the material surface in the presence of fine abrasive particles. The tool travels vertically or orthogonal to the surface of the part at amplitudes of 0.05 to 0.125 mm (0.002 to 0.005 in.).[1] The fine abrasive grains are mixed with water to form a slurry that is distributed across the part and the tip of the tool. Typical grain sizes of the abrasive material range from 100 to 1000, where smaller grains (higher grain number) produce smoother surface finishes.[1]

Ultrasonic vibration machining [2] is typically used on brittle materials as well as materials with a high hardness due to the microcracking mechanics.

Process[edit]

An ultrasonically vibrating machine consists of two major components, an electroacoustic transducer and a sonotrode, attached to an electronic control unit with a cable. The abrasive grains in the slurry now act as a free cutting tool as they strike the workpiece thousands of times per second.[3] An electronic oscillator in the control unit produces an alternating current oscillating at a high frequency, usually between 18 and 40 kHz in the ultrasonic range. The transducer converts the oscillating current to a mechanical vibration.

Two types of transducers have been used in ultrasonic machining; either piezoelectric or magnetostrictive:

Piezoelectric transducer

This consists of a piece of piezoelectric ceramic, such as barium titanate, with two metal electrodes plated on its surface. The alternating voltage from the control unit applied to the electrodes causes the piezoelectric element to bend back and forth slightly, causing it to vibrate.

Magnetostrictive transducer

This consists of a cylinder of ferromagnetic material such as steel inside a coil of wire. Magnetostriction is an effect which causes a material to change shape slightly when a magnetic field through it changes. The alternating current from the control unit, applied to the coil, creates an alternating magnetic field in the magnetostrictive cylinder which makes it change shape slightly with each oscillation, causing it to vibrate.

The transducer vibrates the sonotrode at low amplitudes and high frequencies.[4] The sonotrode is usually made of low carbon steel.[1] A constant stream of abrasive slurry flows between the sonotrode and work piece. This flow of slurry allows debris to flow away from the work cutting area. The slurry usually consists of abrasive boron carbide, aluminum oxide or silicon carbide particles in a suspension of water (20 to 60% by volume).[1] The sonotrode removes material from the work piece by abrasion where it contacts it, so the result of machining is to cut a perfect negative of the sonotrode's profile into the work piece. Ultrasonic vibration machining allows extremely complex and non-uniform shapes to be cut into the workpiece with extremely high precision.[4]

Machining time depends on the workpiece's strength, hardness, porosity and fracture toughness; the slurry's material and particle size; and the amplitude of the sonotrode's vibration.[4] The surface finish of materials after machining depends heavily on hardness and strength, with softer and weaker materials exhibiting smoother surface finishes. The inclusion of microcrack and microcavity features on the materials surface depend highly on the crystallographic orientation of the work piece's grains and the materials fracture toughness.[5]

Mechanics

Ultrasonic vibration machining physically operates by the mechanism of microchipping or erosion on the work piece's surface. Since the abrasive slurry is kept in motion by high frequency, low amplitude vibrations, the impact forces of the slurry are significant, causing high contact stresses. These high contact stresses are achieved by the small contact area between the slurry's particles and the work piece's surface. Brittle materials fail by cracking mechanics and these high stresses are sufficient to cause micro-scale chips to be removed from its surface. The material as a whole does not fail due to the extremely localized stress regions. The average force imparted by a particle of the slurry impacting the work piece's surface and rebounding can be characterized by the following equation:

Where *m* is the mass of the particle, *v* is the velocity of the particle when striking the surface and t_o is the contact time, which can be approximated according to the following equation:

Where r is the radius of the particle, c_o is the elastic wave velocity of the work piece, E is the work pieces Young's Modulus and ρ is the materials density.[1]

Types

Rotary ultrasonic vibration machining

In **rotary ultrasonic vibration machining (RUM)**, the vertically oscillating tool is able to revolve about the vertical center line of the tool. Instead of using an abrasive slurry to remove material, the surface of the tool is impregnated with diamonds that grind down the surface of the part.[1] Rotary ultrasonic machines are specialized in machining advanced ceramics and alloys such as glass, quartz, structural ceramics, Ti-alloys, alumina, and silicon carbide.[6] Rotary ultrasonic machines are used to produce deep holes with a high level of precision.[*citation needed*]

Rotary ultrasonic vibration machining is a relatively new manufacturing process that is still being extensively researched. Currently, researchers are trying to adapt this process to the micro level and to allow the machine to operate similar to a milling machine.[*citation needed*]

Chemical-assisted ultrasonic vibration machining

In **chemical-assisted ultrasonic machining (CUSM)**, a chemically reactive abrasive fluid is used to ensure greater machining of glass and ceramic materials. Using an acidic solution, such as hydrofluoric acid, machining characteristics such as material removal rate and surface quality can be improved greatly compared to traditional ultrasonic machining.[7] While time spent machining and surface roughness decrease with CUSM, the entrance profile diameter is slightly larger than normal due to the additional chemical reactivity of the new slurry choice. In order to limit the extent of this enlargement, the acid content of the slurry must be carefully selected as to ensure user safety and a quality product.[7]

Applications

Since ultrasonic vibration machining does not use subtractive methods that may alter the physical properties of a workpiece, such as thermal, chemical, or electrical processes, it has many useful applications for materials that are more brittle and sensitive than traditional machining metals.[7] Materials that are commonly machined using ultrasonic methods include ceramics, carbides, glass, precious stones and hardened steels.[1] These materials are used in optical and electrical applications where more precise machining methods are required to ensure dimensional accuracy and quality performance of hard and brittle materials. Ultrasonic machining is precise enough to be used in the creation of microelectromechanical system components such as micro-structured glass wafers.[8]

In addition to small-scale components, ultrasonic vibration machining is used for structural components because of the required precision and surface quality provided by the method. The process can safely and effectively create shapes out of high-quality single crystal materials that are often necessary but difficult to generate during normal crystal growth.[5] As advanced ceramics become a greater part of the structural engineering realm, ultrasonic machining will continue to provide precise and effective methods of ensuring proper physical dimensions while maintaining crystallographic properties.[*speculation?*]

Advantages

Ultrasonic vibration machining is a unique non-traditional manufacturing process because it can produce parts with high precision that are made of hard and brittle materials which are often difficult to machine.[1] Additionally, ultrasonic machining is capable of manufacturing fragile materials such as glass and non-conductive metals that can not be machined by alternative methods such as electrical discharge machining and electrochemical machining. Ultrasonic machining is able to produce high-tolerance parts because there is no distortion of the worked material. The absence of distortion is due to no heat generation from the sonotrode against the work piece and is beneficial because the physical properties of the part will remain uniform throughout. Furthermore, no burrs are created in the process, thus fewer operations are required to produce a finished part.[9]

Disadvantages

Because ultrasonic vibration machining is driven by microchipping or erosion mechanisms, the material removal rate of metals can be slow and the sonotrode tip can wear down quickly from the constant impact of abrasive particles on the tool.[1] Moreover, drilling deep holes in parts can prove difficult as the abrasive slurry will not effectively reach the bottom of the hole.[9] Note, rotary ultrasonic machining is efficient at drilling deep holes in ceramics because the absence of a slurry cutting fluid and the cutting tool is coated in harder diamond abrasives.[1] In addition, ultrasonic vibration machining can only be used on materials with a hardness value of at least 45 HRC.[9]

Electrical discharge machining

Electrical discharge machining (**EDM**), also known as **spark machining**, **spark eroding**, **die sinking**, **wire burning** or **wire erosion**, is a metal fabrication process whereby a desired shape is obtained by using electrical discharges (sparks).[1] Material is removed from the work piece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. One of the electrodes is called the tool-electrode, or simply the *tool* or *electrode*, while the other is called the workpiece-electrode, or *work piece*. The process depends upon the tool and work piece not making physical contact. Extremely hard materials like carbides, ceramics, titanium alloys and heat treated tool steels that are very difficult to machine using conventional machining can be precisely machined by EDM.[2]

When the voltage between the two electrodes is increased, the intensity of the electric field in the volume between the electrodes becomes greater, causing dielectric break down of the liquid, and produces an electric arc. As a result, material is removed from the electrodes. Once the current stops (or is stopped, depending on the type of generator), new liquid dielectric is conveyed into the inter-electrode volume, enabling the solid particles (debris) to be carried away and the insulating properties of the dielectric to be restored. Adding new liquid dielectric in the inter-electrode volume is commonly referred to as *flushing*. After a current flow, the voltage between the electrodes is restored to what it was before the breakdown, so that a new liquid dielectric breakdown can occur to repeat the cycle.

History

The erosive effect of electrical discharges was first noted in 1770 by English physicist Joseph Priestley.

Die-sink EDM

Two Soviet scientists, B. R. Lazarenko and N. I. Lazarenko, were tasked in 1943 to investigate ways of preventing the erosion of tungsten electrical contacts due to sparking. They failed in this task but found that the erosion was more precisely controlled if the electrodes were immersed in a dielectric fluid. This led them to invent an EDM machine used for working difficult-to-machine materials such as tungsten. The Lazarenkos' machine is known as an R-C-type machine, after the resistor–capacitor circuit (RC circuit) used to charge the electrodes.[3][4][5][6]

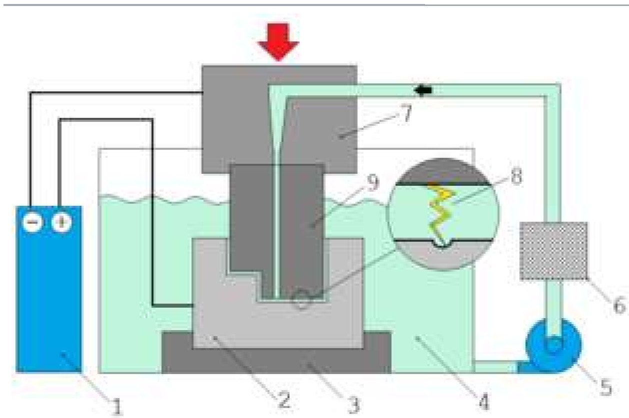
Simultaneously but independently, an American team, Harold Stark, Victor Harding, and Jack Beaver, developed an EDM machine for removing broken drills and taps from aluminium castings.[7] Initially constructing their machines from under-powered electric-etching tools, they were not very successful. But more powerful sparking units, combined with automatic spark repetition and fluid replacement with an electromagnetic interrupter arrangement produced practical machines. Stark, Harding, and Beaver's machines produced 60 sparks per second. Later machines based on their design used vacuum tube circuits that produced thousands of sparks per second, significantly increasing the speed of cutting.[8]

Wire-cut EDM

The wire-cut type of machine arose in the 1960s for making tools (dies) from hardened steel. The tool electrode in wire EDM is simply a wire. To avoid the erosion of the wire causing it to break, the wire is wound between two spools so that the active part of the wire is constantly changing. The earliest numerical controlled (NC) machines were conversions of punched-tape vertical milling machines. The first commercially available NC machine built as a wire-cut EDM machine was manufactured in the USSR in 1967. Machines that could optically follow lines on a master drawing were developed by David H. Dulebohn's group in the 1960s at Andrew Engineering Company[9] for milling and grinding machines. Master drawings were later produced by computer numerical controlled (CNC) plotters for greater accuracy. A wire-cut EDM machine using the CNC drawing plotter and optical line follower techniques was produced in 1974. Dulebohn later used the same plotter CNC program to directly control the EDM machine, and the first CNC EDM machine was produced in 1976.[10]

Commercial wire EDM capability and use has advanced substantially during recent decades.[11] Feed rates have increased[11] and surface finish can be finely controlled.[11]

Generalities



1 Pulse generator (DC). **2** Workpiece. **3** Fixture. **4** dielectric fluid. **5** Pump. **6** Filter. **7** Tool holder. **8** Spark. **9** Tool.

Electrical discharge machining is a machining method primarily used for hard metals or those that would be very difficult to machine with traditional techniques. EDM typically works with materials that are electrically conductive, although methods have also been proposed for using EDM to machine insulating ceramics.[12][13] EDM can cut intricate contours or cavities in pre-hardened steel without the need for heat treatment to soften and re-harden them. This method can be used with any other metal or metal alloy such as titanium, hastelloy, kovar, and inconel. Also, applications of this process to shape polycrystalline diamond tools have been reported.[14]

EDM is often included in the "non-traditional" or "non-conventional" group of machining methods together with processes such as electrochemical machining (ECM), water jet cutting (WJ, AWJ), laser cutting, and opposite to the "conventional" group (turning, milling, grinding, drilling, and any other process whose material removal mechanism is essentially based on mechanical forces).[15]

Ideally, EDM can be seen as a series of breakdown and restoration of the liquid dielectric in-between the electrodes. However, caution should be exerted in considering such a statement because it is an idealized model of the process, introduced to describe the fundamental ideas underlying the process. Yet, any practical application involves many aspects that may also need to be considered. For instance, the removal of the debris from the inter-electrode volume is likely to be always partial. Thus the electrical properties of the dielectric in the inter-electrodes volume can be different from their nominal values and can even vary with time. The inter-electrode distance, often also referred to as spark-gap, is the result of the control algorithms of the specific machine used. The control of such a distance appears logically to be central to this process. Also, not all of the current between the dielectric is of the ideal type described above: the spark-gap can be short-circuited by the debris. The control system of the electrode may fail to react quickly enough to prevent the two electrodes (tool and workpiece) from coming into contact, with a consequent short circuit. This is unwanted because a short circuit contributes to material removal differently from the ideal case. The flushing action can be inadequate to restore the insulating properties of the dielectric so that the current always happens in the point of the inter-electrode volume (this is referred to as arcing), with a consequent unwanted change of shape (damage) of the tool-electrode and workpiece. Ultimately, a description of this process in a suitable way for the specific purpose at hand is what makes the EDM area such a rich field for further investigation and research.[16]

To obtain a specific geometry, the EDM tool is guided along the desired path very close to the work; ideally it should not touch the workpiece, although in reality this may happen due to the performance of the specific motion control in use. In this way, a large number of current discharges (colloquially also called sparks) happen, each contributing to the removal of material from both tool and workpiece, where small craters are formed. The size of the craters is a function of the technological parameters set for the specific job at hand. They can be with typical dimensions ranging from the nanoscale (in micro-EDM operations) to some hundreds of micrometers in roughing conditions.

The presence of these small craters on the tool results in the gradual erosion of the electrode. This erosion of the tool-electrode is also referred to as wear. Strategies are needed to counteract the detrimental effect of the wear on the geometry of the workpiece. One possibility is that of continuously replacing the tool-electrode during a machining operation. This is what happens if a continuously replaced wire is used as electrode. In this case, the correspondent EDM process is also called wire EDM. The tool-electrode can also be used in such a way that only a small portion of it is actually engaged in the machining process and this portion is changed on a regular basis. This is, for instance, the case when using a rotating disk as a tool-electrode. The corresponding process is often also referred to as EDM grinding.[17]

A further strategy consists in using a set of electrodes with different sizes and shapes during the same EDM operation. This is often referred to as multiple electrode strategy, and is most common when the tool electrode replicates in negative the wanted shape and is advanced towards the blank along a single direction, usually the vertical direction (i.e. z-axis). This resembles the sink of the tool into the dielectric liquid in which the workpiece is immersed, so, not surprisingly, it is often referred to as die-sinking EDM (also called conventional EDM and ram EDM). The corresponding machines are often called sinker EDM. Usually, the electrodes of this type have quite complex forms. If the final geometry is obtained using a usually simple-shaped electrode which is moved along several directions and is possibly also subject to rotations, often the term EDM milling is used.[18]

In any case, the severity of the wear is strictly dependent on the technological parameters used in the operation (for instance: polarity, maximum current, open circuit voltage). For example, in micro-EDM, also known as μ-EDM, these parameters are usually set at values which generates severe wear. Therefore, wear is a major problem in that area.

The problem of wear to graphite electrodes is being addressed. In one approach, a digital generator, controllable within milliseconds, reverses polarity as electro-erosion takes place. That produces an effect similar to electroplating that continuously deposits the eroded graphite back on the electrode. In another method, a so-called "Zero Wear" circuit reduces how often the discharge starts and stops, keeping it on for as long a time as possible.[19]

Definition of the technological parameters

Difficulties have been encountered in the definition of the technological parameters that drive the process.

Two broad categories of generators, also known as power supplies, are in use on EDM machines commercially available: the group based on RC circuits and the group based on transistor-controlled pulses.

In both categories, the primary parameters at setup are the current and frequency delivered. In RC circuits, however, little control is expected over the time duration of the discharge, which is likely to depend on the actual spark-gap conditions (size and pollution) at the moment of the discharge.[20] Also, the open circuit voltage (i.e. the voltage between the electrodes when the dielectric is not yet broken) can be identified as steady state voltage of the RC circuit.

In generators based on transistor control, the user is usually able to deliver a train of pulses of voltage to the electrodes. Each pulse can be controlled in shape, for instance, quasi-rectangular. In particular, the time between two consecutive pulses and the duration of each pulse can be set. The amplitude of each pulse constitutes the open circuit voltage. Thus, the maximum duration of discharge is equal to the duration of a pulse of voltage in the train. Two pulses of current are then expected not to occur for a duration equal or larger than the time interval between two consecutive pulses of voltage.

The maximum current during a discharge that the generator delivers can also be controlled. Because other sorts of generators may also be used by different machine builders, the parameters that may actually be set on a particular machine will depend on the generator manufacturer. The details of the generators and control systems on their machines are not always easily available to their user. This is a barrier to describing unequivocally the technological parameters of the EDM process. Moreover, the parameters affecting the phenomena occurring between tool and electrode are also related to the controller of the motion of the electrodes.

A framework to define and measure the electrical parameters during an EDM operation directly on inter-electrode volume with an oscilloscope external to the machine has been recently proposed by Ferri *et al.*[21] These authors conducted their research in the field of μ-EDM, but the same approach can be used in any EDM operation. This would enable the user to estimate directly the electrical parameters that affect their operations without relying upon machine manufacturer's claims. When machining different materials in the same setup conditions, the actual electrical parameters of the process are significantly different.[21]

Material removal mechanism

The first serious attempt at providing a physical explanation of the material removal during electric discharge machining is perhaps that of Van Dijck.[22] Van Dijck presented a thermal model together with a computational simulation to explain the phenomena between the electrodes during electric discharge machining. However, as Van Dijck himself admitted in his study, the number of assumptions made to overcome the lack of experimental data at that time was quite significant.

Further models of what occurs during electric discharge machining in terms of heat transfer were developed in the late eighties and early nineties. It resulted in three scholarly papers: the first presenting a thermal model of material removal on the cathode,[23] the second presenting a thermal model for the erosion occurring on the anode[24] and the third introducing a model describing the plasma channel formed during the passage of the discharge current through the dielectric liquid.[25] Validation of these models is supported by experimental data provided by AGIE.

These models give the most authoritative support for the claim that EDM is a thermal process, removing material from the two electrodes because of melting or vaporization, along with pressure dynamics established in the spark-gap by the collapsing of the plasma channel. However, for small discharge energies the models are inadequate to explain the experimental data. All these models hinge on a number of assumptions from such disparate research areas as submarine explosions, discharges in gases, and failure of transformers, so it is not surprising that alternative models have been proposed more recently in the literature trying to explain the EDM process.

Among these, the model from Singh and Ghosh[26] reconnects the removal of material from the electrode to the presence of an electrical force on the surface of the electrode that could mechanically remove material and create the craters. This would be possible because the material on the surface has altered mechanical properties due to an increased temperature caused by the passage of electric current. The authors' simulations showed how they might explain EDM better than a thermal model (melting or evaporation), especially for small discharge energies, which are typically used in μ-EDM and in finishing operations.

Given the many available models, it appears that the material removal mechanism in EDM is not yet well understood and that further investigation is necessary to clarify it,[21] especially considering the lack of experimental scientific evidence to build and validate the current EDM models.[21] This explains an increased current research effort in related experimental techniques.[

Abrasive Jet Machining

Abrasive jet machining (**AJM**), also known as **abrasive micro-blasting**, **pencil blasting** and **micro-abrasive blasting**,[1] is an abrasive blasting machining process that uses abrasives propelled by a high velocity gas to erode material from the workpiece. Common uses include cutting heat-sensitive, brittle, thin, or hard materials. Specifically it is used to cut intricate shapes or form specific edge shapes.[2][3][4]

Process

Material is removed by fine abrasive particles, usually about 0.001 in (0.025 mm) in diameter, driven by a high velocity fluid stream; common gases are air or inert gases. Pressures for the gas range from 25 to 130 psig (170–900 kPa or 4 bars) and speeds can be as high as 300 m/s (1,000 km/h).[2][3]

Equipment

AJM machines are usually self-contained bench-top units. First it compresses the gas and then mixes it with the abrasive in a mixing chamber. The gas passes through a convergent-divergent nozzle before entering the mixing chamber, and then exits through a convergent nozzle. The nozzle can be hand held or mounted in a fixture for automatic operations.[2][3]

Nozzles must be highly resistant to abrasion and are typically made of tungsten carbide or synthetic sapphire. For average material removal, tungsten carbide nozzles have a useful life of 12 to 30 hours, and sapphire nozzles last about 400 hours. The distance of the nozzle from the workpiece affects the size of the machined area and the rate of material removal.[3]

Grit size and orifice diameters for various abrasive materials[3]

Abrasive material	Grit size (μin)	Orifice diameter (in)
Aluminum oxide	10–50	0.005–0.018
Silicon carbide	25–50	0.008–0.018
Glass beads	2500	0.026–0.05

Advantages and disadvantages

The main advantages are its flexibility, low heat production, and ability to machine hard and brittle materials. Its flexibility owes from its ability to use hoses to transport the gas and abrasive to any part of the workpiece. Normally inaccessible portion can be machined with good accuracy. [3][4]

One of the main disadvantages is its slow material removal rate; for this reason it is usually used as a finishing process. Another disadvantage is that the process produces a tapered cut.[3][4]

Laser Beam Machining

Laser beam machining (**LBM**) is a form of machining that uses heat directed from a laser beam. This process uses thermal energy to remove material from metallic or nonmetallic surfaces. The high frequency of monochromatic light will fall on the surface, thus heating, melting and vaporizing the material due to the impinge of photons (see Coulomb explosion).[1] Laser beam machining is best suited for brittle materials with low conductivity, but can be used on most materials.[2]

Laser beam machining can be done on glass without melting the surface. With photosensitive glass, the laser alters the chemical structure of the glass allowing it to be selectively etched. The glass is also referred to as photomachinable glass. The advantage of photomachinable glass is that it can produce precisely vertical walls and the native glass is suitable for many biological applications such as substrates for genetic analysis.

Types of lasers

There are many different types of lasers including gas, solid states lasers, and excimer.[3]

Some of the most commonly used gases consist of; He-Ne, Ar, and Carbon dioxide laser.

Solid-state lasers are designed by doping a rare element into various host materials. Unlike in gas lasers, solid state lasers are pumped optically by flash lamps or arc lamps. Ruby is one of the frequently used host materials in this type of laser.[3] A ruby laser is a type of the solid state laser whose laser medium is a synthetic ruby crystal. The synthetic ruby rod is optically pumped using a xenon flashtube before it is used as an active laser medium.[4]

YAG is an abbreviation for yttrium aluminum garnet which are crystals that are used for solid-state lasers while Nd:YAG refers to neodymium-doped yttrium aluminum garnet crystals that are used in the solid-state lasers as the laser mediate.

YAG lasers emit a wavelength of light waves with high energy. Nd:glass is neodymium–doped gain media made of either silicate or phosphate materials that are used in fiber laser.

Cutting depth

The cutting depth of a laser is directly proportional to the quotient obtained by dividing the power of the laser beam by the product of the cutting velocity and the diameter of the laser beam spot.

where t is the depth of cut, P is the laser beam power, v is the cutting velocity, and d is the laser beam spot diameter.[5]

The depth of the cut is also influenced by the workpiece material. The material's reflectivity, density, specific heat, and melting point temperature all contribute to the lasers ability to cut the workpiece.

The following table[6] shows the ability of different lasers to cut different materials:

material	wavelength (micrometer) CO2 laser: 10.6	wavelength (micrometer) Nd:YAG laser: 1.06
ceramics	well	poorly
plywood	very well	fairly well
polycarbonate	well	fairly well
polyethylene	very well	fairly well
Perspex	very well	fairly well
Titanium	well	well
Gold	not possible	well
Copper	poorly	well
Aluminium	well	well
stainless steel		very well
construction steel		very well

Applications

Lasers can be used for welding, cladding, marking, surface treatment, drilling, and cutting among other manufacturing processes. It is used in the automobile, shipbuilding, aerospace, steel, electronics, and medical industries for precision machining of complex parts.

Laser welding is advantageous in that it can weld at speeds of up to 100 mm/s as well as the ability to weld dissimilar metals. Laser cladding is used to coat cheap or weak parts with a harder material in order to improve the surface quality. Drilling and cutting with lasers is advantageous in that there is little to no wear on the cutting tool as there is no contact to cause damage.

Milling with a laser is a three dimensional process that requires two lasers, but drastically cuts costs of machining parts.[2][7] Lasers can be used to change the surface properties of a workpiece.

The appliance of laser beam machining varies depending on the industry. In light manufacturing the machine is used to engrave and to drill other metals. In the electronic industry laser beam machining is used for wire stripping and skiving of circuits. In the medical industry it is used for cosmetic surgery and hair removal.[2]

Advantages

1. Since the rays of a laser beam are monochromatic and parallel (i.e. zero etendue) it can be focused to a small diameter and can produce as much as 100 MW of power for a square millimeter of area.
2. Laser beam machining has the ability to engrave or cut nearly all materials, where traditional cutting methods may fall short.
3. There are several types of lasers, and each have different uses.
4. The cost of maintaining lasers is moderately low due to the low rate of wear and tear, as there is no physical contact between the tool and the workpiece.[3]
5. The machining provided by laser beams is high precision, and most of these processes do not require additional finishing.[3]
6. Laser beams can be paired with gases to help the cutting process be more efficient, help minimize oxidization of surfaces, and/or keep the workpiece surface free from melted or vaporized material.

Disadvantages

1. The initial cost of acquiring a laser beam is moderately high. There are many accessories that aid in the machining process, and as most of these accessories are as important as the laser beam itself the startup cost of machining is raised further.[3]
2. Handling and maintaining the machining requires highly trained individuals. Operating the laser beam is comparatively technical, and services from an expert may be required.[3]
3. Laser beams are not designed to produce mass metal processes.
4. Laser beam machining consumes a lot of energy.
5. Deep cuts are difficult with workpieces with high melting points and usually cause a taper.

Electrochemical machining (ECM)

Electrochemical machining (**ECM**) is a method of removing metal by an electrochemical process. It is normally used for mass production and for working extremely hard materials, or materials that are difficult to machine using conventional methods.[1] Its use is limited to electrically conductive materials. ECM can cut small or odd-shaped angles, intricate contours or cavities in hard and exotic metals, such as titanium aluminides, Inconel, Waspaloy, and high nickel, cobalt, and rhenium alloys.[2] Both external and internal geometries can be machined.

In the ECM process, a negatively-charged (cathode) cutting tool is advanced into a positively-charged (anode) workpiece. Pressurized electrolyte is injected at a set temperature into the area being cut, at a feedrate equal to the rate of "liquefication" of the anode material. The gap between the tool and the workpiece varies within 80–800 micrometers (0.003–0.030 in.)[1] As electrons cross the gap between the tool and workpiece, material from the workpiece is dissolved, as the tool forms the desired shape in the workpiece. The electrolytic fluid carries away the metal hydroxide formed in the process.[2]

ECM is often characterized as "reverse electroplating", in that it removes material instead of adding it.[2] It is similar in concept to electrical discharge machining (EDM) in that a high current is passed between an electrode and the part, through an electrolytic material removal process involving a cathode tool, electrolytic fluid, and anode workpiece; however, in ECM there is no tool wear.[1] The ECM cutting tool is guided along the desired path close to the work but without touching the piece. Unlike EDM, however, no sparks are created. High metal removal rates are possible with ECM, with no thermal or mechanical stresses being transferred to the part, and mirror surface finishes can be achieved.

Electrochemical machining, as a technological method, originated from the process of electrolytic polishing offered already in 1911 by a Russian chemist E. Shpitalsky.[3] As far back as 1929, an experimental ECM process was developed by W.Gussef, although it was 1959 before a commercial process was established by the Anocut Engineering Company. B.R. and J.I. Lazarenko are also credited with proposing the use of electrolysis for metal removal.[2] Much research was done in the 1960s and 1970s, particularly in the gas turbine industry. The rise of EDM in the same period slowed ECM research in the West, although work continued behind the Iron Curtain. The original problems of poor dimensional accuracy and environmentally polluting waste have largely been overcome, although the process remains a niche technique.

The ECM process is most widely used to produce complicated shapes such as turbine blades with good surface finish in difficult to machine materials. It is also widely and effectively used as a deburring process.[2] In deburring, ECM removes metal projections left from the machining process, and so dulls sharp edges. This process is fast and often more convenient than the conventional methods of deburring by hand or nontraditional machining processes.[1]

Advantages

- Complex concave curvature components can be produced easily by using concave tools.
- Tool wear is zero, same tool can be used for producing infinite number of components. [4]
- High surface quality may be achieved.
- No direct contact between tool and work material so there are no forces and residual stresses. [5]
- The surface finish produced is excellent.
- Less heat is generated.

Disadvantages

- The saline (or acidic) electrolyte poses the risk of corrosion to tool, workpiece and equipment.[2]
- Only electrically conductive materials can be machined.
- High Specific Energy consumption. [6]
- It cannot be used for soft materials.