BASIC THEORY—ELECTRICAL DISCHARGE MACHINING
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Back to Basics
In our "Letters to the Editor" department, several readers have suggested that we include a Basic EDM Theory article for the newest members of our EDM community. The "old timers" out there might also find it interesting reading and it always pays to refresh your memory. For the readers that requested it, here is The Basic Theory of EDM:

Introduction
EDM. The very mention of "EDM" brings shivers to the spines of the uninformed, and knowing smiles to the knowledgeable. Although the EDM process has been in use for decades, it is still widely misunderstood by many in the manufacturing community. EDM is the process of electrically removing material from any conductive workpiece. This is achieved by applying high frequency, pulsed, DC current to the process of electrically removing the workpiece through an electrode or wire, which melts and vaporizes the workpiece material. Positioned very precisely near the workpiece, the electrode never touches the workpiece but discharges its potential current through an insulating dielectric fluid (water or oil) across a very small spark gap. This spark vaporizes and melts the workpiece material. This process is used when the workpiece material is too hard, or the shape or location of the detail cannot easily be conventionally machined. This makes many formerly difficult projects more practical and many times it can be the only feasible way to machine a part or material.

EDM was first implemented over 40 years ago, and used primarily to remove broken taps and drills from expensive parts. These were quite crude in construction with hand-fed electrodes. During World War II, two Russian scientists, the Lazarenkos, adapted the first servo-system to an EDM machine. This offered some semblance of the degree of control that is required for efficient but safe EDM machining today.

Through the years the machines have improved drastically. Progressing from RC (resistor capacitance or relaxation circuit) power supplies and vacuum tubes, to solid-state transistors with nanosecond pulsing. From hand-fed electrodes to modern CNC-controlled, simultaneous six-axes machining. And now, augmented by it’s younger brother, the wire-cut EDM, these two have combined to revolutionize many industries and to change long-standing and generally accepted processes of manufacturing.

To better understand all this, it is best to start at the beginning...

Theory
Assuming the electrode is positively charged and the workpiece and table are negative (or vice-versa). The electrode is advanced into the workpiece through an insulating liquid, or dielectric fluid. This is usually a paraffin, kerosene or silicon-based dielectric oil for vertical machines, and de-ionized water for wire-cut machines. The dielectric fluid is integral to the process. It provides insulation against premature discharging, cools the machined area and flushes away the "chips."

As the electrode or wire, charged with a high voltage potential nears the workpiece, an intense electromagnetic flux or "energy column" is formed and eventually breaks down the insulating properties of the dielectric fluid. Picture the ends of two bar magnets with the north and south poles held apart. If one were to lay a piece of white paper over the magnets and sprinkle fine iron filings onto it, these filings would be caught in this magnetic flux, aligned by polarization in the same way the dielectric is affected.

At this time, with the "grain" of trapped ions in polar alignment and the resistivity of the fluid at its lowest, a single spark is able to flow through this ionized "flux-tube" and strike the workpiece. The voltage drops as current is produced and the spark vaporizes anything in contact with it, including the dielectric fluid, encasing the spark in a sheath of gasses composed of hydrogen, carbon and various oxides. The area struck by the spark will be vaporized and melted, resulting in a single crater being formed. Due to the heat of the spark and the contaminants being produced by the workpiece, electrode (or wire), and the dielectric fluid, the field of ionized particles becomes "lazy," the alignment is disrupted and resistivity increases rapidly. Voltage will rise as resistivity increases and the current will drop as the dielectric can no longer sustain a stable spark. At this point, the current must be switched off.

During the time current was flowing through the spark gap, the plasma-hot area was rapidly expanding away from the heat source; the spark. When the current is switched off, there is no more heat source and the sheath of vapor that was around the spark, implodes. Its collapse creates a void or vacuum and draws in fresh dielectric fluid to flush away swarf and cool the area. This off period allows the re-ionization process of the dielectric fluid to be completed, and provides favorable conditions for the next spark. The duration of the off-time must be sufficient enough to flush away the spark debris and damaged dielectric or stability will be difficult to maintain, resulting in DC arcing or a broken wire. This briefly describes one EDM cycle and in order to machine with this process, it must be repeated over and over again, switching on and off thousands of times a second.

Together, the "on" and "off" pulses (in units of micro-
seconds, or μsec), describes a single cycle of electrical discharge machining. The length and duration of these parameters will depend upon the work piece, electrode material, flushing, speed required and surface finish. Generally speaking, low frequencies are used for rough machining and high frequencies are used for finish machining. Some materials due to density, conductivity and/or melting temperature, must be machined with higher frequencies even during roughing operations. (titanium, carbide, copper, etc.) This will result in improved finishes and surface integrity, but with substantially increased electrode wear.

The relationship of the on-time to the off-time is the measure of efficiency, better known as the Duty Cycle. This is calculated by adding the on-time and the off-time together and dividing this total into the on-time. Multiply this quotient by 100 for the percentage of efficiency or duty cycle. See below for examples.

<table>
<thead>
<tr>
<th>ON time/(ON + OFF time) x 100 = % (DUTY CYCLE)</th>
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<tbody>
<tr>
<td>EXAMPLES:</td>
</tr>
<tr>
<td>25 ON / 25 OFF = 25/50 = 50%</td>
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<tr>
<td>75 ON / 10 OFF = 75/85 = 88%</td>
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Obviously, it would be desirable to reduce the OFF time to the smallest possible increment, but many variables such as flushing conditions, electrode material, workpiece material, dielectric condition, etc., can drastically affect the ability to maintain concurrent efficiency and stability.

Many of the modern power supplies have the ability to monitor and change conditions and duration of the spark by using "adaptive" controls. This ability can compensate for marginal cutting conditions automatically, even allowing untended operations.

**More About On & Off Time**

Knowing how EDM works isn't enough. We need to make it work for us. We need to know how to get good machining speed and good finishes with minimum wear and the lowest possible chances of DC arcing or wire breaks. We'll need to examine this in depth because, on and off time are much more than just a switching cycle. Together, they control the basic parameters of the EDM process. They are as follows:

**ON TIME**

Speed: All of the work is done with on-time. The spark gap is bridged, current is generated and work is being accomplished. The longer the spark is sustained (the higher the duty-cycle), the more workpiece material will be melted away.

Finish: Consequently, with a longer period of spark duration, the resulting craters will be broader and deeper, therefore the surface finish will be rougher. Obversely, with a shorter spark duration, the finishes will be finer. We will discuss the related conditions of spark frequencies, recast and HAZ elsewhere.

Wear: With positively charged electrodes, the spark leaves the electrode and strikes the workpiece, doing most of the thermal damage to the workpiece (hopefully). Except during certain roughing operations using elevated on-times when a phenomena occurs known as "plating," every spark leaving the electrode can take a microscopic particle with it. The more sparks that are produced within a unit of time will produce proportionately more wear. That is why EDM behaves just the opposite of chip-cutting operations. Roughing electrodes tend to last much longer than finishers. Electrode material will also play a large factor concerning the amount of wear, but will not be discussed here.

**OFF TIME**

Speed: While the actual work, or metal removal, is accomplished by the spark only during the on-time, the duration of rest pauses required for reionization of the dielectric, can drastically affect the speed of the operation. The longer the period of rest or off-time, the longer the job will take. Unfortunately, off-time is a necessity and an integral part of the EDM process, but the smaller this increment is, the faster the machining operation will proceed — to a point.

Stability: Just as important as machining speed is to an EDM operation, stability is the key to maintaining this speed. Although increasing the off-time will slow down the process, it can provide the stability required to successfully EDM a given application. If the off-time is insufficient, it will cause erratic cycling and retraction of the advancing servo(s), slowing down the operation more than a less efficient, but stable, off-time would.

Analogy: Would you travel farther in a car that could do 100 mph for only very short intervals, or a car that could do a steady 55 mph all day?

continued on page 30
Note: An argument has been presented to me on occasion, claiming that wear is also a factor influenced by off-time. Perhaps this perception is with the reasoning of: if 10% wear is incurred in one hour, then by doubling the off-time, the job would take twice as long, then the total wear should be 20%. (if the job takes longer, there must be more wear).

"Maintaining any kind of sustained machining speed is practically impossible without cutting stability."

I beg to differ with this opinion, based upon simple logic and undeniable physics: When the current is switched off, it is exactly that—off! Nothing (other than the recovery of the dielectric), is occurring. No work is being produced, nor any wear. If only the off-time is changed, only the time required to complete the job will change.

An abstract, but adequate description of this might be; a certain cavity might require 1000 individual sparks to complete. If these sparks are only 10 micro seconds apart, the job will take much longer, but with no increase in wear. 1000 sparks is 1000 sparks—no matter how far apart in time they are! Therefore the duration of off-time will not affect wear; only time.

There may be some very fine points to discuss with theorists such as; increased off-time would allow the workpiece temperature to cool more between each pulse, (how much can this area cool in a few micro-seconds?), thus requiring the spark to "work harder" in elevating the impact area to the vaporization/melting temperature, but I have never found a change of off-time alone to affect wear characteristics—only the speed and stability.

Minimal off-time is a key to machining speed, but unfortunately a sufficient amount of off-time is required to maintain machining stability. Stability is more important
than speed, in fact, maintaining any kind of sustained machining speed is practically impossible without cutting stability.

**Polarity**

In EDM, polarity describes which side of the spark gap is positive or negative. Polarity can affect speed, finish, wear and stability.

Vertical machines can use both positive and negative polarity, depending upon the application, but most operations are performed using a positive electrode. Positive polarity will machine slower than negative polarity, but is used most of the time to protect the electrode from excessive wear.

Negative polarity is used for high-speed metal-removal when using graphite electrodes, and should be used when machining carbides, titanium and refractory metals using metallic electrodes. Negative electrode polarity used with metallic electrodes is slow, but it is used because no other method is as successful. With graphite electrodes, negative polarity is much faster than positive polarity by as much as 50% or more, but with as much as 30% to 40% wear. This is a good choice for large cavities or with shapes that can easily be redressed or abraded.

Wire machines almost always run with negative polarity — that is, the wire is negative and the workpiece is positive. As in vertical applications, metal removal rates are higher using negative polarity, but since the electrode (wire) is constantly renewed, electrode wear is not a consideration. However, if the wire is burned deep enough, usually about 20% of its diameter, it can no longer withstand the tension and will break. Increasing the speed of the wire will reduce the severity of the wire erosion and help eliminate wire breakage, at the small expense of increased wire consumption.

**The Recast Layer**

One drawback of the EDM process is something called the recast layer or remelt. This recast layer is an inherent by-product of the EDM process and although new technology allows recast to be controlled to a very fine degree, the thermal nature of the EDM process itself makes it impossible to eliminate entirely. Here is a brief description of recast:

After the initial spark has produced a crater and been switched off, a quantity of molten material will be drawn back into the spark crater by surface-tension and cooling effects. This molten material will "re-freeze" back onto the cooler crater walls. This layer tends to be highly carbonaceous and is called recast material, or the "white layer." Just below the white layer is the area called the "Heat Affected Zone" (or HAZ). This area is only partially affected by the high temperatures. The thickness of the recast layer and the Heat Affected Zone (HAZ) immediately below it depends upon the current and frequencies used during machining and the heat-sinking ability of the material itself. Recast can affect the structural and/or surface integrity of the EDMed area.

If the recast layer is too thick or is not reduced or removed by polishing, AFM, ECM, etc., this very hard and brittle recast layer can cause cracking, flaking, impart stress-risers and cause premature failure of the part. In severe cases, recast removal and/or stress-relieving of the...
part is sometimes necessary. This has been a major concern of the aerospace/aircraft industries for years and only recently, with the improvement in modern power supplies, has acceptance of EDMed parts for aircraft and aerospace industries become routine.

While on the subject of recast and finishes; there are distinct differences between the recast layer left by wire EDM and the recast left by vertical EDM. This is attributed to the different dielectric fluids used which are usually oil for vertical machines and water for wire-cut. (Sinkers have been modified to use water dielectrics and a production model has recently been re-introduced to the United States market. Wire-cut machines using oil and oil/water dielectrics are also available and can provide improved surface finishes, but with a significant reduction in cutting speeds).

Oil dielectrics change the parent material by producing an uncontrolled heat-treating process; heating the metal to a very high temperature and then quenching it in oil. The high heat breaks down the oil into hydrocarbons, tars, and resins. The molten metal draws the carbon atoms from the oil and they become trapped within the recast layer, creating a “carburized” surface. While this is a far cry from the carefully produced carburized surfaces obtained during professional heat-treating operations, it is nevertheless hard. Glass hard, in fact. Even when EDMing pre-hardened materials, the recast surface produced in oil will generally be several points higher in hardness than the parent material. Ask anyone who has stone-polished an EDMed cavity just how hard the recast or “white layer” is.

Recast produced in water dielectrics is different from oil because oxides produced by the vaporizing water, along with electrolysis, can deplete carbon from the material’s surface. In addition, copper atoms freed from the brass wire can be assimilated into the exposed surface of the workpiece material, further contributing to an alloying process and softening the parent material. In ferrous materials, wire-cut surfaces can be several points lower in hardness than the parent material.

Carbides also can be EDM machined, but improper power settings will deplete the cobalt binder material that holds the tungsten particles in place, resulting in flaking or cracking. Fortunately, most modern power supplies are capable of reducing most of this concern of controlling the thickness of the recast material by constantly monitoring and controlling the spark/servo conditions during high-frequency machining. Another reason for the improvements in the surface integrity of EDMed carbides, especially in newer wire-cut machines, is the absence of capacitors.

**Machining Tips**

The following recommendations are guidelines only. Your single best source of cutting technology is from the applications engineers employed by the builder of your machine.

**For speed:** As usual, EDM is always a fine line of compromise. In this case, it’s speed vs. stability. If the overcut, wear and finish are satisfactory and flushing is adequate, the machining speed of an EDM operation can be increased by slowly decreasing the on or off-time in small increments (1 to 5 μsec), until machining becomes erratic, quickly returning to the last stable setting. Now, this isn’t a very technical sounding solution, nor does it require a lot of formulas, but not many of us are mathematicians, nor do we desire to be. We just need results in a hurry and this method works.

As you do this, the machining or gap voltage will slowly decrease as the working current (Amps) will slowly increase. If the room is quiet enough, you may also be able to actually hear the discharge frequency change as you increase or decrease the on or off-time. Try not to let the gap voltage drop below 35 to 40V as this can be risky even with optimum flushing. Of course, all of this depends upon your application, flushing conditions, electrode selection, servo voltage and other power supply settings.

**For wear:** Wear is not a serious consideration for wire EDM because of variable wire speeds and the constantly renewable electrode material from the spool. For vertical EDM, leaving a minimal amount of stock for finishing will also help keep electrode wear to a minimum. Using no or low-wear settings to remove most of the material and leaving only the smallest amount of stock for “changing the finish,” is the correct method.

**Logic:** If there is only a few thousandths (.003 -.005) of stock left for finishing operations, even at 20% wear, how much could this possibly amount to? (20% of .001 = .0002).

**For finish:** In EDM, surface finishing is usually the most time consuming, therefore, the most expensive. Careful planning and preparation can offset this. For both wire-cut and vertical CNC machines, careful selection of the current and frequencies used and the amount of material left to remove is paramount. Whether you are skim-cutting with wire or orbiting with ram, the remaining amount of material for each step should be only slightly more than the maximum crater depth left by the previous cut, otherwise you can wind up “chasing” old finishes and heat affected zones.

The old shop saying, “Rough it out to size,” almost applies here, as long as the heat from the roughing.
operation doesn't penetrate too deeply into the workpiece and there is sufficient stock remaining to remove all traces of the previous finish.

When attempting parts or details requiring minimal recast or "mirror finishes," you should not be concerned with metal removal in the final steps, as this is the duty of the roughing and semi-finishing operations. At this point, your part or cavity should be only a few tenths away from its finished dimensions, so we want only to change the surface finish, actually removing very little material. Using low power, very high frequencies and minimal amount of offset for each cut is the best strategy.

Fine finishing on manual machines is more difficult because of the inability to orbit the ram or X/Y axes. Most jobs on manual machines are finished with several passes of a slightly larger, finishing electrode. The problems with this operation are: the time required for each finishing "pass," uneven electrode wear and the time and support equipment used to make or redress multiple electrodes. The reason for the difficulty in this type of operation is the very small area remaining for finishing (usually .005 - .010" per side), cannot accept very much current. In addition, while using finishing conditions (high-wear settings), excessive wear of the leading edges of the electrode occurs because it must cut the entire Z-depth again to finish the side walls, instead of just the few thousandths of material actually remaining in the X and Y planes. So, even though the cavity has been "finished," it usually isn't. The worn electrode must be redressed or replaced by a new one to remove the material left by the first finisher. In many cases, several dressings and re-entries must be made before the electrode "sparks-out" and side-wall taper and corner radii are within blueprint requirements.

The speed and performance of finishing operations on manual machines can be greatly improved at a relatively small cost, by adding an after-market orbiting device to the head or ram. While an orbiting device will not make a manual machine into a CNC, it will help improve speeds, finishes, flushing and reduce electrode corner wear.

"Knowing how EDM works isn't enough. We need to make it work for us."

Mirror finishes are different in their approach and electrode preparation, and are seldom obtained without motion during machining, whether by orbiting or electrode rotation. Longer machining times and higher wear are unavoidable and should be factored into the price of the job.

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