Application Note 1

Closing the quality control loop with capacitive discharge spot welders.

This application note sets out to factually demystify many of the common operational welding process challenges encountered when choosing or using capacitive discharge micro spot welding power supplies.

In providing the reader with an impartial, technically explained overview and understanding of how C.D. Spot welders work and how this affects the resistance welding process, the aim is to provide sufficient detail to allow the reader to then make informed decisions about equipment choices, setup and use.

This application note is divided into subject sections with the more tricky engineering maths and electronics appearing after Page 4 ; generally it starts easy and gets a bit harder as you go on !

Questions for Choosers

Not sure if you need a more expensive controlled power supply or will a CD welder do ?

What are the pros and cons for quality control with a capacitor discharge welder ?

Not sure if you need or want an internal weld monitor ?

Not sure if you need or want an external weld monitor ?

Questions for Users

Not sure why you sometimes need to adjust the output settings during daily production ?

How can I reduce arcing at the weld and extend electrode life with my CD welder ?

Not sure if you need or want an external weld monitor ?

How can I be sure my welding power supply is working consistently ?

Did you know you can sometimes get more weld heat with less current from a CD welder ?

Introduction

Regardless of the manufacturer, Capacitive Discharge (CD) micro welding power supplies for the most part, operate in the same way. That is to say, they charge up a capacitor bank to a user defined energy level and then “switch” or “dump” or DISCHARGE the energy into the welding circuit.

The technology has been around for years and it offers two primary features, namely **Low cost** and **High current**. While some CD welding power supplies incorporate some rudimentary current modifying facilities, essentially there is very little other than the welding circuit (*weld head, welding cables, electrode holders, electrodes and product*) itself controlling the heat energy that arrives at the welded joint.

Thus, Cap discharge welders are referred to as Open Loop and/or Uncontrolled devices - in other words, there is no controlling servo loop governing the power supply output. **Q. Does that really matter ?**

The answer is very often **NO**, it doesn’t really matter **IF** you are able to keep the welding circuit under control and the materials being welded are not sufficiently demanding to require greater sophistication from dynamic electronic servo controls.

Moreover, if you need to weld highly conductive materials together, such as battery tab welding in battery pack manufacturing, then the relatively low cost high currents available from capacitor discharge machines, make them an attractive proposition.

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Controlling the uncontrolled !

With high quality DC resistance spot welding, the name of the game is to keep as many process variables as far as possible the same, each and every time a weld is made.

This essentially breaks down into two areas, namely the control of the welding energy (power supply and electrical welding circuit) and the control of the electro-mechanical aspects of the welding circuit, i.e. the materials, the forces and the dimensions.

With high quality manufacturing processes, independent checks and measures are put in place to check and verify the process parameters are working as desired and expected, so that if any equipment should fail or drift, it is immediately detected. Thus, assuming your CD welder produces a repeatable output **AND** your welding circuit is exactly the same, each and every time.. then by definition, you should have a totally repeatable process.

Sounds great, but it's far from the real world reality, simply because the welding circuit does not always stay the same. Furthermore, because CD welders are uncontrolled, the actual welding energy is far more prone to variations in the welding circuit compared with controlled power supplies, implying that the more discerning quality minded user needs to pay more attention to keeping the welding circuit under control or at least monitored in some way, in order to ensure their welding energy remains stable.

Consistency in material preparation, presentation and handling along with consistency in electrode materials, shapes and forces, are all additional process factors effecting both uncontrolled CD welder applications as well as controlled Linear and/or HFDC and/or inverter applications. These aspects are covered in a separate application note and should be considered with equal weighting for all types of power supply. They are of course a fundamental part of the welding circuit, so for the purpose of comparison, this application note will focus on the variables involved with the welding circuit and how these affect capacitor discharge welders in particular.

N.B What you set, is most definitely NOT what you get !

How many Watt/Seconds do you need to make good toast ?

Capacitive Discharge (CD) micro welding power supplies let you set the output energy in Joules (or watt/seconds, the same thing). As stated, they charge a capacitor bank to a user set energy level and then discharge it into the welding circuit (weld head, cables, electrodes and welded product).

In resistance welding, the actual electrical heat energy at the weld is determined from ohms law and is defined by the **Current x Current x Weld Resistance x Time** or **I^2R x time**. The problem is, without any actual control, the current in the welding circuit is entirely dynamic and determined by the overall and total electrical aspects of the electrical circuit, which are practically impossible to measure to any real degree of certainty.

Thus, the actual useful heating current / energy arriving at the weld is entirely defined by the welding circuit itself and is often a fraction of the energy actually available !! **Why ?** Because a lot of the energy is used to over come circuit inductance and heat cables and weld head connections, all of which then dynamically affect and reduce the overall circuit current.

A detailed mathematical model and explanation is presented later, but for now, the point is that the W/S (Joule) value is simply a starting point reference value and it is electrically related to the output by virtue of the physical setup.

When you make toast, you put energy in over time.. you have a light to dark scale on the toaster and by trial and error, you soon discover the right setting, even though you have no idea how many joules are involved.

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How many Watt/Seconds do you need to make good toast ? Continued….

Hopefully you don't need the mathematics later to realise that a CD welder programmed for 50W/S is going to deliver a different welding (I^2R) payload at the weld if it has a one mile long welding cable on it, compared to one with two feet of cable !

The same could be said if you changed from conductive copper electrodes to resistive tungsten ones. Hence, the notion of S.I. units such as Joules (W/S) at the welder starts to become meaningless, other than to provide a numeric reference. Obviously you will know that increasing the output Joules will increase the current, but by how much, very much depends upon the welding circuit !

Thus, the toaster analogy starts to make more sense.. What happens is, you set the weld circuit as best you can, then gradually tweak the welder until you get good toast at the welding. You have a set input (the W/S), you have a process (the welding circuit) and you have an output (the weld heat created by I^2R at the weld).

Immediately you can see that the welding circuit is defining the output, so how do you know it hasn't changed over time. The reality is, without some kind of additional monitoring, you don't and hence from a quality control standpoint, you are exposed.

When you make toast, how many times do you visually check or smell (monitor) that all is well with the bread and toaster ? You may have some thicker slices, or perhaps some from frozen, so you may be aware of a slight process change. This is where you, as the monitor, provide the additional process feedback to what is a relatively open loop system.

Hence, by introducing a monitor, you are providing a reference to the desired output, which after all, is all that matters. **As with toast, the units of measure don't really matter, all you really want to know is, is it Good or Bad or at least, the same as before.**

But I know my process, it's as stable as it can be !

You might have a controlled process in terms of material handling, electrode preparation and trained operators, BUT as a famous engineer once said, "You cannot change the laws of physics Captain !".

A 35mm² Copper welding cable has a thermal resistive temperature coefficient of around 0.393% per degree centigrade and 0.595 mOhms per metre, meaning that from a cold start in the morning through a hot day of welding, you might see a 20 degree change, or 7.28% change in the welding cable circuit resistance.

Add that to the additional thermal resistive affects coming from the changing internal series resistance of the capacitors plus those coming from the various mechanical joints and weld head flexures, you now have a recipe for uncontrolled process change, which by definition, will change the output current and weld heat energy.

This also provides the reasoning as to why in some CD applications, experienced, trained users are allowed to tweak the CD power supply up or down a bit, when they suspect the joints don't quite look the same during the course of a day.

The problem with this approach of course, is that it is very subjective and runs the risk that the operator may not have spotted the true cause of the problem.

Again, a measuring weld monitor that is checking the welder output energy at the weld, provides a viable improvement. As with monitoring toast, process feedback monitoring allows the user to make an adjustment that results in an output that fits between some predetermined limits.

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What to monitor and how ?

It should be clear by now that monitoring the energy change just at the output of a CD power supply does not give a clear indication of what is happening in terms of heat energy at the weld. In the mathematical and electronic explanations later, we might approximate and model a typical CD welder setup, comprising a capacitor (0.5F) charged to 10 Volts, discharging into an overall circuit resistance of 2 milliohms, with a circuit inductance of 1µH. If the cables and head are 1 milliohm and the weldment is 1 milliohm, then the total heat energy at the weld will be 4.167 J with a peak current of 1924 Amps. The available output is 25 J !

Now, if we increase the weld circuit by 0.5 milliohms and decrease our weldment by 0.5 milliohms, the overall circuit resistance remains as 2 milliohms **BUT** the heat energy at the weld is halved and becomes 2.083 J, still with a peak current of 1924 Amps - remember the R in I^2R ! Also bear in mind, the available output is still 25 J !

This tells us several things about choosing and using a weld monitor for a Capacitor Discharge application.

- Monitoring the energy released at the welder output **CANNOT** give a clear indication of the energy changes at the weldment.

- Monitoring a peak current as a process indicator, **CANNOT** give a clear indication of the energy changes at the weldment.

- Monitoring energy released or a peak welding current **CAN** indicate a process change, but **CANNOT** discern how that might effect the heat energy at the weldment.

And here's one you might not know or expect..

- Monitoring a peak current can be counter intuitive. It is perfectly feasible to have a higher peak current with a lower weld heat energy !!!

If we take the above setup and assume a circuit resistance of 2 milliohms and a weldment resistance of 1 milliohm and then increase the weldment resistance by 0.5 milliohms, the peak current will reduce from 1867 Amps to 1782 Amps but the welding heat increases from 4.72 J to 6.943 J.

Peak current drops by 4.76%, while weldment heat energy increases by 32.02% !!! - remember the R in I^2R !

It therefore stands to reason and the laws of physics that if you simply want to detect **SOME** process changes, you can do this quite easily with a simple monitoring system looking at just source energy or peak currents.

However, as we have seen, the circuit current can stay the same, but the weld heat energy can change enormously, so such a monitor will have inherent short comings. Furthermore, if a change in current is detected, you will still have the problem of knowing what to do, because you don't know what has actually changed and by how much.

Have the cables heated up or has the product changed or both ? You don't know and can't tell !

If however, you want to know and monitor that your weld heat energy is remaining within your pre-defined process limits, then you actually have to quantify and monitor the weldment heat energy, which is to say, the cumulative sum of electrical energy going into the actual weld.

This latter method, then provides the means by which any uncontrolled process changes can be readily detected AND manually (or automatically) compensated for, essentially **closing the quality control loop on an uncontrolled process.**

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How to monitor the weldment electrical heat energy

External quality control weld monitoring generally forms part of a process quality assurance program. In the case of an uncontrolled open loop process such as capacitor discharge, an external weld monitor can be used to check the welding equipment is functioning correctly and delivering weld energy within certain limits.

As with making toast, we don't actually need an absolute measurement, we simply need to know that given a certain weldment heat energy, we get a good welded joint and if that energy goes above or below certain limits, then we need to flag a problem.

The electrical energy appearing at the weldment equates to current x voltage x time. This is the same measurement as is made at your electricity meter.

Another way of finding this value is from current x current x resistance (I^2R) x time. It's the same thing, but since we don't know what the weldment resistance is, we need to use current x voltage x time by measuring the voltage as close as possible to the weldment. Measuring the current is simply a case of adding a low loss series current shunt or by using a hall effect device.

Without a real time voltage measurement close to the weldment, it is impossible to measure or quantify the electrical heat energy delivered into the weldment. For effective weld monitoring, this is essential.

Fig 1 - An electronic schematic model of a CD welder and weld head

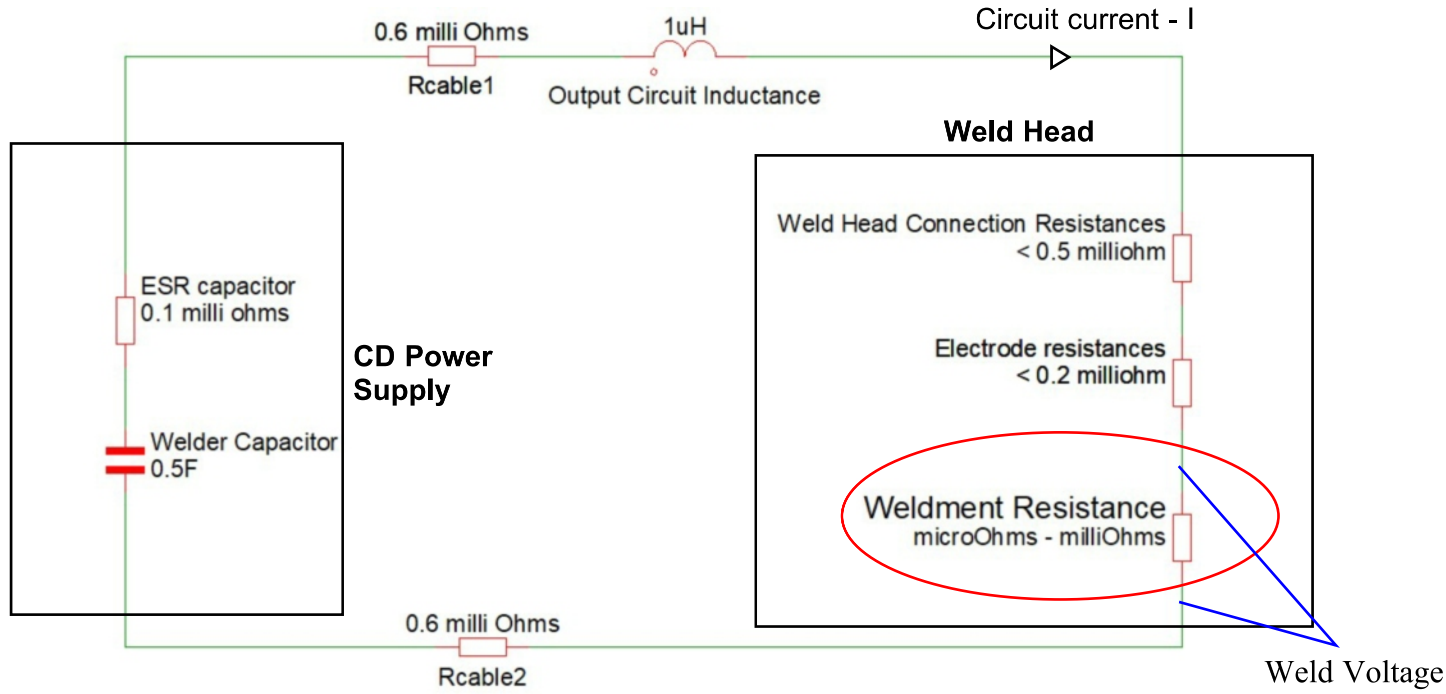

Fig 1 above shows the primary electrical aspects in a CD welder application setup. It can be seen that the welding current is driven in series through many elements that can effect it's amplitude.

N.B. For effective weld monitoring purposes, the heat energy at the weld must be measured as a combination of weld voltage and current as close as possible to the weldment.

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Data capturing challenges of a weld monitor - Speed and accuracy

In addition to having the ability to measure the real time voltage and current at the weldment, it is important for any weld monitoring system to be able to turn that information into an accumulated summation value that accurately represents the overall energy delivered.
In mathematical terms, this is known as the integral of power over time = Energy.

One of the real world challenges with digitally based measurement systems is in applying a suitable data sampling bandwidth coupled with an appropriate scaling system. In order to take make an accurate energy measurement, a digital system must sample each of the current and voltage measurements in small time increments and then multiply the values and add them to a running total. This takes computational power, with an accuracy that is intrinsically linked to the speed at which samples can be made along with the system signal to noise scaling accuracy.

As we know, with capacitor discharge systems, the welding pulses are relatively short in duration, perhaps a few milliseconds. This means, that if you want to digitally and accurately compute the total energy, you will require relatively fast sampling speeds in order to keep up with the weld pulse speed and to collect sufficiently accurate data with which to compute the answer.

Failure to sample fast enough and/or failure to operate with a meaningful signal to noise ratio, simply results in an approximation value which is then prone to the inaccuracies of not having enough data to work with.

Therefore without relatively powerful and hence relatively expensive real time digital sampling methods, basic digital analysis of fast signals as a basis for weld monitoring can and will be highly highly prone to measurement inaccuracies and thus, will degrade the weld monitors ability to detect real world changes at the weldment.

Data capturing challenges of a weld monitor - Scaling & resolution

Most CD welders allow user incremental adjustments of output level of perhaps 0.1J or 0.1%. As we have seen, these values are relatively meaningless in terms of quantifying the weld heat energy.

Process control is all about determining a working normal reference and then some upper and lower tolerance limits. As with making toast or a cup of tea, the working normal needs to be a fixed reference, but doesn’t necessarily need to have any units of measure, since that doesn’t really matter.

What really does matter in process control is the ability to clearly discern levels of change around the desired operating norm. With a piece of toast or a cup of tea, this is done visually by the human eye & brain.

For a weld monitor to work well, we have seen that it must accurately capture the actual weldment heat energy value with real time voltage and current measurements, but it must also be able to detect changes around the defined norm. A common challenge with digital capturing systems is in their ability to discern relatively small changes, or at least, proportionally small changes over a wide range of signals. Accurately capturing the energy in electrical spikes for a matter of microseconds requires high accuracy conversions with high sampling rates.

A CD welder with an output resolution of 0.1J provides a convenient output adjustment method but this should not be confused with an appropriate monitoring scale.

For example, if we have CD welder with 100 W/S output capability and 0.1W/S incremental adjustments, this gives us 1000 adjustment steps. From a weld monitoring standpoint, we know the actual energy appearing at the weld is lower and usually very different to the one potentially available at the output, so any weld monitoring should take this into consideration.

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Data capturing challenges of a weld monitor - Scaling and resolution continued

Furthermore, even if the output were the same as the weld energy, it should be clear that if you want to operate with a 5 W/S pulse, then a 0.1W/S increment represents a 2% change in value, whereas at 50W/S it would be just 0.2%.

Therefore, in order to implement an effective weld monitoring system, the weld monitor resolution and scaling should ideally be adjustable, so that changes in sensitive signals are effectively amplified in order to provide better resolution of signals and process limits.

Weld monitors that operate with a fixed electrical scale augmented with software scaling and graphical representations are by design, less able to discern small signal changes i.e. process changes.

At lower signal levels, the ratio of inherent electrical noise versus signal amplitude (signal to noise ratio) introduces further inaccuracies if mitigating physical amplifier gain changes are not also included.

As a simple example, if we scale a 4096 Amp signal with a 12 bit analogue to digital convertor, said convertor has 4096 steps. Ignoring quantization and sampling errors in the ADC itself, that's 1 Amp per step. If the ADC operates with a 4.096V signal reference, then that's 1Amp = 1mV. So if the system noise floor is at 10mV, the ability to measure 10 amps accurately becomes far more challenging and potentially erroneous, compared to pre-amplifying and scaling our 10 amp signal upward.

It is therefore important to understand and check the real measurement resolution, sampling speed and signal scaling capability of any weld monitoring equipment and to consider how this might affect it's ability to perform in your application and with your equipment.

Fig 2 - A mathematical model of a CD welder and weld head

$t := 0, 0.00001 .. 0.01 \quad Vin := 4 \quad L := 1\cdot 10^{-6} \quad C := 0.5$

$RCircuit := 1.5\cdot 10^{-3} \quad Rweld := 1\cdot 10^{-3} \quad Rtotal := Rweld + RCircuit$

$V(t) := Vin\cdot e^{\frac{-t}{Rtotal\cdot C}} \quad I(t) := \frac{V(t)\cdot\left(1 - e^{-Rtotal\cdot\frac{t}{L}}\right)}{Rtotal} \quad OutputEnergy := \frac{1}{2}\cdot C\cdot Vin^2$

$OutputEnergy = 4$

$TotalWeldEnergy := \int_0^{0.01} \left(I(t)^2\cdot Rweld\right) dt \quad TotalWeldEnergy = 0.739098$

$ENRG(t) := V(t)\cdot I(t) \quad ENRG(.005) = 2.146953$

$IHEAT(t) := I(t)^2\cdot Rtotal \quad IHEAT(.005) = 2.146945$

$iHeat := \int_0^{0.01} I(t)^2\cdot Rtotal\, dt \quad iHeat = 1.847745$

Available output energy is much larger than the total weld energy

4J compared to 0.739J at the weld

Volts x Current is the same as I²R

Much of the stored energy is lost as heat in other areas of the circuit - the remainder is used to drive the circuit inductance and is effectively lost.

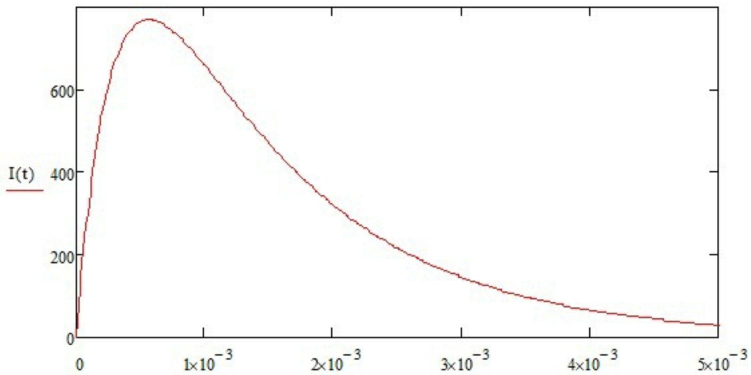

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Fig 3 - A mathematical model of a CD welder and weld head - no inductance

$t := 0, 0.00001 .. 0.01 \quad Vin := 4 \quad L := 1\cdot10^{-96} \quad C := 0.5$

$RCircuit := 1.5\cdot10^{-3} \quad Rweld := 1\cdot10^{-3} \quad Rtotal := Rweld + RCircuit$

$V(t) := Vin\cdot e^{\frac{-t}{Rtotal\cdot C}} \quad I(t) := \frac{V(t)\cdot\left(1 - e^{-Rtotal\cdot\frac{t}{L}}\right)}{Rtotal} \quad OutputEnergy := \frac{1}{2}\cdot C\cdot Vin^2$

$OutputEnergy = 4$

$TotalWeldEnergy := \int_0^{0.01} \left(I(t)^2\cdot Rweld\right) dt \quad TotalWeldEnergy = 1.6$

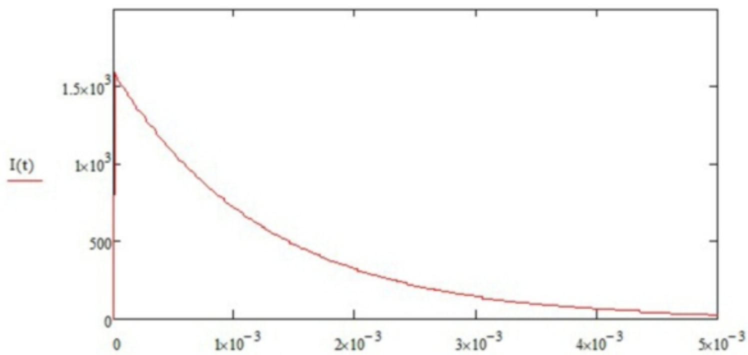
$ENRG(t) := V(t)\cdot I(t) \quad ENRG(.005) = 2.146961$

$IHEAT(t) := I(t)^2\cdot Rtotal \quad IHEAT(.005) = 2.146961$

$iHeat := \int_0^{0.01} I(t)^2\cdot Rtotal\, dt \quad iHeat = 4$

Inductance is artificially modelled as close to zero to show what happens

If there were no inductance, the weld energy would be much higher, the current rise time would be instantaneous and the total heating energy to the circuit would match the stored capacitor energy.



So what is welding circuit Inductance and why should you care ?

Inductance is the electromagnetic tendency for of an electrical conductor to oppose a change in the electric current flowing through it. A coil of wire has more inductance than a straight piece, so the physical layout of an electric circuit will affect it's inductance.

In welding where high currents are involved, the welding circuit inductance has the effect of limiting the rate at which current can rise. In a capacitor discharge application, the welding circuit resistance in combination with the available voltage from the capacitor bank, effectively determines the maximum current level. This comes from ohms law, V = current x resistance.

At the start of a capacitor discharge, the capacitor voltage is at it's maximum, hence the peak possible current is determined by the V / R = I. At the point of discharge, this maximum current would be instantaneous, going from nothing to maximum instantly. In reality, the circuit inductance acts to slow this rate of rise down, which in most cases is a good thing.

Capacitor discharge welders have the capability of achieving very high current levels, very quickly. This is a good combination when trying to weld highly conductive materials because the high current is able to generate more heat in a lower resistance at the weld by virtue of the I^2R rule.

The cabling and weld head inductance will play a significant part in determining how quickly the peak current can be achieved and since all the while the capacitor bank voltage will be decreasing, the overall peak current achieved will be set by the combination resistance and inductance in the circuit.

There are therefore tradeoffs to be had between achieving high peak currents, practical circuit inductances and rates of current rise that do not adversely effect electrode wear through micro arcing.

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Altering the inductance

Short, close together welding cables will create much less inductance compared with long, spaced out welding cables. Thus short tight cables are preferred for conductive material welding.

Knowing that fast current rise times and high peaks can add to the likelihood of micro arcing, arcs and sparks at the weldment and faster electrode wear; longer, wider cable layouts can be used to advantageously increase the circuit inductance for joints that are less conductive and/or less able to withstand fast thermal shocks.

With a higher inductance in the circuit, the electrode aggressive effect of fast current rise and high peaks can be reduced.

A quick note on electrode micro arcing

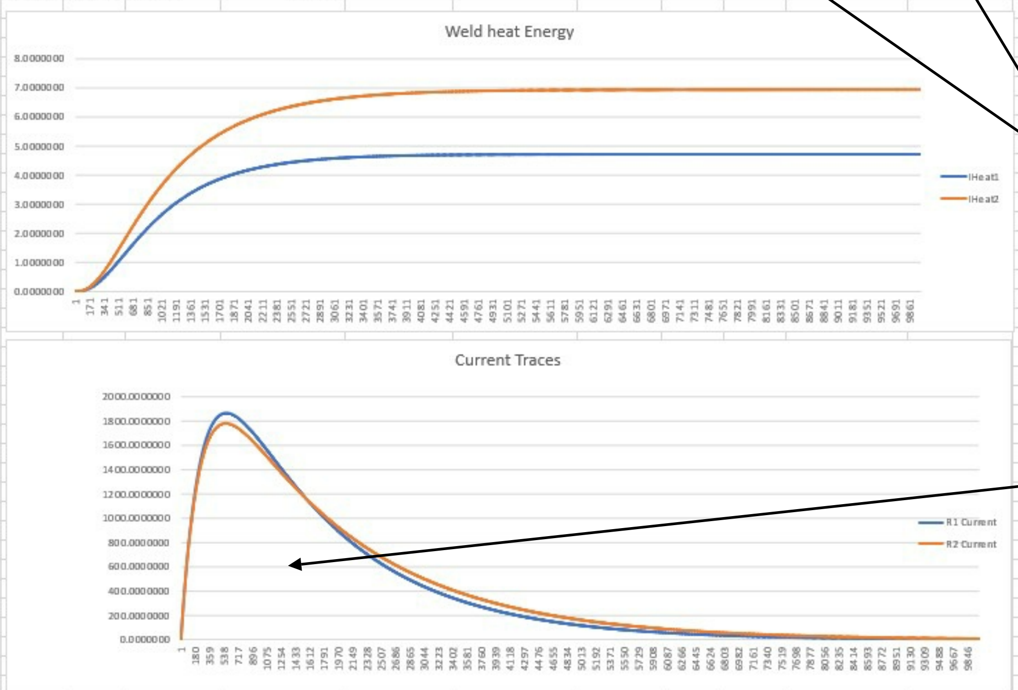
Electrode tip wear occurs through both mechanical work and electrical wear. Where high currents are passed, there is a tendency for micro arcs to develop on a microscopic level at the electrode surface, which ultimately cause surface degradation. This happens as a result of the contact area being unable to fully sustain the energy density at the microscopic peaks and troughs along the electrode surface.

As current is increased, so is energy density, hence higher currents tend to lead to more micro arcing and faster electrical degradation of the electrode tip. To counter these effects, welding force is often increased, forcing the contact points tighter together, but again, a balance must be found, since increasing the welding force, also decreases the resistance and hence decreases the heat energy for any given current level.

Finding an ideal balance of welding force versus contact resistance versus peak current usually forms part of a welding trial and helps to minimise the potential for unwanted arcs and sparks and the electrodes.

Fig 4 - A spreadsheet mathematical model of a CD welder and weld head

	Inductance	Capacitance	Supply Volts	Total Cct R	Rcct	Rweld		Pk Current	Tot Weld Heat Energy
Condition1	0.0000010	0.5000000	10.0000000	0.0030000	**0.002000**	**0.001**		1867.254	4.720
Condition2	0.0000010	0.5000000	10.0000000	0.0035000	**0.002000**	**0.002**		1782.473	6.943
Peak Current Change		-4.76%						Output Energy	25
% Heat Energy Change		32.02%							



Note : In knowing that peak current does not determine the peak weld heat energy, we can readily understand that simply monitoring the peak current will not help us visualise the capacitive discharge process.

In this example, we see a one milliohm increase at the weldment ; this decreases the peak circuit current by 4.76% BUT increases the weld heat energy by 32% !

The area under the curves in combination with the weldment voltage multiple, determines the welding heat energy.

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Weld energy heat density - the real process control parameter !

For the purpose of explanation, simplicity and general rule of thumb, this application note has described the process of generating and monitoring weld heat energy at the welded joint as a consequence of passing current through the weldment resistance.

For a DC micro spot welding process to be effective and consistent, it is clear that the weldment resistance should be kept as repeatable as possible from weld to weld. We may not know it's static and dynamic value, but we do know that if these values can be kept the same as far as possible, then the same amount of heat energy will be developed from weld to weld.

We may now have control and monitoring of our weld heat energy BUT we must also consider how that energy is used and dissipated.

The actual melt temperatures of the materials and the average weld temperature are going to be governed by the **weld energy heat density.**

In other words, if we take a certain amount of energy and focus it into a small area, then the energy density is going to be greater and hence, so is the temperature. Conversely, if we spread that energy out over a wide area, then the temperature will be lower.

The same also applies if we were to make the materials thicker for example, while still achieving the same resistance and using the same currents.

While it is outside the scope of this application note, consideration must be given to the physical electrode presentation to the items to be welded as well as the physical presentation and interface of those items to be welded, since these factors will affect the resistance.

Moreover, if the joint is not designed or presented correctly, then it is conceivable that the same energy level might be created in or over an area that is changing. If so, this would change the **weld energy heat density** and hence change the actual weld characteristics.

It is something to be aware of and represents a fundamental limitation for any type of electrical weld monitoring system. i.e. Even if we have a known current and a known resistance and hence a known heat energy, if exactly the same values could be achieved through adverse dimensional changes in materials and electrode setup, then a different physical weld can occur even though electrically, everything has stayed the same.

Furthermore, the dynamics introduced by the welding force applied will also affect how the weld takes place.

This is why proper process control in DC resistance welding MUST ALSO include understanding and proper control over weld head forces, electrodes, dimensions, materials and fit up.