

Overview of Resistance Welding

Introduction

In simplest terms, welding is a process by which two or more pieces of metal are joined by applying heat and pressure. Back in the good old days, blacksmiths and other crafty people would heat metals in a furnace and then weld them by hammering the red-hot metals together. By hammering the metals as they cooled, the weld would be made stronger. This heating-and-hammering method is known as forge welding. While forge welding worked quite well for most of the welding done back then, today's welding requirements are a bit more advanced. After all, it would be pretty difficult to heat all the metal needed to build an automobile in a big factory furnace and expect workers to hammer together each specific part used in the manufacturing process. We'd all still be riding horses to work!

Fortunately, there are always a handful of brilliant people throughout history who are kind enough to invent newer, faster, and better ways of doing things. One of these people was a professor by the name of Elihu Thompson. Sometime in the year 1885, Professor Thompson invented a process called electric resistance welding. He discovered that to weld metals together, one could fire an electric current through the metals while they were tightly clamped together. When the current passed through the metals, it would create such a high heat that the metals would melt and run together and a weld would be made. Many times, the welded metal would be even stronger than the original metals used in the welding process.

Today's resistance welders work almost exactly the same way they did when Thompson invented the process. The current is generated by a transformer, and is fired through electrodes, which hold the metal pieces in place. These electrodes also apply force to the metal pieces, usually before, during, and after the firing of the electric current. This method is called *resistance* welding because it is the resistance between the contact surfaces of the metals being welded that generates the heat to fuse them together.

Resistance is the opposition that a substance offers to the flow of electric current. The less resistance a metal has, the less heat is generated when current passes through it. Conversely, the higher the resistance of a metal, the more heat is generated when that same current passes through it. This behavior can be paraphrased as follows: the heat is where the resistance is, and the resistance is where the heat will be. Obtaining the best results in resistance welding requires a thorough understanding of the materials being welded, careful control of the heat and pressure at the weld point, and consideration of numerous other factors. This chapter will deal with the basics of resistance welding, the variables involved, and why they're so important to the welding process.

Variables in the Welding Process

The many variables involved in welding can be broadly categorized into two basic sections: process variables and material variables.

Process variables include:

- Weld current
- Squeeze time
- Weld time
- Hold time
- Electrode force
- Design of the electrode
- Workpiece material

Material variables include:

- Coating thickness and type
- Part fit-up
- Surface condition & cleanliness of materials

The Weld Cycle

A typical resistance weld is broken down into several distinct periods, as shown in figure 1-1 below:

The **Squeeze Time** is when the weld heads (electrodes) come together and build up to a specified amount of force before the current is fired.

The **Weld Time** is when the current is actually passing through the workpieces. This is when the metals are being heated enough to melt and fuse together to form what is called a weld nugget.

During the **Hold Time**, electrode force is still applied, even after the weld current has ceased. During this period, the weld nugget cools and the metals are forged under the force of the electrodes. The continuing electrode force helps keep the weld intact until it solidifies, cools, and the weld nugget reaches its maximum strength.

Critical Factors in Welding

Understanding the resistance weld process requires an understanding of the main factors involved and how they work together. This section will review current, voltage, resistance, and power, as well as the various functions of the electrodes and how they affect surface contact and current density.

Current

Current, usually measured in Kilo-Amperes (KA — one Kilo-Amp is equal to 1,000 Amps), is one of the most important factors. A resistance weld cannot be made unless there is sufficient weld current. According to the RWMA, the typical

amount of current needed to weld low-carbon steel, for example, is about 10,000 Amps (10 KA) at about 5 Volts. To put this in perspective, a normal household or office outlet provides a maximum of 15-20 Amps (0.015-0.020 KA) at 120 Volts, while a power circuit in a factory may only be capable of providing 200 Amps (0.200 KA) at 500 Volts to a welder. The factory's 200 Amps is then converted to the 10,000 Amps needed to weld by means of a welding transformer.

A transformer consists of two coils of wire, called the primary and the secondary, wound around an iron core. Power is transferred from primary to secondary via the magnetic properties of the iron. The factor by which the current and voltage is stepped up or down is equal to the ratio between the number of turns of wire in the coils forming the primary and secondary windings of the transformer. Consider the steel that needs 10,000 Amps (10 KA) of current to be welded in a factory that can only provide 200 Amps (0.200 KA). If the welding transformer had 100 turns on the primary and 2 turns on the secondary, the 'turns ratio' would be 100 to 2, or more simply, 50 to 1. The 200 Amp current in the primary would then be converted (stepped up) to 10,000 Amps (200 Amps x 50 turns = 10,000 Amps) in the secondary, which would yield enough amperage to make a weld.

Voltage

If current is the amount of electricity flowing, then Voltage (measured in Volts) is the pressure or force that's causing the flow. A good analogy is water flowing through a pipe. A larger voltage will result in greater water pressure, which will cause more water (current) to flow through the pipe. Using the transformer example above, after the 200 Amps at 500 Volts on the primary passes through the transformer coils, the secondary amperage increases to 10,000 Amps, but the voltage actually drops to 10 Volts. This decrease in voltage occurs because the amount of power coming out of a transformer isn't actually *increased*, but more accurately *exchanged*.

Power

Power is Voltage multiplied by Current, and is measured in Watts, or KVA (KVA stands for Kilo-Volt-Amperes. Watts and KVA will be used interchangeably in this text). This means that the amount of current flowing times the pressure that's causing it to flow equals the amount of power generated. A basic law to bear in mind is that the power going into a transformer will always equal the power coming out of it. Returning to the transformer example, 200 Amps coming in at 500 Volts ($200 \times 500 = 100,000$ KVA) on the primary with a 50 to 1 turns ratio in the transformer will be converted into 10,000 Amps at 10 Volts ($10,000 \times 10 = 100,000$ KVA) going out. As the math illustrates, the results are the same. The initial and final amperage and voltage may be different, but because the ratio is the same, the total amount of power is also the same.

Resistance

As mentioned earlier, resistance is defined as the opposition that a substance offers to the flow of electric current. Resistance is calculated by dividing the

Voltage by the Current, and is measured in Ohms. (When written, Ohms are represented by the Greek letter Omega: Ω). Since resistance to the current is what generates the heat in the workpiece, it is critically important that the area with the greatest resistance be at the interface between the two parts being joined. This interface is also known as the faying surfaces. Remember that the heat is where the resistance is, and the resistance is where the heat will be. If the area with the most resistance is, for example, where the lower bus bar connects to the transformer of the welder and *not* at the faying surfaces of the workpieces, then that's where the heat will go. Likewise, if the greatest resistance is at the contact area between the electrode tip and the workpiece, the heat generated there will cause the tip to weld directly to the workpiece.

Electrodes

Typically made of copper alloys, electrodes actually have three separate functions: to conduct current to the workpieces being welded, to transmit the proper pressure or force to those workpieces to produce and forge a good weld, and to help dissipate heat from the area being welded. To ensure that all three of these functions are executed properly, it is important to regularly maintain the electrodes, keeping them clean and in good condition. A reprint of an RWMA chart describing various types of electrode materials and their different uses may be found on page 11-36 in the Appendices of this manual.

Conducting Current

The first of these functions is purely electrical— fire weld current through the workpiece. Taking into account the relationship among current, voltage and resistance, it becomes important to pay attention to the type of electrodes used. For example, it wouldn't be wise to select electrodes made entirely from a high resistance material, since they would get so hot they'd melt before the current even had a chance to flow to the workpiece. It is also important to make sure that the electrodes are the right size for the application; proper electrode sizing is largely dependent on the amount of force being used on the workpieces.

Transmitting Force

The second function of the electrodes is mechanical. The amount of force needed to make a good weld varies, depending on the type of metal being welded and other factors, but a general figure would be about 600-800 lbs. Because electrodes are typically on the small side— roughly from about the size of an acorn to the size of a plum, it is also important to choose electrodes that are able to withstand the force needed to make a good weld.

A key point to understand is that force and resistance have an inverse relationship: more force will result in less resistance, and vice-versa. The equation has to do with surface contact, which refers to the specific area on the workpieces touched by the electrodes. Surface contact will be covered further in the next section, but the following example will begin to illustrate this relationship: if you examine your fingertip under a magnifying glass, what first appears to be a

smooth surface is actually a mass of rough-looking ridges and bumps. The same is true of electrodes and workpieces. The tips of the electrodes and the surfaces of the workpieces may look to be smooth and in good condition, but in reality their surfaces are quite rough, especially if the electrodes are old and worn or if the workpieces are dirty. By applying pressure to these rough surfaces, any microscopic inconsistencies (e.g., dirt or grease on the workpiece and/or pits and cracks in the electrodes) are compressed and the surface actually evens out. This results in improved (increased) surface contact between the electrode tips and the workpiece, and between the workpieces themselves. When the surface contact is increased, current can flow more readily from the tips through the workpieces, which means that the resistance has been lowered.

Force also is what helps to keep the weld intact as it's being formed. As the current generates heat, the workpiece metal begins to melt. A good analogy to this process is a child eating a popsicle on a hot summer day. When the popsicle melts, it doesn't remain on the stick-- it drips everywhere. When metal melts it wants to do the same thing, however because it's molten metal and not a runny popsicle, it doesn't simply drip. It *explodes* out of the workpiece. This is why proper weld force is so important: it literally forces the molten metal to stay put, so it can then cool to form a weld nugget. Without sufficient force, the metal will do what it wants to do, which is what causes expulsion. Expulsion is nothing more than little pieces of molten metal exploding out of the weld because they're not being properly held in. The problem with expulsion is that all the metal flying *out* of the weld is metal that's not going *in* to the weld; a weld cannot be made stronger by removing metal from it. Determining the proper amount of force is entirely application dependent. The RMWA can be contacted for additional recommendations and guidelines.

Cooling the Workpiece

Electrodes get considerably hot with 10-20 KA or more repeatedly flowing under hundreds of pounds of force. Although most welders have an internal water cooling system that allows water to circulate through the tips of the electrodes while welds are being made, a common problem is a lost, damaged or improperly sized cooling water tube. Without anything to cool off the tips, heat can quickly build up to the point where the electrodes will eventually weld to the workpieces. To correct this problem, the water tube should be placed so that the incoming cold water strikes the hottest part of the tip first, as shown in figure 1-2.

Surface Contact

The ultimate goal of the weld process is for the weld current to generate sufficient heat between the workpieces being welded so that the metal will melt, fuse together and form a weld nugget. For this to happen, the surface contact must be maximized. The following experiment may sound silly, but proves an important point: take a piece of Scotch tape and stick it to a clean piece of paper. Assuming that the tape was clean beforehand, it probably sticks very well. Now sprinkle some salt on the piece of paper. Stick another piece of tape to the paper with the

salt on it. Depending on how much salt is there, the tape probably sticks somewhat to not at all. Lastly, stick a third piece of tape to some carpeting, then pull it off. Now try to stick that same tape to the paper. The third piece probably doesn't stick at all.

Compare the electrodes to the tape and the workpiece to the paper. The clean tape sticks best to the clean paper, just like well-maintained, clean electrodes have the best contact with a clean workpiece. The tape sticks so-so to the paper with the salt on it, just like electrodes will have a so-so contact with the workpiece if it's dirty, greasy, etc. Lastly, the tape that has been stuck to the carpet and then restuck to the paper probably doesn't stick well at all, just like worn or pitted electrodes don't have very good contact with the workpiece. By maximizing the surface contact, current density is increased. Both of these factors play key roles in ensuring that enough heat is generated to reach that ultimate goal of forming a weld nugget.

Current Density

Current density describes how much current is being delivered to a specific area. In other words, it describes the concentration of the current in a small area of the workpiece—namely, the area where the weld is. To calculate current density, the amperage (how much current) is divided by the surface area (area of contact between the electrode and the workpiece). As a rule, the smaller the surface area, the denser the current. When the current is denser, the surface area gets hotter and the metal melts faster. Consequently, a current density that is too high for the application may cause expulsion. In contrast, a larger surface area delivers a less dense current. If the current density is too low for the application, there may be cold welds or perhaps no welds at all.

The size, shape and overall condition of the electrodes affect the surface area in contact. Small pieces missing from the tips of the electrodes (pitting) will result in an increased current density due to the decreased surface area. The same amount of current fired through a smaller surface area may cause little hot spots that expel molten metal (expulsion), and/or may result in undersized weld nuggets. Conversely, if the electrode tips mushroom and get bigger, the current density is lower. For example, suppose that there are 6-mm round tips on a welder. The area of each tip is about 28 mm². (The area of a circle is πr^2 : $3^2 \times 3.14 \approx 28$). Suppose the tips deliver 10 KA to a workpiece. Current density equals the amperage divided by the surface area, so the current density will be 0.36 KA, or 36 Amps for every millimeter squared of surface ($10 \text{ KA}/28 \text{ mm}^2 = 0.36 \text{ KA/mm}^2$). What happens if the tips mushroom to measure 7-mm (about 0.040 inches greater in diameter)? Although one millimeter doesn't seem like a significant increase, consider what happens to the current density: The 7-mm tips now have a surface area of about 38 mm² ($3.5^2 \times 3.14 \approx 38$). Dividing the amperage by the surface area results in 0.26 KA or 26 Amps for every millimeter squared of surface. The difference between 36 Amps per mm² and 26 Amps per mm² is a rather significant 28% reduction in current density! ($36 \text{ Amps} - 26 \text{ Amps} = 10$

Amps difference; 10 Amps is 27.78% of 36 Amps).

By allowing the electrodes to mushroom only one millimeter bigger, over a quarter of the current density has been lost, even though the same amount of current is passing through the tips. Imagine the size of the loss if they've mushroomed 2, 3, even 4 millimeters! A constant current control or a weld stepper may be used to regulate the amount of current used, but a controller or stepper does not track the change in surface area. So, even though the *current* is regulated, the *current density* is overlooked. Unfortunately, inadequate current density usually produces inadequate welds. Following proper preventive maintenance schedules can help ensure sufficient current density by ensuring that the electrodes remain in good condition.

As proven in the example above, it is crucial to have the proper current density at the area where the weld is to be made. Depending on the materials being welded, however, 'proper' current density is actually a range, rather than one specific amount. Welding engineers call this range the *weld lobe*. Each parameter involved in making the weld (current, voltage, resistance, etc.) has its own range, or lobe. Quality welds are made when the weld process stays within the lobe. The next chapter will discuss weld lobes and *tolerancing*, which is a way to ensure that the weld process does not fall outside of the lobe.

Ohm's Law and Joule's Laws

The following laws are widely thought to be what make or break resistance welding. While it is true that these laws are very important to resistance welding, there are a few details that should be clarified.

Ohm's Law states that V (Voltage) = I (Current) \times R (Resistance).

What does this mean in real-world terms? Returning to the pipe example, the more water pressure there is in a pipe (more voltage), the more water can flow through that pipe (more current). If the size of the pipe decreases (more resistance), then the water flow will decrease (less current) but the pressure drop along the pipe will increase (more voltage).

Joule's Law states that H (Heat) = I (Current) \times V (Voltage) \times T (Time the current is allowed to flow).

Or, written differently,

H (Heat) = I^2 (Current squared) \times R (Resistance) \times T (Time the current is allowed to flow).

Note: V (Voltage) = I (Current) \times R (Resistance), so the two equations are the same, just stated differently. The second version of this law is probably more common in the field.

Joule's Law is an equation that gives the amount of heat (energy) delivered to *something*. It would seem sensible to assume that it's the amount of heat delivered to the weld. However, it is important to consider all the factors in the equation: Current, Voltage, and Time. Joule's Law assumes that each of these factors remains constant in the secondary of the welding transformer. A weld controller or weld timer may indeed provide a constant amount of current at the electrodes, but recall Ohm's Law: Voltage equals Current times Resistance, or written differently, Current equals Voltage divided by Resistance. Factors like pitting or mushrooming of the electrodes, dirty workpieces, changes in force, etc. all have an effect on the surface area (the area of contact) between the electrode and the workpiece. Since changes in the surface area affect the contact resistance (resistance of the surface area), it is reasonable to say that the resistance at the workpiece is not constant, but rather a factor that can change depending on a number of other conditions. If Resistance is not constant, then according to Ohm's Law, Current is not constant either. This means that the I-squared version Joule's Law will not reveal the amount of heat generated at the workpiece unless the resistance at the tips is known.

Simply put, to determine how much heat is being generated at the workpiece using Joule's Law, current, voltage or resistance must be measured at the workpiece. Although a weld controller may be programmed to deliver 20 KA at 10 Volts, if there is significant resistance in the secondary weld loop, the heat will go there and not to the workpiece. Likewise, if the electrodes are worn or the workpiece is dirty, resistance and current density will be affected. In such a situation, a controller might indicate 10 Volts at the secondary, however there might actually be only 5 Volts at the weld tips. Such a disparity could easily cause bad welds.

Identifying and Correcting Weld Problems

A simple rule to remember is that quality usually equals consistency: welds that are always made within the specified weld lobe will consistently be of high quality. The question is, how can you determine if welds are being made consistently within the lobe? If a weld control is programmed to deliver a certain amount of current at a certain amount of force, how can you ensure that the right amount of current and force was delivered at the tips? The amount of current coming out of the transformer may be correct, but is the current density at the workpiece where it should be? How do you know if the weld is good? The most common method of answering these questions is through destructive testing. It's hard to dispute the quality of a weld after it has been pulled apart and inspected. However, destructive testing produces a lot of scrap metal, and while it will reveal whether the weld is good or bad, it cannot explain the specific details of why or how a weld turned out the way it did.

Resistance weld monitoring provides a way to see what is happening while each weld is being made. Critical parameters, such as resistance and current density,

can be observed and measured *at the workpiece* during the weld process. The next chapter will discuss how this process works. The following is an abbreviated guide of commonly encountered welding problems and their possible causes, adapted from documents published by the Resistance Welder Manufacturers' Association and reprinted with permission.

Recommendations for Producing Quality Welds

To produce high quality welds consistently, follow these tips:

1. Be sure that the electrodes you are using are suitable for the job.
2. Use standard electrodes whenever possible.
3. Select an electrode tip diameter suited to the thickness of the stock being welded.
4. Make use of flow indicators for viewing and assuring proper cooling water flow through the electrodes (typically, 1.5 gallons per minute).
5. Ensure that the internal water cooling tube of the holder projects into the tip water hole to within $\frac{1}{4}$ inch of the bottom of the tip hole.
6. Adjust the internal water-cooling tube of the holder to the appropriate height when switching to a different length tip.
7. Ensure that the top of the adjustable water-cooling tube in the holders is the proper height when changing to a different tip length.
8. Coat the tip with a thin film of cup grease before placing it in the holder to simplify removal.
9. Use ejector type holders for easy tip removal that won't damage the tip walls.
10. Clean the tip taper and holder taper on a regular basis, removing any foreign materials.
11. Perform dressing of electrodes on a regular basis to maintain the correct contour.
12. Use a rubber mallet to align holder and tips, rather than a metallic tool.

Avoid these potential sources of weld problems:

1. Never weld using unidentified electrodes or electrode materials.
2. Avoid using special-purpose or offset tips if the job can be handled with a standard straight tip.
3. Do not use a small tip for welding heavy gauge materials or a large tip on small piece.
4. Do not overlook turning on the cooling water to the appropriate force when beginning to weld.
5. Never use a water hose that does not firmly fit the water connection nipples.
6. Avoid leaky, clogged or broken water connections.
7. Do not use holders that have leaking or deformed tapers.
8. Do not use electrode holders without an adjustable internal water cooling tube.
9. Avoid leaving the electrodes unused in tapered holder seats for long periods.
10. Do not use pipe wrenches or similar tools when removing electrodes.
11. Never dress an electrode using a coarse file.

These recommendations can help improve the quality and consistency of your welds. For more information, you can contact the RWMA or AWS directly:

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