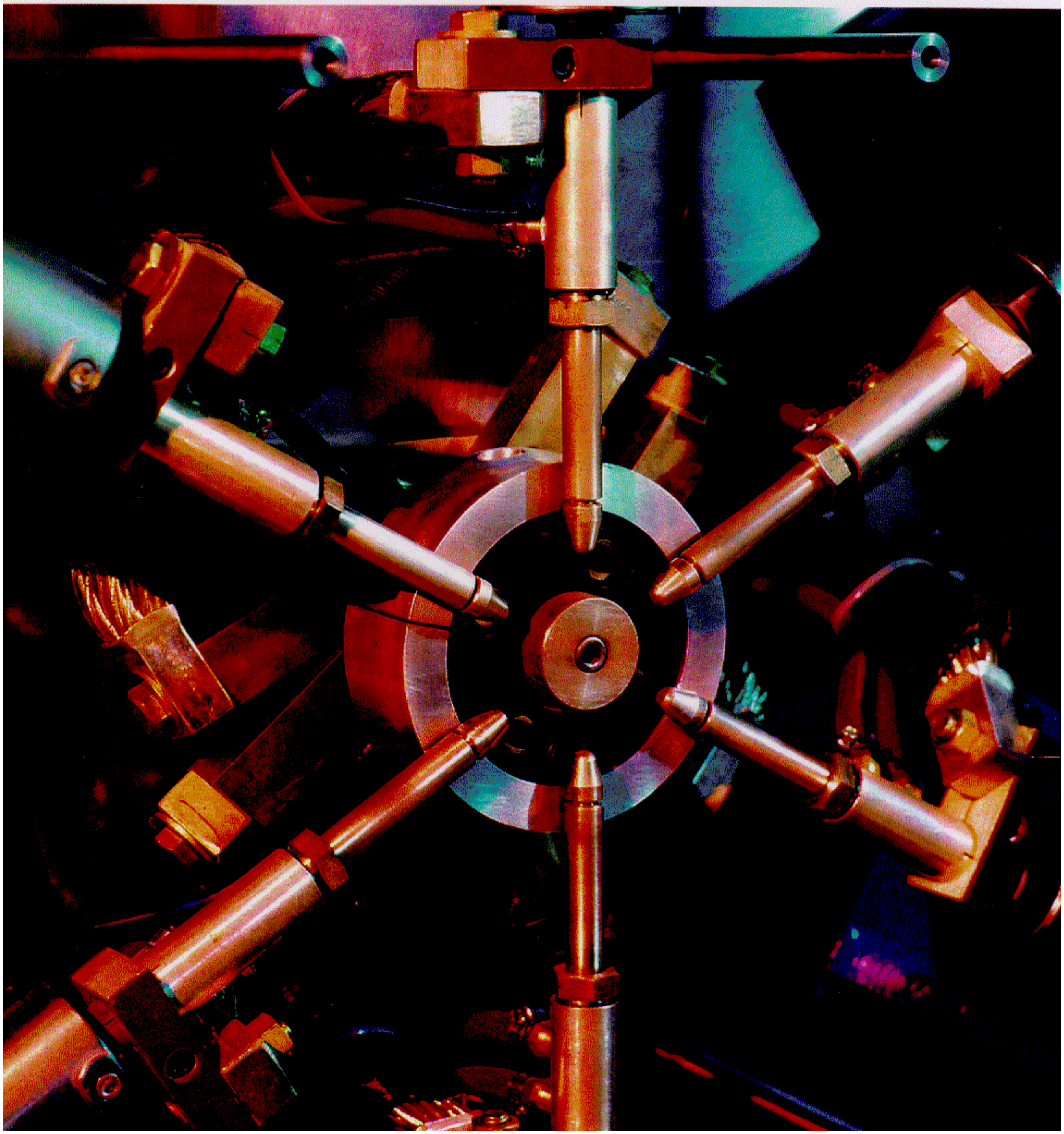
Applying Joule's Law to resistance welding

How current, time, and resistance affect heat energy



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By Robert Cuff

For two metals to be joined by resistance welding, they must be clamped together under pressure, and an electric current must be passed through them for a specific time. The heat generated creates a plastic state and produces fusion at the interface surfaces.

The resistance welding process involves some basic laws of physics and mechanics that must be understood for quality welds to be made consistently. Although the derivation of these basic laws may require some knowledge of mathematics, the impact on the resistance welding process can be demonstrated with very simple explanations and examples.

One of these basic laws is Joule's Law. This law is used to define the heat energy (generated by the flow of electric current through the workpiece) applied to form a weld nugget in the resistance welding process.

Joule's Law states that 1 joule is the heat energy produced when 1 amp of electric current flows through a resistance of 1 ohm for 1 second of time.

The equation for Joule's Law is stated as:

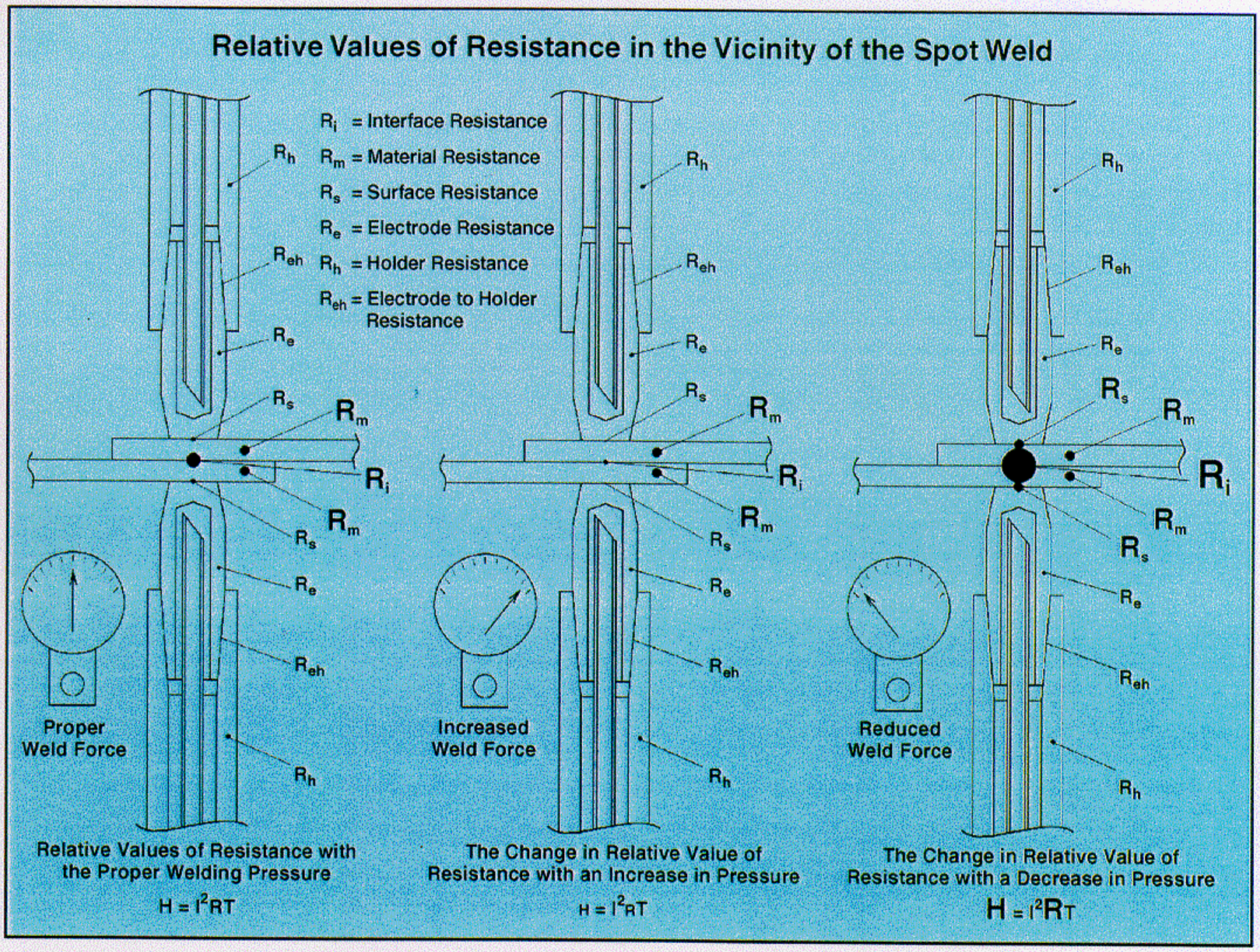
$H = I^2RT$

where: H = heat energy
I^2 = square of the value of the current in the circuit
R = resistance in the circuit
T = amount of time the current flows through the circuit

Joule's Law makes the resistance welding process work. Changes in I^2, R, or T allow changes in the value of H. Simply, as I^2, R, and T vary, so does H.

To demonstrate how Joule's Law works, a schedule for welding 16-gauge mild steel will be used here, with selected values taken from a weld schedule chart for spot welding mild steel.

A weld schedule for 16-gauge mild steel may recommend a current (I^2) of 10,000 amps and a weld time (T) of about 12 cycles (0.2 second). Assuming that for the weld force required, the



Relative Values of Resistance in the Vicinity of the Spot Weld

Relative Values of Resistance with the Proper Welding Pressure
$H = I^2RT$

The Change in Relative Value of Resistance with an Increase in Pressure
$H = I^2RT$

The Change in Relative Value of Resistance with a Decrease in Pressure
$H = I^2RT$

material and interface resistance (R) would be about 1 ohm, then Joule's Law would produce heat energy (H) of about 20,000,000 joules:

20,000,000 joules = 10,000 amps^2
x 1 ohm x 12 cycles (0.2 second)

How Current Affects Heat Energy

What would happen to the heat energy in this formula if the current were much larger than shown in this equation? H would become larger because of the increase in I^2.

Using the same values for resistance and weld time but increasing the current to 14,000 amps, the heat energy would increase to 39,200,000 joules, or almost double the heat energy of the previous example. This is a case of overwelding that could produce severe metal expulsion:

39,200,000 joules = 14,000 amps^2
x 1 ohm x 12 cycles (0.2 second)

If the current in the circuit is reduced, the heat energy also is reduced.

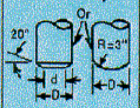
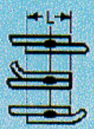
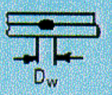
Again, using the same values for resistance and weld time but decreasing the weld current to 7,000 amps, the heat energy decreases by about half, to 9,800,000 joules. This could result in underwelding or no weld at all:

9,800,000 joules = 7,000 amps^2
x 1 ohm x 12 cycles (0.2 second)

Maintaining the Same Heat Energy

Changes in current, resistance, or weld time directly affect the heat energy in the weld. However, in the previous examples, as the current changed, heat energy could have been kept the same by adjusting one of the other variables: resistance or time.

In the first example in which current increased, if weld time had been reduced, the net value of heat energy would not have changed. Increasing the current to 14,000 amps and reducing the weld time to 6 cycles can produce about the same heat energy to make a good weld as produced in the

Thickness "T" of Thinnest Outside Piece	Electrode Diameter and Shape 		Net Electrode Force	Weld Time (Single Impulse)	Welding Current (Approx.)	Minimum Contacting Overlap 	Minimum Weld Spacing ℄ to ℄	Diameter of Fused Zone 	Minimum Shear Strength Lb. Ultimate Tensile Strength of Metal		Thickness "T" of Thinnest Outside Piece
In.	D In. Min.	d In. Max.	Lb.	Cycles (60 per Sec.)	Amps	In.	In.	In., Approx.	Tensile Strength Below 70,000 PSI	Tensile Strength 70,000 PSI & Above	In.
0.010	3/8	1/8	200	4	4,000	3/8	1/4	0.10	130	180	0.010
0.021	3/8	3/16	300	6	6,500	7/16	3/8	0.13	320	440	0.021
0.031	3/8	3/16	400	8	8,000	7/16	1/2	0.16	570	800	0.031
0.040	1/2	1/4	500	10	9,500	1/2	3/4	0.19	920	1,200	0.040
0.050	1/2	1/4	650	12	10,500	9/16	7/8	0.22	1,350	-	0.050
0.062	1/2	1/4	800	14	12,000	5/8	1	0.25	1,850	-	0.062
0.078	5/8	5/16	1,100	17	14,000	11/16	1 1/4	0.29	2,700	-	0.078
0.094	5/8	5/16	1,300	20	15,500	3/4	1 1/2	0.31	3,450	-	0.094
0.109	5/8	3/8	1,600	23	17,500	13/16	1 5/8	0.32	4,150	-	0.109
0.125	7/8	3/8	1,800	26	19,000	7/8	1 3/4	0.33	5,000	-	0.125

Notes:

1. **Type of steel – SAE 1010.**
2. **Material should be free from scale, oxides, paint, grease, and oil.**
3. **Welding conditions determined by thickness of thinnest outside piece "T".**
4. **Data for total thickness of pile-up not exceeding 4 "T", maximum ratio between two thicknesses 3 to 1.**
5. **Electrode material** **Class 2**
   Minimum conductivity **75% of Copper**
   Minimum hardness **75 Rockwell "B"**
6. **Minimum weld spacing is that spacing for two pieces for which no special precautions need be taken to compensate for shunted current effect of adjacent welds. For three pieces, increase spacing 30 percent.**

Figure 2
Sample of a weld schedule table for single-impulse (spot-sequence) welding of low-carbon steel.

first example—in this case, 19,600,000 joules:

19,600,000 joules = 14,000 amps^2
x 1 ohm x 6 cycles (0.1 second)

In the second example in which the current decreased, an increase in the weld time would have resulted in the same heat energy to the weld. In this example, the current is reduced to 7,000 amps, and the weld time is increased to 24 cycles. However, the heat energy to the weld remains the same:

19,600,000 joules = 7,000 amps^2
x 1 ohm x 24 cycles (0.4 second)

Changes in Resistance

Weld time generally is easy to control and can be held constant at any setting by today's welding controls. Voltage and power factors also are well-regulated by controls. The current output can be made constant within a small error, possibly within ±3 percent.

Generally, resistance is the most difficult variable to control and may vary considerably. Variations in the weld force applied to the workpieces and the size and shape of the electrodes may contribute to a variation in the heat energy applied to the weld.

Too great a weld force can reduce the resistance at the interface between the workpieces. At this point, the greatest amount of heat energy should be generated, but the resistance becomes too small to create the heat energy necessary to make a weld. Even though both weld time and current are constant, the decrease in resistance results in a decrease in heat energy.

In the previous examples, if the current and the weld time are held constant at 10,000 amps and 12 cycles, respectively, but the force is increased to reduce the resistance to only 0.5 ohm, then the heat energy would be reduced by one-half:

10,000,000 joules = 10,000 amps^2
x 0.5 ohm x 12 cycles (0.2 second)

Weld time generally is easy to control and can be held constant at any setting by today's welding controls.

In fact, the force can be increased to the point at which insufficient heat energy is generated to make a weld, even though the current and weld time are of the correct values to weld the materials to be joined.

The opposite is also true. A decrease in the welding force increases the resistance to the point at which the results may be dramatic metal expulsion caused by the increase in heat energy.

Again, the values of current and weld time are held constant but the resistance is doubled to 2 ohms, doubling the heat energy to 40,000,000 joules:

40,000,000 joules = 10,000 amps^2
x 2 ohms x 12 cycles (0.2 second)

This, of course, produces a serious hazard to workers from possible metal expulsion and would damage the material being welded and the electrodes. **Figure 1** demonstrates what these changes in resistance can be. In some cases, they may be dramatic.

Electrode Maintenance

Proper electrode maintenance is important in making consistently good welds. As the face of the electrode wears and becomes larger (electrode mushrooming), the heat energy of the welder is dissipated over a larger area. Current density decreases, and the heat energy per unit area at the face of the electrode decreases, producing poor weld nugget quality.

Proper water cooling of the welding electrodes or fixtures is absolutely necessary. If the electrodes are not sufficiently cooled, they will begin to heat, increasing their resistance to the flow of the welding current. It is possible for the resistance of the electrodes to become greater than the resistance of the workpieces and the interface resistance between the workpieces.

Joule's Law applies to creating heat energy at the workpieces, but it also applies to other remittances in the circuit through which the current must flow. Therefore, heat energy also will be dissipated in the heated electrodes. In fact, enough heat may be dissipated in the electrodes to prevent a weld from being made between the workpieces.

Selecting and Changing Weld Schedules

When selecting a weld schedule for a particular material of a given thickness and strength, the following rule of thumb should be used:

The *lowest* welding transformer tap switch setting at the *highest* percent current setting on the weld control for the *shortest* weld time setting

Selecting the correct relationship between current, resistance, and time will allow Joule's Law to work to provide the correct amount of heat energy to the weld. It also helps produce the most efficient electrical, mechanical, and thermal operating conditions at the machine.

The Resistance Welder Manufacturers' Association (RWMA) and the American Welding Society (AWS) publish tables of recommended schedules for weld setup. These tables are based on the application of Joule's Law to the resistance welding process. They provide for the proper relationship between current, pressure, and time for a setup to make good welds.

Figure 2 shows a sample of a weld schedule table for single-impulse (spot-sequence) welding of low-carbon steel. Tables of schedules for welding other materials and for multiple-impulse welding and seam welding also are published.

Changes can be made to these weld schedules that won't jeopardize good weld quality. For example, for a specific production scheduling requirement, perhaps the weld time must be reduced to increase a given production rate.

If the weld time were decreased from the published time on the table, then the welding current could be increased accordingly to provide the same total heat energy to the weld. Likewise, the weld force could possibly be reduced slightly, increasing the interface resistance and thus increasing the heat energy into the weld.

With a knowledge of Joule's Law, it becomes apparent that in almost every instance it is better to adjust the percent current than the time. The current is a squared function, so a small change in the percent current results in a larger increase or decrease in the total power, or energy, into the weld.

Increasing time has a lesser effect on the total power and may introduce another source of energy loss. As the weld time is increased, the thermal considerations of the system come into play.

The workpieces are thermal conductors and will begin to conduct heat energy away from the weld area during the longer time. Water-cooled electrodes also become less efficient in conducting heat away from the weld as time is extended.

Making Joule's Law Work

Welders can make Joule's Law work by having a better understanding of the relationship of current, circuit resistance, and time. With the correct variable choices, welders can use Joule's Law to produce the proper amount of heat energy at the weld and make consistently better welds. ■

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