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## KEYNOTE ADDRESS

# Resistance Welding: A Fast, Inexpensive and Deceptively Simple Process

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### Abstract

Even though resistance welding has been used commercially for nearly a century and is one of the most widely used forms of fusion welding, relatively little fundamental research has been performed on this process. The process involves mechanical, electrical and thermal energy flows, each of which is coupled intimately with the others. This makes the process extremely difficult to model mathematically; nonetheless, a number of key features which should be included in a model of the process are discussed. These include current type and distribution, electrode geometry, thermoelectric effects, contact area, tip wear, as well as heat generation and dissipation.

SINCE ITS INVENTION BY ELIHU THOMSON over 100 years ago, resistance welding has become widely used in the manufacture of a host of products ranging from automobiles to assembly of small parts. It is presently used to join sheets ranging from approximately 10 micron foils to nearly one centimeter thick plates or to join rods and bars end to end; Recent advances in stored energy devices permit areas of more than 50 square centimeters to be joined (1). Currents range from hundreds of amperes to well over one million amperes with typical welding times of a millisecond to a second.

On first inspection, the resistance welding process is relatively simple. Two metals, of various geometries, are squeezed together and an electric current of 10,000 to 100,000 amperes per square centimeter is passed. The greater electrical resistance of the interface, as compared with the bulk metal, creates preferential heating which produces melting, fusion, and the formation of a weld upon solidification. When the equipment is properly maintained, the process is generally reproducible and reliable. In considering the power densities which are achieved, Fig. 1 shows the equipment is relatively inexpensive, and hence more productive than most other welding processes (2). For these reasons, over 100 billion resistance welds are produced each year to assemble sheet metal for automobiles, and trillions of additional welds are produced for a wide variety of industries.

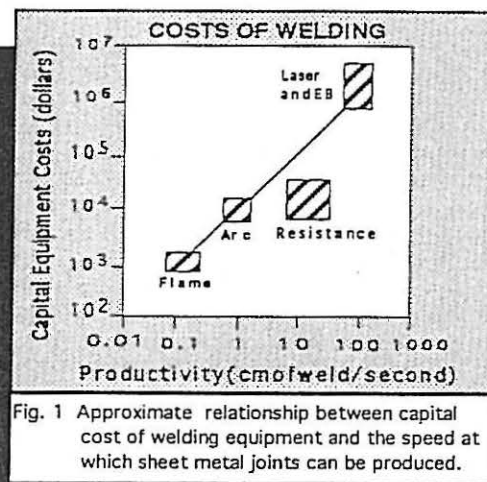


Fig. 1 Approximate relationship between capital cost of welding equipment and the speed at which sheet metal joints can be produced.

Resistance welding is one of a number of important joining processes that has received relatively little scientific investigation in spite of its widespread use. In the United States, the intellectual focus of the process resides with the Resistance Welding Manufacturers Association, which is composed primarily of electrical engineers who have interests in equipment design rather than process physics or materials behavior. Most users approach the process empirically, adjusting parameters more or less at random until a good weld is obtained. There is relatively little research money to improve or better understand the process since it usually works well; there is a philosophy of, "If it isn't broken, don't fix it."

In fact, the more one studies the resistance welding process, the more one appreciates how complex the process is. There are coupled electrical, mechanical and thermal energy flows, none of which is constant enough or independent enough to be studied separately. All but the most simplistic mathematical models of the process quickly exceed the capabilities of the largest supercomputers. The process creates temperature gradients on the order of 100,000 degrees per centimeter with heating rates exceeding 10<sup>5</sup> degrees per second and cooling rates only marginally lower. For all of its widespread use and apparent simplicity, the resistance welding process is exceeding complex.

Attempts to control the process range from simple monitors of a given parameter to computer codes and sensors which have cost millions of dollars to develop. Inspection of the final product is often cursory since the most reliable test methods are destructive and those that are not destructive often exceed the cost of the weld itself. It is generally more cost effective to produce two or three resistance welds than to inspect a single weld. For this reason, a given assembly may contain "one thousand welds because five hundred good welds are required".

In this paper, some of the key physical features of the resistance welding process are described with the hope that this description will encourage others to more fully investigate the process, as well as to assist practitioners in understanding some physical observations.

## Physics of the Process

As noted above, resistance welding involves mechanical clamping of two pieces of metal, with subsequent passage of electric current to generate heat which produces melting. As a result, the process includes mechanical, electrical and thermal energies which are intimately coupled. An important part of the complexity of the process is related to the interactions among these energies. In the following sections, a number of the factors are discussed. Most of these factors are described with respect to resistance spot welding of two sheets as this is the most commonly studied geometry. Nonetheless, much of the discussion relates to other electrode/material geometries as well.

The general geometry and nomenclature of the process are shown in Fig. 2 below.

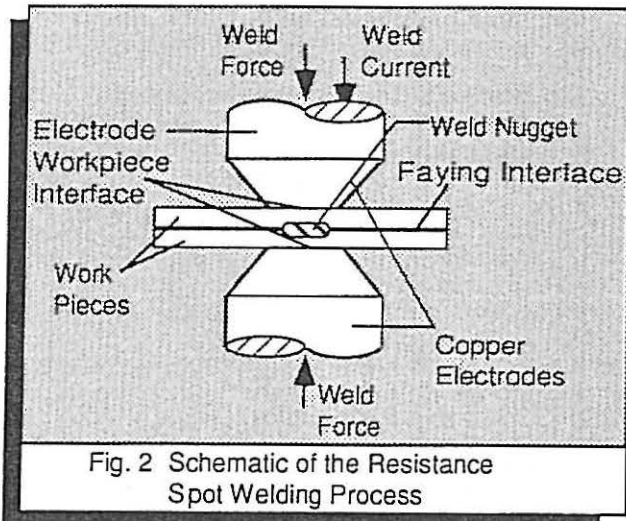


Fig. 2 Schematic of the Resistance Spot Welding Process

As shown in Fig. 3, heat is generated through a series of resistances which includes the electrode-workpiece interface resistance, the bulk resistance of the metal, and the faying interface resistance. When copper-base electrodes are used, the Joule heating of the electrodes can generally be neglected (except when welding other high electrical conductivity metals).

Heat flows throughout the assembly governed by the thermal resistances analogous to a series of electrical resistances.

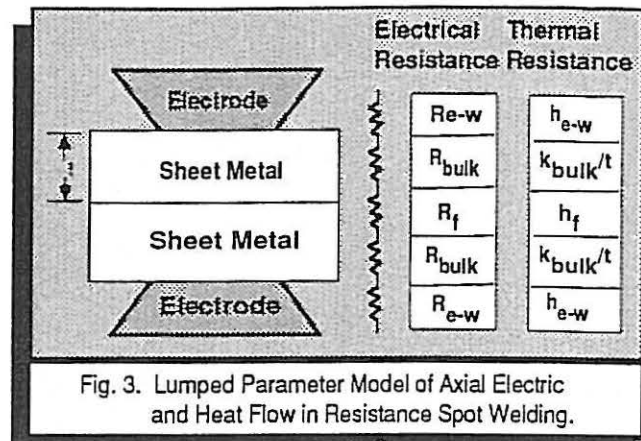


Fig. 3. Lumped Parameter Model of Axial Electric and Heat Flow in Resistance Spot Welding.

**1. Type of Current.** There are at least three forms of current commonly employed, viz. AC, DC, and capacitive discharge. Direct current is the easiest to analyze as its distribution relies primarily on the geometry and the temperature field present in the workpiece and the electrodes. Both AC and capacitive discharge welding involve the diffusion of magnetic flux into the material, in some cases producing a localization of the current near the surface. This is often called the skin effect. At 60 Hz, the skin depth is on the order of 1 to 2 centimeters in copper alloys; hence current localization in the electrode due to magnetic flux diffusion is generally negligible. However, in a ferromagnetic material such as steel, the skin depth at 60 Hz is 5 to 10 times lower and current localization, due to magnetic flux diffusion, should not be ignored. The situation becomes even more complex when one remembers that the heat generated by the process will increase the temperature of the steel above the Curie point, thus producing a complex, time varying "composite" structure with regard to magnetic fields. This problem of coupling the magnetic diffusion to the thermal fields produced by resistance welding is so difficult that no quantitative solution is known.

**2. Electrode Geometry.** Because resistance spot welding is a complex process, with electrical, mechanical, and thermal energy flows, the optimum electrode geometry must take into account all of these energies.

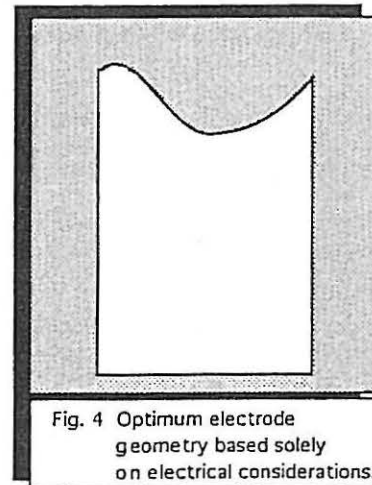


Fig. 4 Optimum electrode geometry based solely on electrical considerations.

When one considers the optimum geometry for each of these conditions, one immediately sees that some compromise must be reached. The optimum geometry for electrical properties is a very long cylinder of finite radius (Fig. 4). For this geometry, the DC current density will be uniform across the electrode face. This creates uniform heating and weld formation. The optimum geometry for mechanical properties is a very long cylinder of a very large radius (Fig. 5). This electrode has the maximum stiffness possible to reduce electrode displacement and has the electrode face well constrained to reduce wear.

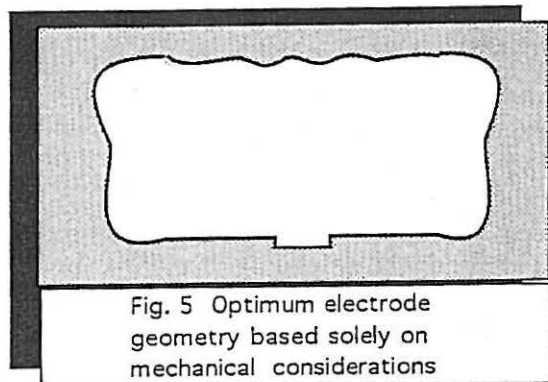


Fig. 5 Optimum electrode geometry based solely on mechanical considerations

For thermal properties, the optimum electrode will have a finite thickness and a large radius (Fig. 6). The large radius will allow regions in the electrode far away from the weld to cool the region near the weld. The finite thickness will have enough mass to allow the copper to cool the electrode face during the weld time and be thin enough to allow the water to effectively cool the copper during the non-welding time.

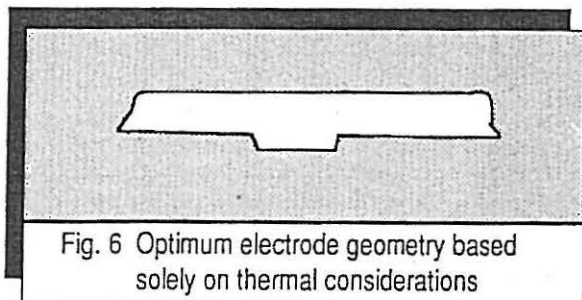


Fig. 6 Optimum electrode geometry based solely on thermal considerations

The optimum geometry electrically is very poor thermally and mechanically as it has very little material to cool or constrain the face. The optimum geometry mechanically is very poor electrically and thermally, as it will cause a very nonuniform current distribution across the electrode face and will not be able to be sufficiently water-cooled. The optimum thermal geometry is poor electrically and mechanically as it too will cause a nonuniform current distribution and lacks the necessary mechanical stiffness. Electrode geometry, then, is definitely a compromise of

electrical, thermal, and mechanical properties. It has been shown that variations in electrode geometry can have a significant influence on the wear rate of the electrode (3).

**3. Thermoelectric Effects.** An electric current flowing across an interface between dissimilar metals will either absorb or release heat at the interface depending on the direction of the current flow. This is called the Peltier effect. While this is generally less than one percent of the Joule heat when welding 0.1 cm thick steel sheet, it can produce 10 to 15 percent heat absorption or heat release when welding 0.01cm thick nickel with molybdenum electrodes (4). Thus, with foil materials the Peltier effect can be very important.

In addition, when a temperature gradient is present, both the Seebeck effect (electric potential difference between two metals) and the Thomson effect (current flow in a homogeneous material in a non-uniform temperature field) are present. The Seebeck effect rarely exceeds several tens of millivolts and hence is generally small, while the Thomson effect may produce a 5 to 10 percent redistribution of the heat in some cases (4).

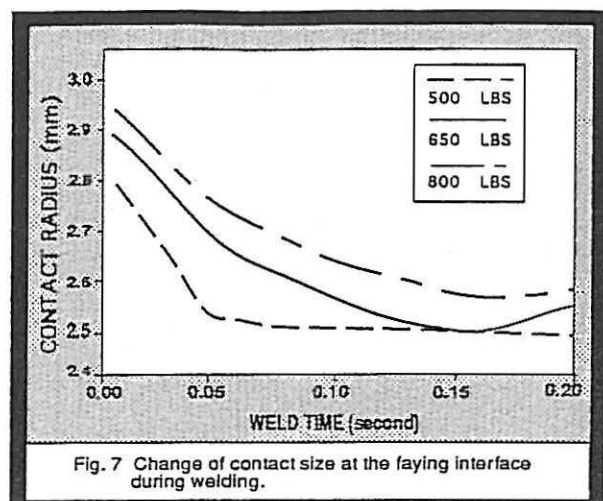
The electrical resistivity of some metals varies markedly with temperature. For example, low carbon steel will increase its resistivity by 500 to 1000 percent between room temperature and 1000°C (5), whereas the electrical resistivity of nickel base alloys is nearly constant over similar temperature ranges. Metals, such as steel, which have a strong variation of resistivity versus temperature will produce a significant redistribution of current during the spot welding process. Most analyses decouple the current distribution from calculation of the temperature field in order to simplify the calculation and hence ignore what may be a very significant effect.

**4. Contact Area.** When two solids are pressed together, they contact at local asperities on the surface. Even if the normal force equals the macroscopic yield stress of the metals, the true microscopic area of asperity contact will not exceed more than one-third of the apparent macroscopic contact area (6). Thus, the electrical contact resistance is influenced markedly by the applied force (7) and the presence of insulating (oxide) films. As the metal is heated, the films are destroyed and the asperities collapse, resulting in a decrease in the contact resistance. The variation of this resistance with temperature has created a long debate between modelers of the process. Recent measurements have helped to resolve some of these questions (5,7,8).

Measurement of the contact resistance is also a function of the current used to measure the resistance (7). This is due to current channeling through the local asperities at low loads and low currents, and collapse of the asperities due to heating at high loads and high currents. Contact resistances measured at room temperature with low currents can result in predicted heat generation rates that are several orders of magnitude too large.

Mechanical models and measurements of two sheets clamped between two electrodes at room temperature give a realistic measure of the effective initial contact area at the faying interface; however during welding, the localized heating between the electrodes causes the sheets to expand, separating the sheets and decreasing the area of contact. As seen in Fig. 7, Kim estimated that the contact area may decrease by more than 25 percent during the first 100 milliseconds due to this thermal expansion (5).





Indeed, it is partially this localized thickness expansion with reduction of the contact area which concentrates the current and makes resistance spot welding possible. If the contact area did not decrease initially, the heating volume would be diffuse and the metal would flow plastically due to the electrode force, squeezing a hole into the sheet before melting at the faying interface occurs.

**5. Tip Wear.** A tapered electrode will produce current localization near the edges of the electrode (3). This produces preferential heating which will lead to increased wear and rounding of the electrode tips. Mechanical models also show greater contact pressures at the edges of flat faced electrodes due to bowing of the sheets due to the contact force (5,9). In addition, at the center of the electrode, the metal is triaxially constrained, resulting in less local deformation than at the edges (10). Each of these three factors, geometric current constriction, increased edge contact pressure and increased center deformation resistance will contribute to non-uniform current distribution across the face of the electrode. Bowers (3) showed that this can cause a 30 percent reduction in electrode life. In addition, welds may be formed with an initial toroidal shape that grows radially inward to form the nugget rather than growing radially outward from the center (11). As the electrode begins to wear and become rounded, the current localization may shift from the edges to the center and back again, until a worn shape which produces a nearly uniform current distribution is created. This oscillation of current localization from one area of the electrode face to another may be responsible for "burn-in" or "conditioning" of the electrode tips as is often found in welding of galvanized steel. A consistent welding behavior may not be found for 50 to 200 welds, as the electrode tip wears to a preferred shape. The preferred shape is the one which produces the most uniform current distribution across the electrode due to both current constriction at the edges and local contact pressure variations.

**6. Heat Generation and Dissipation.** As shown in Fig. 3, heat is generated at both the interfaces and in the bulk of the metal. Kaiser (7), Gedeon (12), and Kim (5) suggested that there is a balance between these interfacial resistances and bulk resistances which should

be maintained for good weldability. Essentially, the interfacial resistance should be several times the bulk resistance to produce a favorable heat generation pattern. If the interfacial resistance is too high, the heat is generated in too thin a layer causing rapid surface melting and expulsion. If the interfacial resistance is too low, the nugget is formed equidistant from the two copper electrode heat sinks. While this is acceptable when welding equal thicknesses of sheet, it can produce a nugget totally within the thicker sheet (and hence no weld) when welding a very thick sheet to a very thin sheet. Such nuggets totally within a thick sheet without a weld between the sheets have been observed in nickel base alloys which have high ratios of bulk resistance to interfacial resistance.

An analysis by Kim (13) indicates that 50 to 75 percent of the heat is lost to the electrodes during spot welding of one millimeter thick steel sheet. For thinner sheet, over 90 percent of the heat can be lost to the electrodes. When such a large fraction of the heat is lost to the electrodes, even small variations in the thermal contact resistance to the electrode can have significant consequences. For example, Calva (14) recently measured standard deviations of 10 to 25 percent of the measured values of thermal contact resistance in galvanized steel sheets. Such variations can cause either insufficient heat to cause melting, or excessive heating and expulsion from weld to weld in the same material with identical welding power settings. This variation is most significant in thinner sheets.

Finally, in high speed welding on the order of one spot per second, heat can accumulate in the copper electrodes resulting in a higher tip temperature with increased electrode wear. Measurements show that four or five welds are necessary to produce steady thermal profiles in the electrode (15). The earlier welds may be too cold due to the more effective heat sink of the cooler electrodes. Such effects have been noted in production welding and have been solved by programming a higher initial welding current for the first four welds whenever more than five seconds have elapsed since the last weld.

## Conclusion

The coupling of mechanical, electrical and thermal energy flows in resistance welding provide ample opportunities for scientific investigations. Unfortunately, the generally high level of reliability and economy of this process have not produced a need for intensive and extensive study of the process. As a result, our knowledge is primarily qualitative rather than quantitative. Resistance welding represents an area of great opportunity for a clever scientist interested in improving the process.

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