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MODELING OF RESISTANCE SPOT WELDING PROCESS – A REVIEW

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ABSTRACT

Resistance spot welding (RSW) modeling in general and prediction in particular, have been a main topic in research for the last few decades, but although the information is quantitatively enormous, it is also spread widely in the literature, and difficult to find. In this work, a review has been carried out of the history of modeling and prediction of Resistance Spot Welding in metals. Resistance spot welding is a process that is being widely used in the industry for sheet joining purposes. The spot welding process is a complicated phenomenon, which involves the mechanical, thermal, electrical and metallurgical factors. It requires modeling of complex interaction between electrical, thermal, metallurgical and mechanical phenomena to the process and to get the optimum weld quality. This paper reviews the research trends in modeling of the resistance spot welding process.

KEYWORDS: Resistance Spot Welding, Quantitative Analysis, Mechanical Phenomenon, Metallurgical Characterization and Numerical Modeling

INTRODUCTION

A joining process coming under the category of pressure welding and widely used for the mass production applications is resistance welding. This process is applied to assembly of steel body of cars and its sheet metal parts [1-7]. The resistance welding has wide alterations. This has been brought about by its technical advantages and the low cost. There are a number of resistance welding processes as shown in Figure 1 [1-34]. Further, resistance spot welding is one of the basic sheet metal welding processes for automotive applications [8-13]. The basic advantage of resistance spot welding is the absence of extra material applied for generating the joint. Further, the distortion of the panel will not normally occur during the process, and the joint will be sufficiently strong [14-16]. The resistance spot welding is extremely simple, and at the same time a highly reliable technique for welding [17-25]. In particular, the resistance spot welding is widely applied in automobile manufacturing.

This is because of the capability to absorb impact energy. Further, when steels are used, the ductility and tensile strength are also of due consideration. In addition, all the spot welding technologies have been extensively used in these industries for the past 30 years, and hence, is a proven technology [26-30]. Typical advantages of resistance spot welding involve: energy efficiency, quality of welds and cost effectiveness. The cost of consumables used in the process is extremely low. The advanced automation technologies involving robots, transfer lines and assemblies could be successfully integrated with the resistance spot welding systems [31, 32]. It is further known that the operating speeds of the resistance spot welding are very high. This could help improve the productivity of the welding systems. The residual heat generation and residual material deposition is also minimum in the process. There are typical applications for the process in joining of several mechanical components. These components involve sheet metal parts such as clips, bases, covers and lids.

These operations could be performed in a systematic and continuous manner to generate quality welds. However, sufficient quantity of electric heating needs to be applied for continuous operation of the welding system.

At the same time, no other consumable are required for generation of these welds. The range of energy required for generation of resistance weld is between 10 and 15 kJ. The mechanisms involve: i) timing control, ii) automatic control of electricity, iii) control on electrode force and iv) control of heat transferred. The technical skill requirement for operation is very small, and hence the labor cost is also lowers [33]. Considering the aspects of cost and effectiveness of the process, resistance spot welding is better than other joining processes.

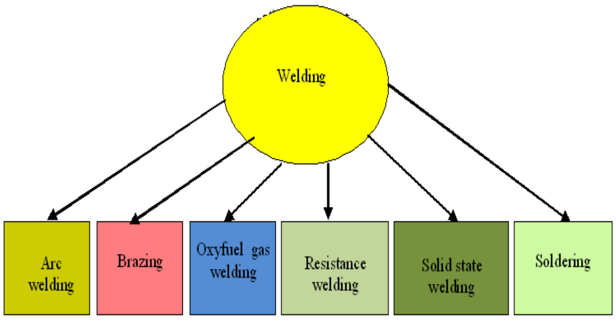

Figure 1: Classification of the Welding Process

PRINCIPLE

In resistance spot welding process, the application of electric current (*I*) causes generation of electrical energy (*E*), in a duration of time (*t*) thereby causing heating of the resistance (*R*), represented as:

$$E = I^2 \times R \times t \tag{1}$$

This electrical energy is converted into heat energy heat energy and causes welding of the closely placed components. Further, forces are applied to hold the pieces together [21].

Normally, the heat and pressure are applied to the workpiece using the electrodes. The heat is generated using the electric current and pressure is applied, which eventually causes the formation of the nugget at the interface. The nugget formation mechanism involves generation of sufficient thermal energy to raise the temperature of the base material. The dimensions of the nugget formed at the weld region also depend upon several parameters as presented in Figure 2. The sheets are placed one over the other and the electric current is applied. The sheets are coated with suitable materials before welding. The characteristics and properties of the weld is influenced by two factors: i) thermal factors and ii) electrical factors. Further, the material chosen for coating the strips also is important. The coating provided significantly influences the energy and force transferred to the strips, at the junction of which the weld is formed.

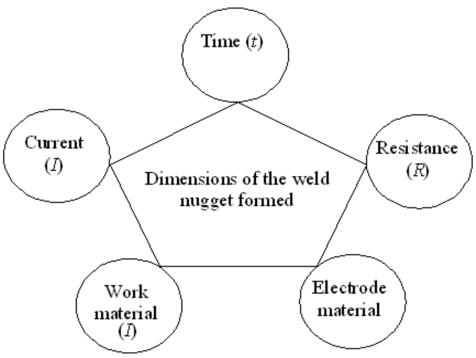

Figure 2: Parameters Influencing Formation of Weld Nugget

In this study, the resistance of the system, current (*I*) and voltage (*V*) are not a constant, but varies with time. Based on this, these parameters influencing the welding process could be expressed as an integral over time. It is known that the generation of the joint and weld area depends on several factors. The transfer of heat energy to the weld area depends on several factors.

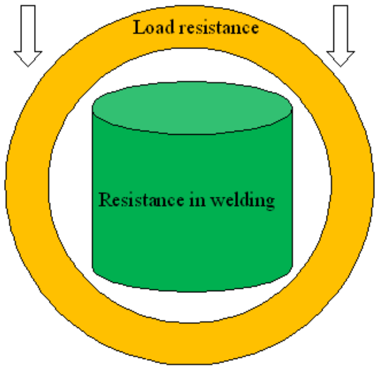

Figure 3: A Schematic Diagram of the Resistance in Welding

These factors involve several sources those contributing to the production of the weld. The most important factor, i.e., the load resistance is presented in Figure 3. The load resistance in turn depends on some minor parameters as presented in Figure 4. These minor parameters are weld force and temperature. Further, the load resistance is a function of the weld force, the materials to be used and temperature during welding. In addition, the Contact resistances between the two workpieces and the contact resistance between the upper/lower electrode and workpiece also influence the load resistance, and at the same time, the welding performance.

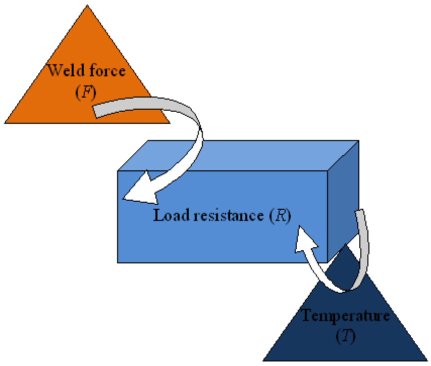

Figure 4: The Relation between Load Resistance, Weld Force and Temperature

The bulk resistance is a significant aspect for evaluating the welding quality in a weld. The pressure has no influence on the bulk resistance. However, the temperature is an important factor in influencing the bulk resistance. For all metals, the bulk resistance increases with temperature. The bulk resistance is a function of temperature via two separate processes. Resistivity is an increasing function of temperature. In addition as temperature rises, the metal expands, causing an increase in resistance as resistance is proportional to the distance the current has to travel. The contact resistance is a strong function of pressure or force, and also affected by the environment of the contact surface. It will change dramatically as melting begins. Hence, the contact resistance is the most important parameter in the beginning few milliseconds in the welding process. The load resistance attributed to the contributions of the contact resistance and bulk resistance is thus not constant during the process, leading to variations in the rate of heating during the weld. Figure 2 shows the trends in changes in resistance during resistance spot welding [22]. The dynamic resistance is the sum of bulk resistance and contact resistance.

Based on the above analysis, the following interpretation for the typical shape of the dynamic resistance curve is given. The stages of spot weld formation can be described as follows [23]: In this, at first, the workpieces are brought into contact under the pressure provided by the electrode force. Then, the voltage is applied between the electrodes causing current to flow at the contact points. The resistance between electrodes at this point is equal to the sum of the bulk resistance of the two workpieces, the two electrode-to-work contact resistance, and the work-to-work contact resistance. It is known that the initial contact resistance will be very high. Therefore, the initial generation of heat will be concentrated at all surfaces, especially at the work-to-work contacts. This heat will cause the surface contaminants to break down resulting in a very sharp drop in resistance. Further, after the breakdown of surface contaminants, metal-to-metal contact exists. The connection of both the electrode to workpiece interfaces and the workpiece to workpiece interface will actually be self-possessed of many disjoint contacts at asperities reducing the contact area to a tiny fraction of the electrode face. Because of this, a relatively large interface resistance.

The generation of thermal energy is therefore focused at the surfaces, and temperature in this region and in the bulk materials will increase. A rise in the temperature result in increasing resistivity thus is providing an conflicting effect. Therefore, the increase in contact area will be overcome by the increasing temperature effect, and the total resistance will begin to rise. All points on the workpiece has also an increase in temperature, thus causing resistivity and resistance to increase. The additional heat generation also results in an additional melting to occur at the surfaces. The gradual growth in the size of the molten region causes a decrease in the resistance. Hence, an overall decrease in the resistance is observed. Further, the expulsion of molten metal will occur if the nugget grows to a size such that the surrounding the metal.

THE CYCLE OF RESISTANCE SPOT WELDING

In the cycle of resistance spot welding, there are several processes. These processes are of discrete nature that occurs over a short period of time as shown in Figure 5. In the first step, i.e., squeezing, the electrodes travel together; the force is applied from a pneumatic cylinder and reaches its preset steady state value. Further, the weld force will make the two workpieces contact well and then provide proper faying resistance for the heat generation. Welding is the second step of the resistance spot welding when the welding current is conveyed by the electrodes to the workpiece. This current generates the energy to melt the contacted parts of the workpieces, so that the weld nugget is formed. The third step of the resistance spot welding is ‘cooling’.

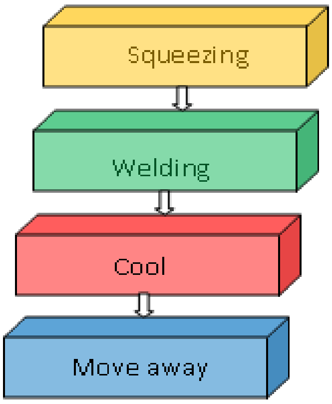

Figure 5: The Sequence of Operations in the Resistance Spot Welding Cycle

The objective of this step is to hold the workpiece and electrode for a certain period of time so that the nugget is cooled down into a solid form. However, the welding force is still ‘ON’ so that the joints are held together. The next stage is move away, in which the workpiece is allowed to move away.

The entire mechanism could be described in terms of certain welding variables [26] as presented in Figure 6.

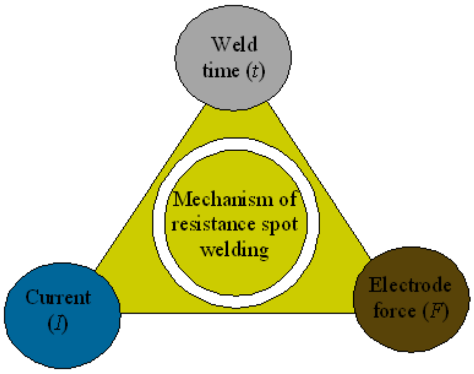

Figure 6: The Parameters Governing the Mechanism of Resistance Spot Welding

The stages involve the initiation of nugget, rapid nugget growth, steadily decreasing growth and the weld metal expulsion. As the contact resistance is strongly influenced by the pressure, electrode force is believed to be a critical factor affecting the process, especially at the early stages in the heating cycle [27]. Higher electrode force usually reduces the contact resistance at the electrode-sheet interface and, hence, would decrease the heat/temperature at the surface, which may reduce the tendency of expulsion. Therefore, electrode force determines the greatest nugget diameter without expulsion when the electrode geometry is kept constant. By delaying expulsion, increasing electrode force can broaden the process window for successful welding. However, a large force reduces the weld resistance requiring higher current levels increasing the cost of the process. Further, a large electrode force leads to damage of the electrode and can lead to excessive surface indentation, which is often undesirable during micro-joining or precision welding. Welding current is another significant variable affecting nugget formation and growth as the power generated is proportional to the square of welding current as indicated in equation (1). The current range is determined by evaluating the minimum 22 and maximum current levels permissible for required joint properties [28].

A certain level of welding current is generally required to produce enough heat energy for a weld with a least amount nugget diameter. An excess welding current results in void and crack formations. The consequence of welding time can be also pragmatic during the formation of weld nugget. A longer weld time allows more heat to be conducted to the sheet metal. However, longer weld time would increase the softening effect at the heat-affected zone and hence decrease the joint strength when welding cold-worked sheet metal [29]. The characteristic of over-welding where molten metal is expelled from the weld nugget as a violent shower of sparks is the amount of removal. The latest theory of expulsion is that it happens when the force from the nugget due to the internal pressure in a liquid nugget caused by melting, liquid expansion, and other factors exceeds the force from the electrodes [31]. Severe expulsion can reduce the joint strength because of the loss of metal volume. In addition, expulsion has a negative influence on adhesive bonding, if it is used in conjunction with spot welding, by damaging the adhesive layer; therefore, it should be avoided. According to this theory expulsion always occurs towards the end of the weld time as a nugget must have overdeveloped in order for this condition to have occurred. This is produced when worn or misaligned electrodes are used. Degradation of the tip of the electrodes increases the resistance of the interface between the electrode and the workpiece.

The molten material may then be released via a similar mechanism to normal expulsion; however, this condition is generally less violent. The high electrode temperatures generated by this condition promote further erosion of the electrodes thus adversely affecting electrode life. A severe under-welding where a weld nugget does not form. Insufficient current or a short weld duration causing insufficient energy to be put into the weld zone can cause welding defects. A spot weld where a nugget has formed; however, the nugget diameter is less than the minimum size specified in the design. The required nugget diameter is reliant on the classification of the spot weld. Both expulsion and undersize welds are often used as visual indicators of a correct welding process. The sparks are generated when the electrodes contact the workpieces resulting in erosion on the electrode surface and may result in the electrodes becoming bonded to the workpiece. In the weld, the sparking can cause damage on the surfaces, beyond certain limits.

CLASSIFICATION OF RESISTANCE SPOT WELDING

The resistance spot welding could be classified into three: micro, small scale and large scale. This is according to the thickness of the metal sheet used for joining.

Micro-resistance spot welding (less than 0.0125-0.251 mm)	Small scale resistance spot welding (0.125 mm < T < 0.51 mm)	Large scale resistance spot welding (0.41 mm < T < 1.57 mm)

Figure 7: Classification of Resistance Spot Welding Based on the Thickness of Metal Sheet [25]

It is known that the large-scale resistance spot welding is well over 100 years old and represents a mature joining process [32]. There has been ample time for materials to become standardized as to alloy types, plating, and thickness. These factors have driven the formation of welding tables that evidently define the large-scale resistance spot welding process for many standard materials. Small and micro-scale resistance spot welding is being driven by the explosion to make everything smaller. The small and micro scale process is relatively fast, the welding time being typically tens of milliseconds instead of hundreds of milliseconds. The monitoring and control of the small and micro scale resistance spot welding process is less commonly addressed in the literature than the LSRSW process although there are some noteworthy differences between the two processes [33]. The workpiece in the small and micro scale process is relatively thin. Furthermore, the electrode displacement monitoring requires higher resolution in this case, it is difficult than for the large-scale process.

MODELING APPROACHES

The modeling of the resistance spot welding could be performed with different concepts. The modeling techniques are classified and this methodology is presented in Figure 8.

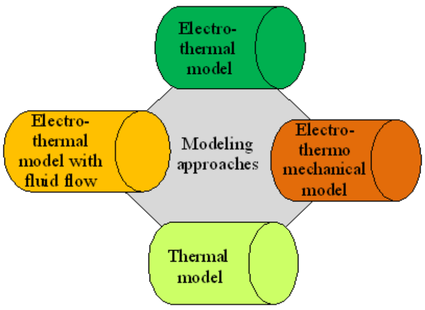

Figure 8: Modeling Approaches for Resistance Spot Welding

Each of these modeling approaches for resistance spot welding are discussed in the following paragraphs:

Electro-Thermal Model

The electrothermal model was first introduced as the first axisymmetric electrothermal model, which included geometry of a flat-end electrode in contact with the workpiece, temperature-dependent material properties of both the workpiece and electrode, and the latent heat effect by using a fictitious specific heat increasing at the temperature between solids and liquids [6]. The model measured the influence of electrode on thermal conduction and pointed out that the heat generated by electrode is relatively small. Solutions were obtained by using the finite difference technique. The results showed that the axisymmetric electrothermal model provided information on current density and temperature distribution in both the workpiece and electrode. Besides the relationship between weld nugget side and welding parameters, the temperature curve of interface between electrode and workpiece and its relationship with nugget thickness were also obtained. In addition, the radial electric current density curve is also acquired. Thus this model can further predict the temperature of electrode, and the wearing of it.

However, the influence of contact resistance was not included in this model. Cho [7] furthered the research of axisymmetric electrothermal model through including the interface contact resistance by relating it with the rigidity property of materials. Chart for ratio of voltage at electrode interface, workpiece interface and workpiece was obtained, form which rules of contact resistance changes can be acquired. By using finite difference method for solution, the nugget side relative to welding parameters and temperature distributions was acquired. However, the theoretic nugget size calculated is smaller than the experimental result. Theddeus [8] employed a coupled electrothermal model of axisymmetric sheet-electrode geometry to predict RSW nugget diameter, penetration, and electrode face heating at any instant throughout the welding time. Non-linear, temperature dependent, thermophysical material properties were incorporated while effects of different welding currents, welding times, electrode forces and surface conditions of the aluminium sheets were systemically studied. Also, the initial surface condition influences the growth of the fusion zone to a great extent.

Electro-Thermo Mechanical Model

Nied [9] built the first two-dimensional axisymmetric model considering both mechanical and thermal responses of RSW process using the commercial finite element software ANSYS. His model included most major factors: contact area (surface effects: electrical resistance, thermal conductivity, local deforming), local heat flux, latent heat of fusion associated with phase change, bulk Joule heating, and temperature-dependent electrical and thermal properties. The analysis provided current density, deformation of workpiece, stress distributions which vary from the centerline of the model towards the edge of the electrode and the sheets and temperature distributions showing the characteristic isotherms of an elliptic-shaped weld nugget. The highest temperature was found at a distance from the center of the contact area and the author concluded that the melting also occurred first at a distance from the centerline of the workpieces, different from the earlier researchers' considered.

For the extended range and high precision of the prediction the model can make, the nonlinear thermo-mechanical coupling provided a more realistic simulation of the welding process. However, the contact behavior and the thermo-mechanical coupling mechanism were not demonstrated clearly. In 1992, Tsai [10] created a 2-dimensional axisymmetric model using ANSYS similar to Nied's model to do further parametric studies on the RSW process. The model used three element types: thermoelectric solid element for thermal analysis, isoparametric solid element for stress analysis, and surface element for coupling. The model included contact resistance varying with temperature, Young's modulus, coefficient of expansion, specific heat and temperature- dependent thermal conductivity. Electro-thermal coupling was first carried out and then the calculated temperatures were imposed on the isoparametric solid elements through computer coupling routines and calculations continued for stresses developed from thermal strains and electrode squeezing.

The model showed that nugget initiated in a ring shape at a distance from the electrode center expanded inward and outward during the welding cycles. The three main parameters of RSW, which are electric current, electrode pressure and hold time, affected the thermomechanical interactions of the welding process and changed the thermomechanical interactions of the welding process and the final nugget geometry. In addition, with workpieces of unequal thickness, it was found that the weld nugget formed mostly in the thicker workpiece than in the thinner workpiece, and with dissimilar materials, the weld nugget formed more in the workpiece of lower thermal conductivity or higher electrical resistivity. In 1998, Feng and Gould [11] developed an incrementally coupled electrical-thermo mechanical finite element model to simulate the RSW process. Electro-thermo-mechanical model is the best developed and most widely used model so far, enabling cost reduction of weld quality testing and better development of various welding schedules. This mature model has been widely used in study of new materials, such as Al alloy, Mg alloy, TRIP steel and so on. However, this model is not perfect for its neglecting the fluid flow field and the electromagnet stirring effect, generated by electric current and induced magnet field, on the thermal field and mechanical behavior during welding cycle.

Thermal Model

The first simulation model generated using resistance spot welding research is the thermal model. Greenwood [4] developed the first heat conduction model to simulate the RSW process. A linear axisymmetric heat transfer model of the process was built and a finite difference method was employed for the first time to solve the partial differential equation. Particularly, the influence of geometry of the electrode which was not included in the model was simulated by an effective boundary condition. The results revealed temperature concentration occurred at the periphery of the electrode /workpiece interface early in the weld cycle. Temperature distributions were also obtained, showing the characteristic isotherms of an elliptic-shaped weld nugget. This theoretical model is significant in its contribution, since it included the internal heat production (Joule heating) due to current flow and heat transfer in both the axis direction and the radical direction. However, this model neglected heat generated due to contact resistance, latent heat of fusion during phase transformation and temperature-dependent material properties.

In 1987, Gould [5] proposed a one-dimensional heat transfer model taking account of electrode geometry, temperature-dependent material properties, melting, internal heat generation and contact resistance. He measured the contact resistance of the facial resistance in room temperature and assumed a zero value of contact resistance when workpieces are melted and a linear variance of the contact resistance between the above two values. A finite difference technique was used to obtain solutions for the nonlinear differential equations. The inability to consider the axial heat flow into workpiece resulted in the discrepancy of the model whose predicted nugget sizes were much larger than those observed in the experiment. From this model, the relationship between nugget size and electrified time, distribution of temperature and heat circulation curve is achieved.

In addition, a conclusion was drawn that the formation of the nugget can be divided into four stages as follows: gestation period, rapid development period, latent period and expulsion period. In 1990, Wei and Ho [17] developed a three-dimensional transient heat transfer model to predict temperature distribution during resistance spot welding. From the analysis above, although some meaningful outcomes can be obtained from the pure heat transfer models, they are only qualitative results due to the limitation of the models which have large number of simplifications resulting in the lack of actual description of the complicated RSW process. However the relatively rough description of the temperature distributions did provide some guidance to the welding industry for that time.

Electro Thermal Model with Fluid Flow Field

The model which combines the electro-thermal phenomena as well as the fluid flow phenomena is complex. To study the fluid flow within weld nugget, Wei [12] built continuity equation, momentum equation, energy equation and magnetic equation of electrode and workpiece respectively for tape-shape and cylinder-shape electrode. Due to the complex coupling effects of electrical, magnetic, thermal and fluid flow field, he employed difference method to solve these control equations in two-dimensional axi-symmetric coordinate system and explore the fluid flow of melted metal during RSW process for the first time. While his research cannot get the exact values of parameters of fluid flow field and magnetic field, it made study of the RSW process progress into a new stage. In 1999, Khan [13] developed a model to predict the nugget development during RSW of Al-alloys with flat-end electrode. Phase change and temperature-dependent thermal– electrical–mechanical properties were included. The contact area and the pressure distribution were determined by a coupled thermal–mechanical model.

The model calculates the interface pressure varying with time, with which accurate prediction of interfacial heat generation is acquired. The proposed model can be applied to predict the effects of the welding parameters and the electrode shapes on the nugget development. During the RSW process, the current flow and fluid flow of melted metal are greatly influenced by the magnet field while the magnet field is generated and affected by them on the other hand. To solve this coupling problem, more mathematic work and more powerful finite element method should be acquired. In 2007, Li [15], [16] proposed a Magneto- hydrodynamic model achieved improved coincide with experiment data. It is based on a multiphysics coupling, which incorporates phase change and variable electrical contact resistances at faying surface and electrode-workpiece contact surface.

The patterns of the flow field and thermal field at the end of the welding phase under different welding currents are obtained. The analysis results are also compared with a traditional electro-thermal coupled model to obtain the quantitative effects of the magneto-hydrodynamic behavior on the resistance spot weld nugget formation. The model shows that liquid metals in the nugget under different welding currents all make rotational motions in four symmetrical loops. With the increasing welding current, the centers of the loops move towards the nugget centre in the width direction and away from the faying surface in the thickness direction.

CONCLUSIONS

The review of the array of research works on resistance spot welding around the world is presented in this paper. It is evident that the energy transformations during the process involve mechanical, electrical and thermal, thus making the process complex to analyze. Based on this review, the following conclusions can be drawn:

- The resistances influencing the spot welding phenomena are: bulk resistances of the upper/lower part joints, contact resistances between the upper/lower electrode and workpiece, and contact resistance between the two workpieces.
- The weld time, weld current and weld force are the key control variables for regulating the quality of the weld nugget. These variables are strongly cross-coupled and thus any of these parameters may be adjusted to influence the quality of the spot weld produced, within a moderate range of values.
- As the workpiece in the small and micro scale process is relatively thin, electrode displacement monitoring requires higher resolution and is much more difficult than for the large-scale process. The small and micro scale

process is relatively fast, the welding time being typically tens of milliseconds instead of hundreds of milliseconds. The much smaller currents permit the use of higher bandwidth high frequency inverter or linear power supplies rather than low-to-medium frequency inverter used in the large-scale process.

- The commonly used models to represent resistance spot welding are: thermal Model, electrothermal Model, electro Thermo Mechanical Model and electrothermal Model with Fluid Flow Field.

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