Finite-Element Simulation of Resistance Welding Process

Ali. Moarrefzadeh

***Abstract*— Resistance welding is a fusion welding process that requires the application of both heat and pressure to achieve a sound joint. The simplest form of the process is spot welding where the pressure is provided by clamping two or more overlapping sheets between two electrodes. In this paper, the Resistance Welding is studied and Steel temperature field is gained in this process. The thermal effect of Resistance Welding that specially depends on the electrical and temperature field of it in workpiece, is the main key of analysis and optimization of this process, from which the main goal of this paper has been defined. This paper reports the determination of optimum welding conditions (welding intensity and travel speed) for butt joints of Steel Alloys sheets using Resistance Welding. Numerical simulation of welding process in SIMPELC method and by ANSYS software for gaining the temperature field of workpiece, the effect of parameter variation on temperature field and process optimization for different cases are done.. The influence of the welding parameter for each mode on the dimensions and shape of the welds and on their ferrite contents is investigated.**

***Keywords*–** Finite-Element, Resistance, Dimensional, Welding, Temperature Field and Fusion

I. INTRODUCTION

Resistance welding is a fusion welding process that requires the application of both heat and pressure to achieve a sound joint. The simplest form of the process is spot welding where the pressure is provided by clamping two or more overlapping sheets between two electrodes (Fig. 1). A current is then passed between the electrodes, sufficient heat being generated at the interface by resistance to the flow of the current that melting occurs, a weld nugget is formed and an autogenous fusion weld is made between the plates. The heat generated depends upon the current, the time the current is passed and the resistance at the interface. The resistance is a function of the resistivity and surface condition of the parent material, the size, shape and material of the electrodes and the pressure applied by the electrodes.

There are a number of variants of the resistance welding process including spot, seam, projection and butt welding. It is an economical process ideally suited to producing large numbers of joints on a mass production basis. Spot welding in particular has been used extensively in the automotive industry, albeit mostly for the joining of steel and in the aerospace industry for airframe components in aluminum alloys. Seam welding is used in the production of thin sheet, leak-tight containers such as fuel tanks.

F. A. Faculty member of Department of Mechanical Engineering, Mahshahr Branch, Islamic Azad University , Mahshahr, Iran
E-mail: a_moarrefzadeh@yahoo.com
a.moarefzadeh@mahshahriau.ac.ir
Tel: +989123450936

Projection welding is generally used for welding items such as captive nuts onto plate. This variation is not normally used on aluminums and is not covered in this chapter. Flash welding, unlike spot and seam welding that require a lap joint, is capable of making butt welds. This is achieved by resistance heating the abutting faces and then forging them together.

There are a couple of characteristics of aluminum that make it more difficult to resistance weld than steel. The most significant is its high electrical conductivity, requiring high welding currents and large capacity equipment.

Secondly, the electrodes are made from copper which alloys with aluminum, resulting in rapid wear and a short electrode life. As with conventional fusion welding, resistance welding suffers from similar problems of oxide entrapment and hot cracking, the latter not being helped by the lack of a more crack-resistant filler metal, and porosity.

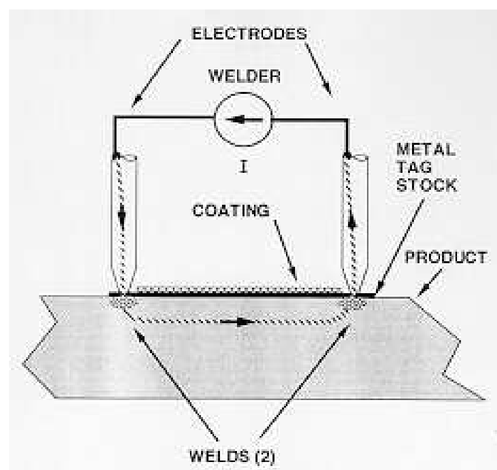

Fig.1: Principles of spot welding process

II. POWER SOURCES

The power sources are normally rated in kV A at 50% duty cycle so, if the maximum primary input power available is known, it is possible to calculate the maximum power output from the welding machine. There are five types of power source commonly used for the welding of aluminum.

These comprise single phase AC or DC machines; three phase DC machines with either primary or secondary rectification and inverter units with secondary rectification. The choice of equipment depends on a number of factors such as the primary current available, the output current required the amount of space required between and around the electrodes, whether the equipment is required to be portable and the equipment cost.

The power source is simple, robust, and relatively inexpensive and maintenance free, comprising little more than a transformer and a suitable timer. For these reasons this form of power source has been popular for low-volume applications. However, the equipment is not very energy efficient as the secondary circuit suffers from substantial inductive losses. Demand on the primary supply is also high and unbalanced between the phases: welding current can be high but the voltage is normally low, between about 3 and 20 volts.

The spot welder may be pedestal mounted (Fig. 2) or portable. With portable equipment the transformer may be remote from or incorporated into the welding gun. With portable equipment the weight of the transformer makes the gun with the built-in transformer difficult to manipulate even with counterweights to ease manual handling. The gun weight may also exceed the carrying capacity of welding robots. Using a power source remote from the gun requires heavy, stiff cables to deliver the welding current, again making the gun difficult to manipulate.

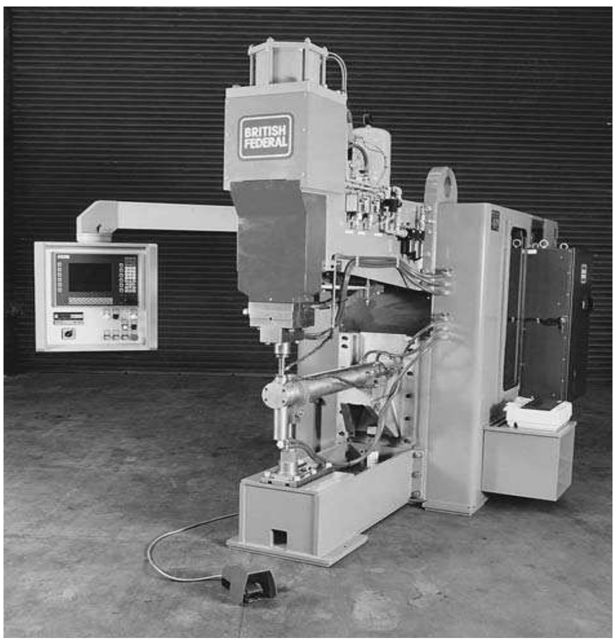

Fig. 2: Modern pedestal mounted spot welder for aerospace applications

Single phase DC units are rather more energy efficient than the single phase AC units as rectification of the current in the secondary circuit reduces losses due to inductance. Power demand across the phases is also more balanced than the single phase units. Although the rectifier adds to the weight the increased efficiency enables a lighter transformer to be used, giving an overall reduction in weight. The equipment cost is greater than the simple transformer AC unit but an improvement in weld quality can be used to justify this increase.

As with the AC unit the welding gun may be pedestal mounted or portable. The limitations in cables apply when the power source is remote from the gun but the potential for a lighter transformer on gun welding head eases the manipulation problems apparent with the AC units.

Primary rectified three phase units predate the advent of solid state electronics, using ignitron or thyratron tubes for current control. They were widely used in high-quality applications in industries such as aerospace.

Half wave rectification of the primary current is used to provide the transformer with DC to give a high-current, low-voltage output. It is possible to weld a wider range of materials and thicknesses with these more efficient units. The length of the current pulse that these units are capable of providing is limited before saturation of the transformer core occurs. Alternate spot welds are generally made with alternate polarities.

As mentioned in other chapters the development of solid state electronics, particularly inverter technology, has resulted in highly energy efficient, compact and light power units with weight savings of up to 50% compared with an AC unit of equivalent output. At high current output there is a risk of overheating and up until perhaps 1997 the maximum output was limited to some 20 kA but this value has now been increased to over 50kA. This enables these units to be used in high utilization activities such as those required in the automotive industry and to be mounted on robots for continuous operation (Fig. 3).

III. SURFACE CONDITION AND PREPARATION

The surface condition of the aluminium sheets is one of the most important deciding factors in achieving consistent quality of resistance spot and seam welds. Variations in the thickness of the oxide film will affect the resistance between both the electrodes and the plates and at the plate interface.

The resistance may be measured by clamping a single plate between two electrodes and applying a set current of some 10–15 A, measuring the voltage and calculating the resistance by the use of Ohm's Law. Material as delivered may have a resistance of between 300 and several million microhms, cleaned and prepared plate should have a resistance of 10–100 microhms. For the highest and most consistent quality this range should be tightened to some 10–30 microhms.

To achieve this low level of resistance the cleaning and storage recommendations in Section 4.7 should be followed. Mechanical abraded surfaces generally provide longer electrode lives than chemically cleaned surfaces, with mill finished sheets giving the shortest lives. Special lubricating oils such as polybutene have been used to extend electrode life by reducing the friction between electrode tip and the sheet but care needs to be taken to ensure that there is not excessive oil present.

Table 1: Typical welding parameters for 50Hz equipment single phase AC units. Valid for 1XXX, 3XXX, 5XXX and 6XXX alloys

Sheet thickness (mm)	Electrode diameter (mm)	Dome radius (top) (mm)	Dome radius (bottom) (mm)	Electrode force (kN)	Welding current (kA)	Welding time (cycles)
0.4	16	1.0	Flat	1.4	15	4
0.5	16	1.0	Flat	1.5	18	4
0.65	16	2.0	Flat	1.75	21	5
0.8	16	2.0	Flat	2.2	26	6
1.0	16	3.0	Flat	2.7	30	7
1.25	16	3.0	Flat	3.0	33	7
1.6	16	3.0	Flat	3.35	35	8
1.8	16	4.0	4.0	3.6	35	8
2.0	22	4.0	4.0	3.8	41	8
2.3	22	6.0	6.0	4.25	46	10
2.5	22	6.0	6.0	4.7	56	12
3.2	22	6.0	6.0	5.8	76	12

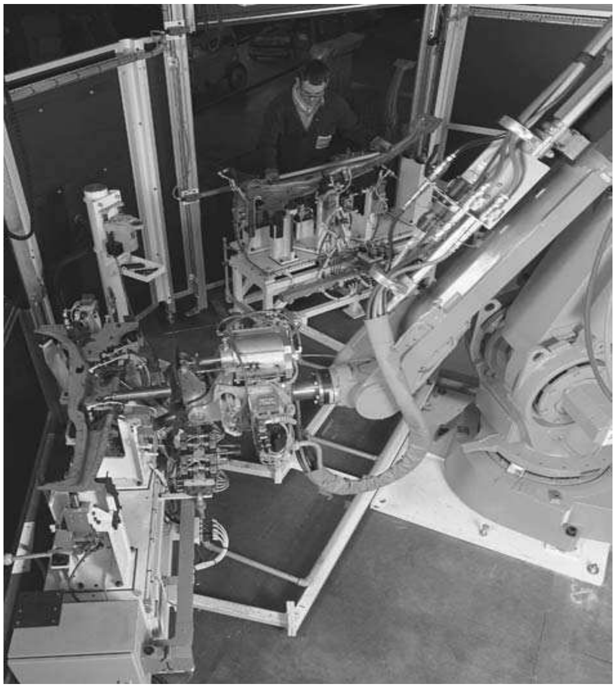

Fig. 3. Modern robotic resistance spot welding cell. The robot welds on one jig while the operator unloads/loads the second jig. Courtesy of British Federal

IV. SPOT WELDING

Spot welding is by far the most widely used variant of the resistance welding process. The basic principles of the technique are illustrated in Fig. 1. As many as five overlapping sheets of aluminium may be welded together in

a single operation. The weld nugget extends through the sheets but without melting the surfaces of the outer plates. The main welding parameters are current, pressure and time – typical parameters are given in Table.1. It is recommended that when developing a welding procedure the electrode sizes, the welding time and the welding force should be selected first and the welding current increased until the desired nugget size is achieved.

The welding head may be mounted on a pedestal, a bench, a dedicated machine, a manually operated boom or a robot.The simplest machine is the manually operated pedestal machine but even this may be supplemented with automatic feed and ejection.The pedestal machines are capable of pro- viding the highest power output, with capacities ranging from 5 to 400kVA. The portable guns such as those used on robots in the automotive industry generally range in capacity from 10 to 150kVA.The design of the welding head is important in reducing electrode tip wear, assisting in reducing porosity and cracking and enabling high production rates to be achieved. The head characteristics that affect electrode wear comprise the speed at which the head approaches the job – larger equipment may have a two-speed head that applies the full force only after the initial electrode contact is made.Although tip life is extended the slow approach speed will increase the weld cycle time and reduce production rates. The inertia of the head affects the speed of acceleration and deceleration and ideally the head should be designed to be as light as possible consistent with rigidity. Too much flexure of the arms will result in accelerated electrode wear due to movement between the electrode and the workpiece and unacceptable electrode alignment.

Low inertia is also required during weld pool solidification. As the molten weld metal cools and solidifies the weld nugget contracts. The electrode must be able to respond rapidly and be capable of following this slight deformation if sound and high-quality welds are to be produced. A 'squeeze' is therefore often applied, which assists in consolidating the weld, reducing shrinkage porosity and hot cracking.

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The bulk of the cost of a spot weld is the cost of dressing or replacing the electrode, the life being defined as the number of spot welds that can be made with a pair of electrodes while maintaining a minimum weld nugget diameter. Pick-up of aluminium on to the tip and rapid wear are the two main reasons for the short life of spot welding electrodes. High welding currents, surface finish and electrode forces further assist in shortening the electrode life. It is not uncommon in very high-quality applications such as aerospace for the electrode to require cleaning after as few as 20 spot welds.

Electrode life may be extended by the use of replaceable caps on the electrode tips or, it is claimed, by the use of copper alloys with increased hardness which reduces mushrooming of the tip. Increases in hardness can be achieved by alloying with zirconium or cadmium–chromium and dispersion hardened with aluminium oxide. Of these the 1% Cd-Cu are used for the softer alloys with the harder 1% Cr-Cu or 21% Cr-Zr-Cu alloys for the welding of the cold-worked or age-hardened alloys.

The profile of the electrode tip is important with respect to both the tip life and weld quality. Tips may be conical, truncated conical, flat, domed or cylindrical. Of these types the truncated cone and the dome predominate.

The most commonly recommended shape is the domed tip, the shape of which is more easily maintained in production than the truncated cone.

Alignment is also less of an issue and is favored particularly for portable equipment. The truncated cone tends to be used for commercial quality applications, mainly because electrode alignment is more critical and difficult to maintain consistently in production. Tip life, however, is markedly better, by a factor of two to three, than can be achieved with the domed electrode. Cone angles vary from 60° to 150° including an angle with a slight radius on the tip which aids in alignment and reduces marking of the sheet.

The tip profile may be maintained by grinding, filing or by the use of abrasive cloth in a shaped former. While this dressing operation may be performed manually it is difficult to maintain the correct tip shape and electrode alignment. The use of automatic tip dressing tools or specially designed hand-held manual or pneumatic tip dressers is strongly recommended.

Efficient electrode cooling is also necessary to maintain tip life. Large diameter electrodes will provide a greater heat sink but efficient water cooling is imperative. The cooling channel should be carried as close to the tip as possible, a distance of between 12 and 20 mm being usual with water flow rates of 5–10 litres/min. Water inlet temperature should be in the region of 20 °C and the outlet temperature in the region of 30°C.

V. NUMERICAL SIMULATION

Finite elements simulations are done in 3 steps with the main pieces:

1- Modeling by FEMB
2- The thermal study and processing
3- Post-Processing result of analysis by ANSYS software for results discussion

Finite-Element Modeling of SAW shows in Fig. 4.

The differential Equations (1) – (2) are solved iteratively by the SIMPLEC numerical procedure:

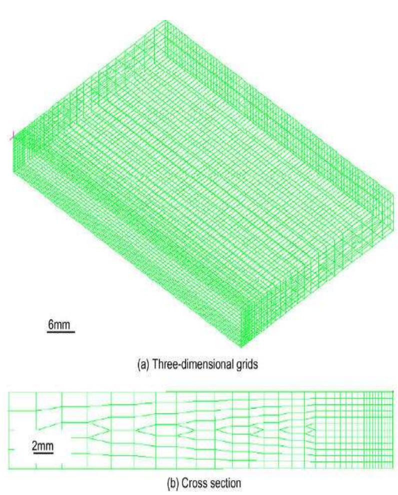

Fig. 4: Finite-Element Modeling of Resistance Welding

For boundary condition of fluid field:

$$\int_{\Omega} \partial P[\frac{1}{C^2}\ddot{P} + (\nabla)^Y \nabla P] d\Omega + \int_{T_1} \partial P n^T \ddot{u}\, dT + \int_{T_3} \partial P \frac{1}{g} \ddot{P}\, dT = 0 \quad (1)$$

For boundary condition of solid field:

$$\int_{\Omega} \partial u [P_s \ddot{u} + S^T DSu] d\Omega - \int_{T_1} \partial u^T \bar{t}\, dT = 0 \quad (2)$$

VI. QUALITY CONTROL

There is no specification available for the quality control of aluminum spot welds within the UK although ASME IX includes rules for procedure approval of spot welds. There is, however, a British Specification for the spot welding of steel, BS 1140, which contains a multitude of recommendations that may also be applied to aluminum. The main method of demonstrating acceptable quality is by means of the peel test, a simple, inexpensive test, but this may be replaced or supplemented by a tension shear test or a twist test. The test piece for all three tests is essentially the same – two overlapping plates welded together with a single spot. An acceptable result in the peel test is when the weld nugget is pulled out of the parent plate.

Monitoring of the welding parameters is an effective method of assuring quality during production welding. This monitoring may be very simple, detecting only the absence of a weld, or may be a sophisticated electronically based monitor which will both monitor and record current, number of cycles, pressure and time. This recording can be augmented by audible or visual warning of out-of-range welding parameters. Finally, one of the most effective quality control methods is visual inspection where surface melting, adhesion of the electrodes, pits, cracks, asymmetry of the weld spot and surface indentation can be readily identified. These features may be used to assess the quality of production batches.

Seam welding uses a wheel-shaped electrode (Fig. 5) to make either a series of overlapping spot welds to form a continuously welded and leak tight seam or a number of spot welds spaced apart – roll-spot welding. The requirements on electrodes and surface finish are the same as for spot welding. The shunt effect of the closely spaced nuggets and the short weld times mean that higher currents are necessary than for spot welds. As the name suggests flash butt welding is capable of making butt joints in bar-like or tubular components, L, T and X-shaped extrusions, etc. The weld is a solid phase joint where the two ends of the component are forged together at high temperature, any molten metal being expelled from between the two faces (Fig. 6). The process takes place in two phases, a 'flashing' and an upsetting phase. The two components to be joined are clamped in electrodes, at least one of which is movable. A low-voltage, high amperage current is applied without the two components being in contact.

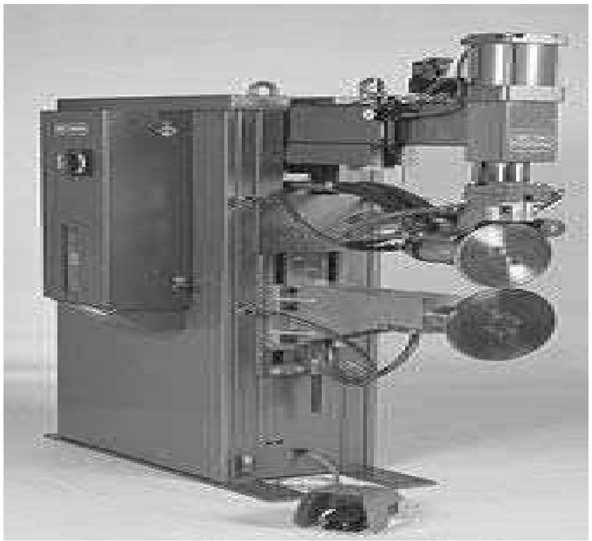

Fig. 5: Typical resistance seam welder showing the copper wheel electrodes.

The parts are then brought together at a controlled rate, resulting in a series of brief short-circuits as the asperities on the faying faces melt and burn off. This continuous series of short-circuits raises the temperature of the ends and expels some of the molten metal, giving the 'flashes' that give the process its name.

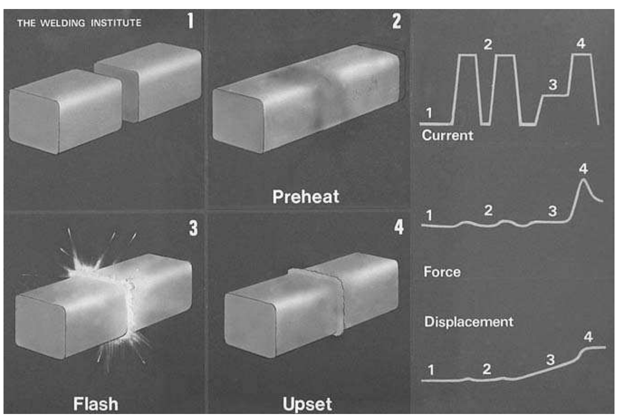

Fig. 6: Principles of flash butt welding. Courtesy of TWI Ltd

VII. CONCLUSIONS

Capacitive discharge resistance welding uses large capacitors to store energy for quick release. Fig. 7 and Fig. 8 show a typical capacitor discharge curve.

Capacitive resistance welders have many advantages. Weld nugget formation takes place during the first few milli seconds. Capacitive discharge welders allow extremely fast energy release with large peak currents. More of the energy goes into weld formation and less into heating surrounding material. The heat affected zone, where the properties of the metal have been changed from rapid heating and cooling, is localized to a small area around the weld spot. The quick discharge rate of CD welders also allows electrically and thermally conductive materials, such as copper and aluminum, to be welded. Capacitive welders deliver repeatable welds even during line voltage fluctuations.

Spot welding relies on the principle of metal resistivity to heat and fuse metal. A large current is passed through the work piece. Energy is dissipated due to the metal resistance in the form of heat which melts and fuses weld materials. There are two phases to the melting process. The welder must overcome the material contact resistance and the bulk resistance of the material. Figure 2 shows an example micro-scale surface profile. On the micro-scale, material surfaces are ruff and only contact in a limited number of locations. In the first few milli-seconds of weld formation these high resistance, microscopic metal bridges melt allowing other bridges to come into contact and fuse. When all of the bridges have fused the contact resistance equals zero. The bulk resistance of the metal then plays the final role in the weld formation.

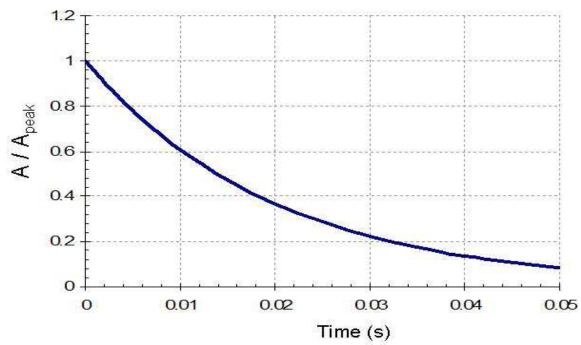

Fig. 7: Sample capacitor discharge curve

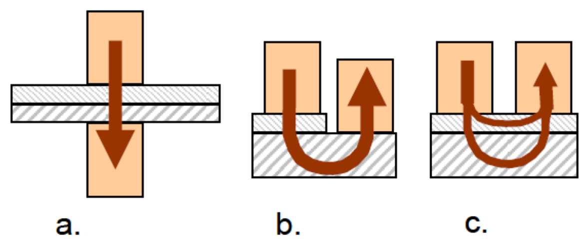

Fig. 8: Examples of resistance welding electrode configurations: a) direct, b) step, and c) series

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Ali Moarrefzadeh

Faculty member of Department of Mechanical Engineering, Mahshahr Branch, Islamic Azad University , Mahshahr , Iran
E-mail: a_moarrefzadeh@yahoo.com
a.moarefzadeh@mahshahriau.ac.ir
Tel: +989123450936