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An efficient method of spot welding Aluminium alloys with induction preheating

Steel has been the material of choice for automobile manufacturers. In the recent years material such as aluminium and its alloys are taking over the market because of their light weight. The use of aluminium, in automobile manufacturing can result in overall fuel efficiency. Spot welding aluminium alloys require higher electric power and less welding time as compared to steel. Welding guns that can produce an electric current which is approximately 2 to 3 times higher, as compared to steel are required for spot welding aluminium. An efficient method of spot welding Aluminium alloys with the preheating process has been proposed in this paper. Preheating Aluminium sheet before spot welding reduces the thermal and electrical resistance which brings down the electric current requirement to spot weld Aluminium structures. Both spot welding and induction preheating process have been modelled in this paper. The test results of the preheating process have also been verified with practical heating trials. The preheating is performed on-the-fly in advance to spot welding process. The results show that spot welding Al 6082 after preheating up to 200°C, the output current requirements to make the spot weld are reduced by 22%..

Keywords: Finite element method, pre heating, resistance spot welding, induction heating, aluminium welding.

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1. Introduction

Professor Elihu Thomson invented spot welding process in 1877 and since then it has been widely used in manufacturing industry, particularly in the automobile and air craft industries [1]. In order to form a spot weld, current is passed through conductive electrodes made of copper or tungsten. The welded parts are held together by a force which is applied during the welding cycle. Heat is generated due to the resistance offered at the junction of the parts being welded. The heat generation depends on the parameters such as weld time, weld current, and the force applied during the process.

In the automobile industry, corrosion resistant galvanized steel sheets are most widely used. In order to enhance the fuel efficiency, lighter materials such as magnesium alloys and aluminium are becoming a popular choice [2]. By using a lighter non-iron alloy in car manufacturing decreases the overall weight of the vehicle. A reduction in the weight of a car by 10% will produce a 6 - 8% saving in terms of gasoline. Reducing the total weight of each 100 pound will involve a saving of 3.4 - 5.3 % per 1000 miles [3]. Automobile manufacturers are shifting to lighter material such as aluminium in the car manufacturing. According to a news release by Detroit, it is expected that aluminium will double its share

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of the average automotive materials by the year 2025. Aluminium and its alloys have densities from 2600 Kg/cm^3 to 3000 Kg/cm^3. The melting point of pure aluminium is 660^{o}C. Aluminium alloys have an approximate melting range between 480^{o}C to 660^{o}C, depending on the alloy's composition. Materials such as copper, zinc, manganese, silicon, and magnesium are used as alloy elements together with aluminium. The mechanical strength of some aluminium alloys exceeds the strength of mild steel. The physical properties of aluminium alloys and mild steel are given in Table.1 [4].

Aluminium alloys have both higher thermal and electrical conductivities and thus a higher rate of heat input for fusion welding. To avoid overheating, aluminium structures must be heated very quickly as compared to steel. Spot welding of aluminium and its alloys require higher power welding guns. An electric current, which is higher approximately by a factor of 2 to 3, is required to spot weld aluminium sheets of the same thickness as compared to steel. The

Table 1 Properties of Al Alloys and Mild Steel

	Melting Temperature [^{o}C]	Electrical Conductivity 10^6[S.m]	Thermal Conductivity [W/cm.K]	Coefficient of Thermal Expansion 10^{-6}.[1/K]
Mild Steel	1560	5-10	0.32-0.66	11.4
Al Alloy	480-660	14.3-37.7	12.-2.37	22-23

spot welding time for aluminium alloys is almost 1/3 of the weld time when compared with steel [5].To avoid the high electric power necessary to spot weld aluminium, pre heating by induction can be applied. The preheating can be performed on-the-fly immediately in advance to the spot welding process. According to the authors knowledge such a technique to preheat the sheets by induction heating prior to spot welding process has not been reported in the literature. The combination of induction preheating and spot welding process are modelled in this paper. The reference [6] has used the preheating technique to raise the temperature of thick steel materials along the weld path. Their results conclude that filler material bind the work pieces better when weld path is preheated.

The most popular software used to model the resistance welding process are ANSYS [7], JWRAIN [8] and ABAQUS [9]. About 90% of FEM programs are generic and use similar matrix solvers, quadrature rules and matrix assembly procedures. COMSOL Multiphysics software [10], [11] has been used to model spot welding process for steel sheets in order to view the weld nugget growth, which varies with the electrode geometry. Both, spot welding and induction preheating processes have been modeled using COMSOL Multi-physics software in this paper. A transient simulation model of spot welding process includes electrical, thermal and structural mechanics module. The applied force on the welding electrodes and the fixed boundary conditions are governed by the structural mechanics module. The input current which is delivered to the welding electrodes is governed by the AC/DC module of the software. The AC/DC module is linked to heat transfer module in order to see the joule heat distribution and is governed by Equation 1.

$$\rho C_P \, {}^{\partial T}\!/_{\partial t} = \nabla(k\nabla T) + Q_T \qquad (1)$$

where k, , C_P, Q_T are thermal conductivity, specific heat, density, specific heat, and heat source term per unit volume.

The induction heating simulation is controlled by the induction heating physics module in the COMSOL software. In this model, a high frequency alternating electric current is passed through the coil which produces a changing magnetic field. Al 6082 sheets are then placed in the field and, due to electromagnetic induction the sheets are pre heated to the desired temperature. The current magnitude and the frequency are parameterized over the range to determine the heating produced in the Al 6082 sheet.

1.1. Important consideration while spot welding Aluminium alloys

Aluminium alloy sheet are difficult to weld because of their high electrical and thermal conductivities. In [12], the authors have compared Silicon controlled rectifier (SCR) type 60 Hz machines to the modern inverter type 1000 Hz medium frequency direct current (MFDC) machine to spot weld aluminium sheets. The results from their research shows that the welding range in the weld lobe diagram for the inverter based machine is larger than for the SCR based machine. Another advantage of inverter based machines is quick and precise welding control. A MFDC spot welding machine, specified for welding aluminium, can spot weld almost the full range of steel within the automotive industry. However, the reverse cannot be stated, as the welding current magnitude required for welding aluminium is approximately 2 to 3 times that of steel and, in addition, the pressure required is also high. Therefore, there is a rapid deterioration of the weld electrode tip surface in the case of aluminium spot welding. Special measures must be considered while spot welding aluminium so that rapid deterioration of the electrode can be avoided which is majorly caused by overheating. Due to this overheating, aluminium deposits on the welding electrode. The aluminium deposits on the welding electrode must be removed by some form of electrode maintenance after a few welds, otherwise, the increase in resistance heating at the surface leads to more aluminium melting and thus more serious electrode damage. In [13], the authors have investigated the use of metal working lubricants that result in a reduction of the alloying, pitting and pickup effects at the sheet and electrode interface, thus causing an extended life of the weld electrodes. To avoid the rapid electrode deterioration, Fronius USA uses a technique using a process tape along with the welding electrode in order to avoid contamination. This protection results in a significantly increased service life for electrodes. Another important point in spot welding aluminium is the formation of an oxide layer Al_2O_3 which has a melting temperature of around 2000^oC. This layer should be removed chemically or mechanically before welding. General Motors uses a special multi-ring domed electrode to weld aluminium to aluminium by disrupting the oxide layer on the metal surface [14].

The remainder of the paper is organized as follows:- the finite element model to spot weld Al 6082 is described in Section 2. Section 3 describes the preheating of Al 6082 by means of an induction heating process. The spot welding process after the preheating is discussed in Section 4 and Section 6 summarizes the conclusions.

2. FEM MODEL FOR SPOT WELDING

The spot welding process involves phenomena such as, heat conduction, latent heat of fusion, joule heating, and phase changes [15]. A 2D axial symmetric model of the spot welding MFDC process for welding Al 6082 has been developed. The developed 2D axial symmetric model can be described as a 3D problem with good accuracy. The geometry includes the welding electrodes and 1mm thick Al 6082 alloy sheets. In order to obtain accurate results in FEM simulation, the developed geometry should be meshed properly.

The software has the capability to draw tetrahedral, triangular, and quad meshes on the boundaries and in the domains. A triangular mesh with 1028 elements is made for the developed 2D axial symmetric model. The welding current is applied to the upper electrode in the simulation model with the lower electrode being grounded. The applied current produces a weld nugget at the two sheets interface as shown in Fig 1.

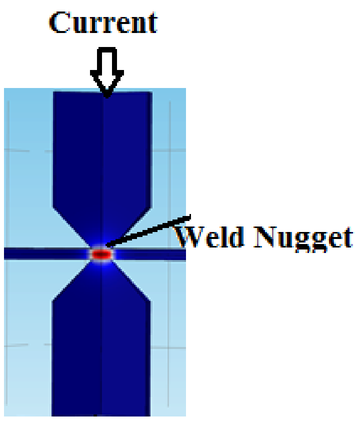

Fig 1 Spot welding process

The welding simulation runs for 100 msec using electro-thermal-mechanical physics. The welding time is 80 msec and the hold time is 20 msec. The electric current applied to the welding electrode ranges from 13 kAmps to 21 kAmps with incremental steps of 1 kAmp. The temperature profile of the spot welding simulation with current magnitude of 18 kAmps after 4 cycles is shown in Fig 2.

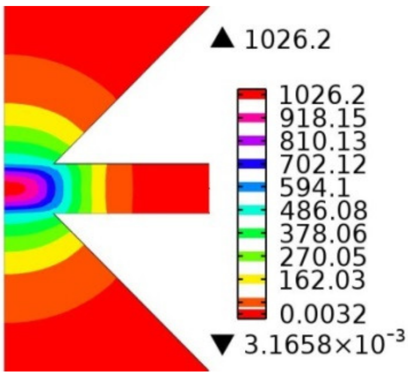

Fig 2 Isothermal profile in ^{o}C

Temperature dependent material properties for both electrode and the work piece are considered in the developed simulation [10], [16].

The timed temperature distribution of a point considered at the center of the weld nugget can be a good indicator of the weld nugget formation as shown in Fig 3

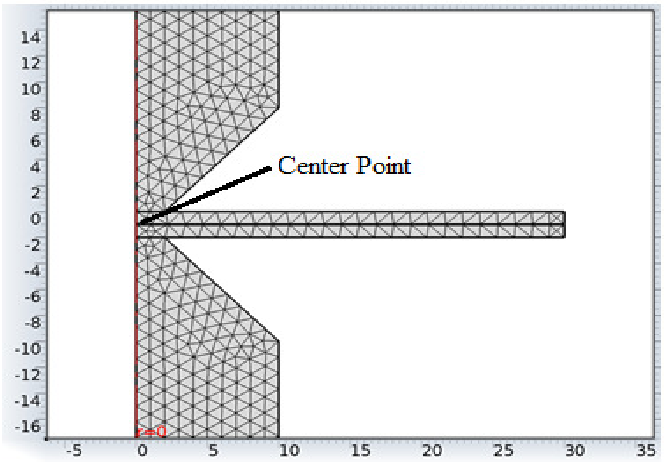

Fig 3 Mesh and center point at weld nugget

Fig 4 shows the temperature changing history of a point shown in Fig 3, considered to be at the center of the weld nugget. The results in Fig 4 also show the effect of enthalpy in the FEM simulation model that forms a plateau where the temperature remains constant while melting. The results show that the minimum current required to obtain the welding condition (650 ^{o}C) is 18 kAmp. This current is approximately 1.8 times the weld current required for steel of the same thickness if same the conditions are maintained.

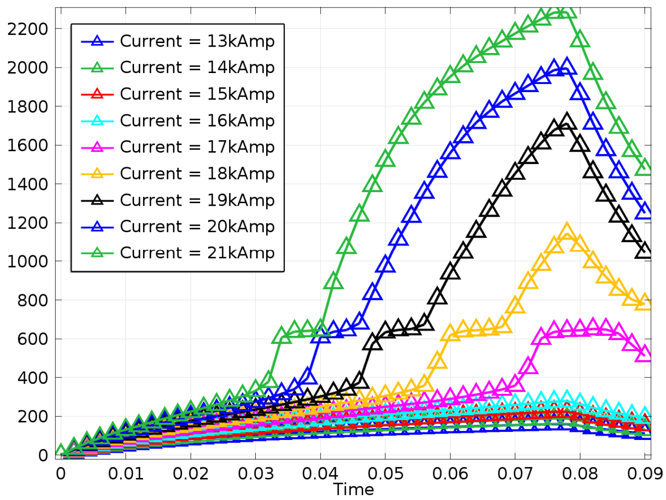

Fig 4 Timed temperature distribution of a point without pre heating

3. INDUCTION HEATING

Induction heating system for preheating the Al 6082 sheets is modelled using COMSOL. In [17], the authors have also used COMSOL software to model the induction heating process to study the difference of inductor width with the current density distribution and the efficiency of the system. The advantage of using induction heating with the existing spot welder for pre heating aluminium sheets is that, unlike, other heating process induction heating does not contaminate the heated material. For an induction heating setup, high frequency alternating current is passed through the work coil. As a result of this high frequency current, changing magnetic field is produced with in the coil.

When the work piece (Al 6082) sheets are placed in this alternating magnetic field, current is induced inside the work piece because of electromagnetic induction phenomenon. This induced current heats the work piece due to phenomenon of joule heating. The coil design and selection of power-supply frequency and current magnitude ensures that there is close control of the heating rate and pattern [18].

3.1. Induction heating simulation

In the induction heating simulation two coils made of a copper material are introduced into the spot welding setup as shown in Fig 5. The preheating is performed before the weld electrode move down to apply the required squeeze force and the welding current for spot welding. For preheating purposes a high frequency alternating electric current is passed through the coil. The developed model can be useful in predicting the amount of current and the range of frequency required to heat the work piece. A magnetic field module is also linked to the induction heating module in order to determine the magnetic flux density distribution and induced current density distribution for different frequency signals.
Fig 6 shows the magnetic flux density distribution at 400 kHz with a current magnitude of 800 Amps. The current magnitude and the frequency are parameterized over the range to determine the best possible conditions to pre heat Al 6082 sheet before spot welding.

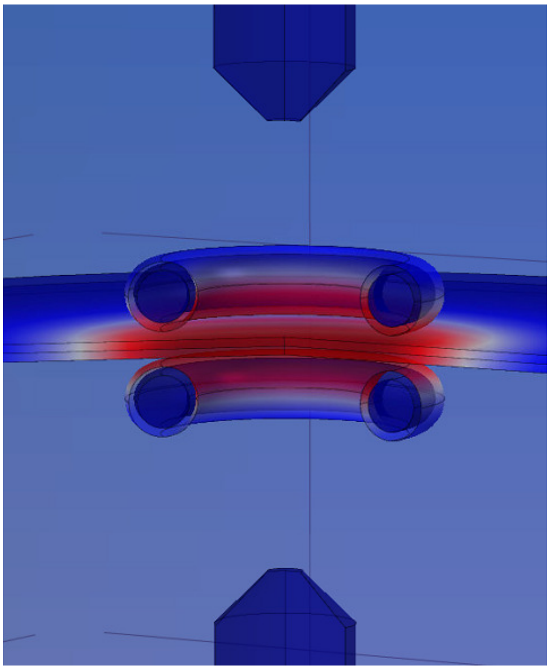

Fig 5 Induction heating for pre heating

The current applied to the copper coil ranges from 100 Amps to 1000 Amps with incremental step of 100 Amps. The frequency is parameterized form 100 kHz to 400 kHz.

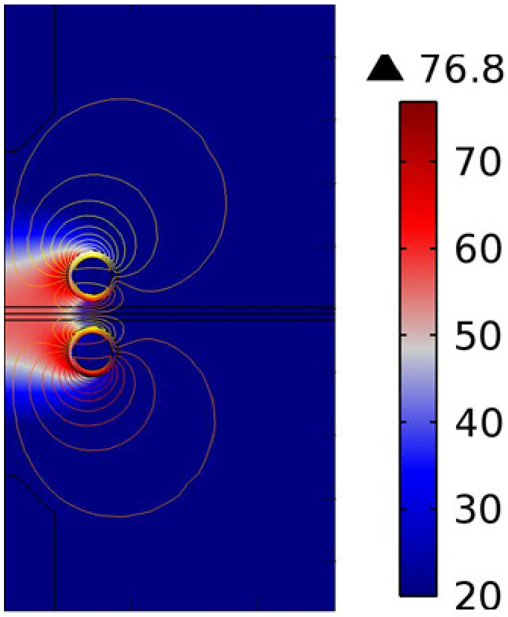

Fig 6 Magnetic flux density distribution [mTesla]

The Al 6082 sheets are preheated up to 200°C. The results in Fig 7 shows the heat profile at the same center point which is considered for the spot welding process at 400 kHz. It can be observed from the simulated results that in order to heat 1mm Al 6082 sheets up to 150°C - 200°C, the amount of current required is around 700 – 800 Amps.

Practical heating trials on the same sheets have been carried out using commercially available induction heating system Easy Heat 8310, 10 kW using a split solenoid coil. The test results showed that in order to heat the sheet up to 150°C the current drawn was 683 Ampere with frequency of 332 kHz.

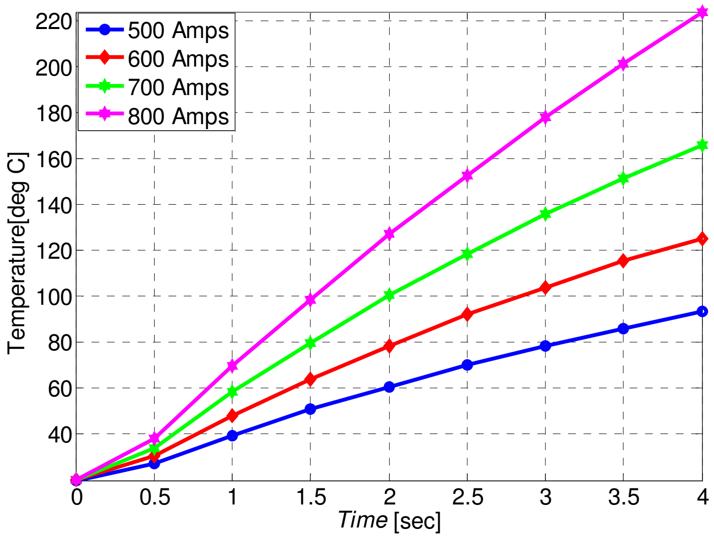

Fig 7 Heat distribution at center point with induction heating

4. SPOT WELDING AFTER PRE HEATING

After the preheating (100°C and 200°C), the welding electrodes are closed and a squeeze force is applied. The welding is carried out using the same current specifications as mentioned in the Section 3. Again the timed temperature distribution of the same point in the middle of the weld is observed. Fig 8 and Fig 9 show the temperature changing history of a point considered to be at the midpoint of the weld. The results show that the minimum current required to obtain the welding condition (650 °C) has been reduced to 16 kAmps and 14 kAmps by preheating the sheets to 100°C and 200°C respectively. The results show that spot welding Al 6082 after preheating up to 200°C, the output current requirements to make the spot weld are reduced by 22%.

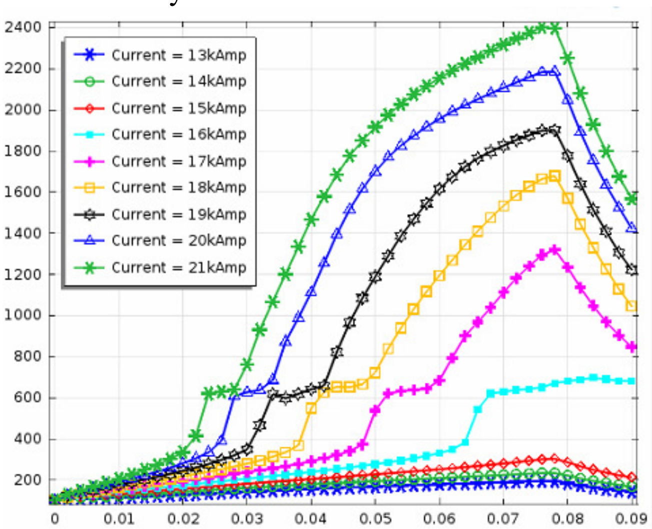

Fig 8 Timed temperature distribution of a point with pre heating 100°C

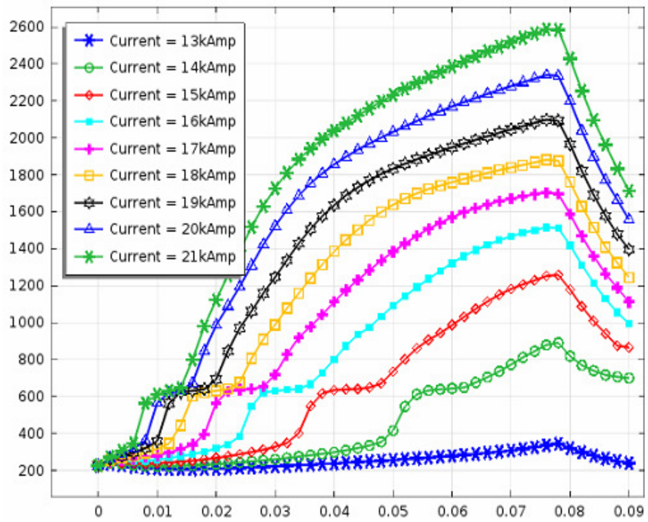

Fig 9 Timed temperature distribution of a point with pre heating 200°C

5. CONCLUSION

With the advancements of numerical tools and the increased computational capability of computers it has become possible to model the complex problems such as welding. The 2D axial symmetric model developed in this paper is advantageous in selecting appropriate welding parameters so as to produce a good welding nugget.

A MFDC spot welding gun in production set-up for spot welding aluminium can weld full range of automotive steels because of its high power capability. However, the reverse is not true. The high electric power requirement for welding aluminium can be reduced by preheating by means of an induction heating technique. The advantage of induction heating process for preheating Al 6082 sheets prior to spot welding is that it is a non-contact heating process and is highly repetitive producing identical heating profiles once the adjustments have been made to the power supply. The developed model is the combination of induction preheating and spot welding process. The results from the simulation shows that the power requirement of the spot welder used for spot welding aluminium can reduce using the preheating process.

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