1. Introduction

Aluminium alloy as the fabrication material has gained significance in the recent past for manufacturing of car, bus and railway bodies, etc. due to its light weight and good formability. Traditionally, resistance spot welding process has been the most successful and widely accepted joining process for steel bodies. However, aluminium as a material for resistance welding calls for special attention due to its alloying tendency with the copper electrode, resulting in increased electrode wear, and thus deterioration of the weld quality.

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Niwa et al.6) included a coupled thermo-mechanical analysis to reflect the influence of the same on current density distribution, which was earlier highlighted by Yamamoto and Okuda.6) In principle, such a thermo-mechanical analysis should consider the in-process growth of electrode–sheet and sheet–sheet interface that decides the pattern of current flow. This influence is expected to be more profound with curved (or domed) face electrodes compared to flat face electrodes. Secondly, the thermo-mechanical analysis should manifest the variation of contact resistance along sheet–sheet or electrode–sheet interface as a function of the contact pressure and the contact temperature distribution. Nishiguchi and Matsuyama9) calculated both the electrode–sheet and the sheet–sheet contact diameters using finite element method; based on which, the electrode–sheet contact diameter was expressed as a function of electrode force and temperature dependent flow stress of material and related the sheet–sheet contact diameter with electrode–sheet contact diameter and sheet thickness. These relations were then used as an a-priori to the complete coupled electro-thermal-mechanical analysis. However, the influence of contact resistance was neglected. Gupta and De10) and De et al.11) included the in-process growth of electrode–sheet contact diameter of spherical tip electrodes as a function of electrode force and temperature dependent flow stress of steel. The sheet–sheet contact diameter was taken to be equal to the electrode–sheet contact diameter thereby assuming a cylindrical current conduct-
ing zone through the bulk material thickness. However, the electrical analysis was done in a simplified, analytical manner.\textsuperscript{10,11} Similar numerical process analyses\textsuperscript{12–17} were reported for aluminium alloys used for automobile and other user industries. It is subsequently established\textsuperscript{13} that resistance spot welding of aluminium sheets is more difficult even compared to galvanized steels, as the electrode wear is extremely rapid. Brown et al.\textsuperscript{12,13} and Murakawa et al.\textsuperscript{16} presented comprehensive electro-thermal-mechanical modelling. While the former authors\textsuperscript{12,13} considered a constant sheet–sheet contact resistance of 450 $\mu$Ω below the bulk material solidus temperature and no contact resistance along the electrode–sheet interface, the other group\textsuperscript{14} neglected contact resistance fully. Matsuayama\textsuperscript{15} reported a numerical model for aluminium alloys with spherical electrodes by which the calculation to find the electrode–sheet contact diameter remained similar to a previous work\textsuperscript{9}, a different relationship here was used\textsuperscript{15} to estimate the sheet–sheet contact diameter. The initial contact resistance along both the electrode–sheet and sheet–sheet interface was assigned through Hertz's law for multiple point contact and the drop in contact resistance was assumed to follow the temperature dependent flow stress curve. Xu and Khan\textsuperscript{16} also developed a electro-thermal-mechanical simulation model for curved face electrode. The initial contact resistance along sheet–sheet and electrode–sheet interface was considered\textsuperscript{16} to be 225 $\mu$Ω and 6.5 $\mu$Ω respectively, which reduce linearly with temperature finally to a very low value at melting temperature. De and Theddeus\textsuperscript{17} recently presented a thermo-electrical analysis of spot welding of aluminium using flat face electrodes.

The review of these literatures indicates that numerical modelling of resistance spot welding process for aluminium sheets especially with curved face electrodes is still in a developing state. This can primarily be attributed to the scarcity of reliable experimental database of contact resistance and its variation with temperature and pressure for various surface conditions of aluminium sheets, which is widely available for steel sheets.\textsuperscript{20} This has forced the researchers to include various considerations—either no contact resistance,\textsuperscript{14} or anticipated values\textsuperscript{2,13} on the basis of experiences from steel sheets or else the estimation\textsuperscript{15} of the same through Hertizan contact theory. With the subsequent publications\textsuperscript{20,23} on contact resistance and its variation for different surface conditions, more reliable analysis can possibly be attempted. While Thornton et al.\textsuperscript{20} showed that contact resistance can cover a wide range of values and the same may not necessarily decrease with load applied, the latter group\textsuperscript{23} presented an exponential decay of contact resistance with temperature on the basis of their extensive experiments. The in-process growth of the electrode–sheet and sheet–sheet contact area with curved face electrodes is another problem, which can be solved either by a rigorous and computationally expensive thermo-elasto-plastic solution\textsuperscript{12–14,16} or through an a-priori elasto-plastic analysis\textsuperscript{8,15} and its adaptation to the real-time analysis. The work-piece in resistance spot welding depicts not only a highly, non-uniform temperature distribution, but also manifests a growing molten zone from the very initial period. Solving such a domain iteratively (or incrementally) for mechanical deformation analysis calls for many simplified assumptions especially on temperature dependence of mechanical properties which are rarely available, intricate iterative procedures often leading to non-convergence of solutions and extremely high-end computational supports.\textsuperscript{10–13,16,22} The other approach\textsuperscript{8,15} is an excellent alternative while needs to be evaluated for different materials, sheet thicknesses and surface conditions, electrode geometries and varying electrode forces and weld currents. A simpler approach to take care of these phenomena without much loss in generality is still demanding.

The present work thus aims at developing an efficient electro-thermal numerical model based on finite element method for resistance spot welding of aluminium alloys with a typical curved face electrodes including temperature dependent material properties and latent heat during phase changes. For this purpose, an in-house software in Fortran-90 is developed. The contact resistance is included following the work of Greitmann and Rothers\textsuperscript{22} since they could manifest a mathematical form representing variation of contact resistance as a function of temperature for different surface conditions. The in-process growth of electrode–sheet contact is accounted for using a simple mechanical analysis which was already applied successfully in the case of uncoated\textsuperscript{16,22} and galvanized steel\textsuperscript{11} sheets. The calculated results of nugget diameter and penetration for different combination of process parameters and contact resistances are presented subsequently.

2. Theoretical Background

2.1. Governing Equations and FEM Discretisation

The complete analysis has been carried out in a cylindrical coordinate system in a two-dimensional axi-symmetric form assuming no temperature or current density variation along $\theta$ axis. Only one quadrant of the complete sheet–electrode geometry is analysed due to the axial symmetry of electrode (Fig. 1). The governing heat conduction equation in such case can be stated as,

$$\frac{1}{r} \frac{\partial}{\partial r} \left( rK \frac{\partial T}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial z} \left( rK \frac{\partial T}{\partial z} \right) + \dot{Q} = sc \frac{\partial T}{\partial t} \quad \text{...(1)}$$

where, $\dot{Q}$ refers to the rate of internal resistive heat generation per unit volume, $r$ and $z$ are radial and axial coordinates and $s$, $c$ and $K$ are density, specific heat and thermal conductivity of the material. The complete analysis has been carried out in a cylindrical coordinate system in a two-dimensional axi-symmetric form assuming no temperature or current density variation along $\theta$ axis. Only one quadrant of the complete sheet–electrode geometry is analysed due to the axial symmetry of electrode (Fig. 1). The governing heat conduction equation in such case can be stated as,

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conductivity of the material respectively. The boundary conditions used in the heat transfer analysis are,

(a) \( T = T_e \) (along the inner face of electrode experiencing cooling water flow) ...........................(2)

(b) \( \frac{dT}{dn} = 0 \) (on the sheet–electrode boundary facing air) ..............................................(3)

(c) \( \frac{dT}{dr} = 0 \) (across the sheet and electrode symmetry line; z-axis in Fig. 1) ............................(4)

\( T_e \) refers to the ambient (or cooling water) temperature and \( n \) denotes normal direction to the surface. The finite element discretisation of the complete sheet–electrode geometry has been carried out using four node iso-parametric elements (Fig. 2). Figure 3 shows the sheet–electrode geometry being analysed. Within an element (Fig. 2), a variable \( \phi(r, z) \) is expressed as,

\[
\phi(r, z) = N_i \phi_i + N_j \phi_j + N_k \phi_k + N_l \phi_l
\]

where, \( N_i + N_j + N_k + N_l = 1 \) ..................................................(5)

\( N_i, N_j, N_k \) and \( N_l \) are the elemental shape functions. The final matrix equation to be solved for Eq. (1) is obtained in the following form.

\[
\begin{align*}
\frac{2}{3}[H] + \frac{1}{\Delta t}[S]((T)_{n+1}) + \left(\frac{1}{3}[H] - \frac{1}{\Delta t}[S]((T)_n\right) + \frac{2}{\Delta t^2} \int_0^M (f) \, dt = 0
\end{align*}
\]

The elements of \([H], [S]\) and \( \{f\} \) matrices are given by

\[
\begin{align*}
\{k\} &= \int_0^L \int_0^\pi \left(k \frac{\partial N_i}{\partial r} \frac{\partial N_j}{\partial r} + k \frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z}\right) 2\pi rdrdz \\
\{s\} &= \int_0^L \int_0^\pi N_i s c \frac{1}{2} \pi rdrdz \\
\{f\} &= -\int_0^L \int_0^\pi \left(\hat{Q} = s c \frac{\partial T}{\partial r}\right) N_i 2\pi rdrdz
\end{align*}
\]

\( t \) refers to time, \( \Delta t \) refers to time increment, \( \{T\}_{n+1} \) and \( \{T\}_n \) are nodal temperature vectors corresponding to \((n+1)-\)th and \( n \)-th time steps respectively. The latent heat of melting and solidification is included in this simulation through an increase or decrease in the specific heat of the material. The specific heat \( c \) is expressed as follows.

\[
\begin{align*}
c &= C_i & \text{for} & \quad T \leq T_{s_1} \\
c &= C_2 & \text{for} & \quad T = T_{l_1} \\
c &= C_m = \left(\lambda(T_L - T)\right) + (C_1 + C_2)/2 & \text{for} & \quad T_{s_1} \leq T \leq T_{l_1}
\end{align*}
\]

where \( \lambda \) is latent heat, \( T_{s_1} \) and \( T_{l_1} \) are solidus and liquidus temperatures. For an element of volume undergoing change the specific heat is obtained as a weighted average of the associated specific heats; viz. \( C_i \) and \( C_m \) (for solid to mushy state or the reverse), \( C_m \) and \( C_2 \) (for mushy to liquid state or the reverse) or \( C_i, C_m \) and \( C_2 \) (for a jump from solid to liquid state or the reverse) \( \frac{10,11,22}{10,11,22} \).  

The governing equation for electrical field analysis is expressed in terms of electrical potential, \( \phi \).

\[
\frac{1}{\rho} \frac{\partial}{\partial r} \left( \frac{1}{\rho} \frac{\partial \phi}{\partial r} \right) + \frac{1}{\rho} \frac{\partial}{\partial z} \left( \frac{1}{\rho} \frac{\partial \phi}{\partial z} \right) = 0 \quad ... (11)
\]

where, \( \rho \) is the electrical resistivity and \( r \) and \( z \) are radial and axial coordinates. The electrical current density \( J \) and the heat generation per unit volume \( q \) can be given in terms of electrical potential, \( \phi \),

\[
\begin{align*}
J &= -\frac{1}{\rho} \nabla \phi & \text{........} (12) \\
q &= \frac{1}{\rho} (\nabla \phi \cdot \nabla \phi) & \text{........} (13)
\end{align*}
\]

The boundary conditions for the electrical field analysis are,

(a) \( \frac{\partial \phi}{\partial n} = 0 \) (on the sheet–electrode boundary facing air) ..............................................(14)

(b) \( \frac{1}{\rho} \int \frac{\partial \phi}{\partial n} ds = I \) (on the top surface of the electrode) ..............................................(15)

The final matrix equation to be solved for Eq. (11) is obtained similarly using four node iso-parametric elements.
expressed as in contact to the electrode face. This can be mathematically total electrode force will be supported by the sheet surface curved face electrodes during welding time. It is presumed area along electrode–sheet interface can grow in the case of

\[ [H][\phi]=0 \] ..........................(16)

where, \([H]\) is the electrical conductivity matrix where the terms of \([H]\) matrix is given as,

\[ h_j^{\nu} = \int \left( \frac{1}{\rho} \frac{\partial N_i}{\partial r} \frac{\partial N_j}{\partial r} + \frac{1}{\rho} \frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} \right) 2\pi rdrdz \] ..........................(17)

Equations (16), (12), (13) and (6) are solved sequentially with a time step increment of 0.0001 s for the complete weld time. The electrode–sheet and the sheet–sheet contact diameter are estimated at the beginning of each time increment as described in Sec. 2.2. One complete solution takes 15–20 min using an Intel Pentium III processor.

2.2. In-process Growth of Electrode–Sheet Contact

Figure 4(i) and 4(ii) show schematically how the contact area along electrode–sheet interface can grow in the case of curved face electrodes during welding time. It is presumed in the present work that at any particular time instant, the total electrode force will be supported by the sheet surface in contact to the electrode face. This can be mathematically expressed as

\[ P = \int_0^{\gamma} \sigma_\nu(T) 2\pi rdr \] ..........................(18)

where \(P\) is electrode force, \(r_c\) is the radius of the projected area of contact surface (Fig. 4) along the electrode–sheet interface and \(\sigma_\nu(T)\) is temperature dependent flow stress. To incorporate this, a thin layer of elements (size 0.1 mm x 0.1 mm) is considered along the top surface of the sheet in contact with the electrode. At the beginning of each time step, \(r_c\) is updated following an incremental procedure where \(\sigma_\nu(T)\) is evaluated at the averaged contact temperature, \(T_{av}\),

\[ T_{av} = \frac{\sum_{i=1}^{m} T_i A_i}{\sum_{i=1}^{m} A_i} \] ..........................(19)

where \(m\) refers to the number of contact elements within \(r_c\) that satisfies Eq. (18) and \(T_i\) and \(A_i\) are the elemental temperature and area respectively for the \(i\)-th element. At the beginning of the first time step, \(T_{av}\) is calculated (Eq. (19)) considering \(m\) as 1 (i.e. only one contact element); \(\sigma_\nu(T)\) is then evaluated and substituted in Eq. (18). If the right side of Eq. (18) is lesser compared to left side, \(m\) is increased by one element (\(r_c\) increases by 0.1 mm as the finite length of each contact element is 0.1 mm) along the radial direction away from the axis. A modified \(T_{av}\) is then evaluated followed by modification in \(\sigma_\nu(T)\) which is next substituted in Eq. (18). This procedure continues until a specific value of \(\sigma_\nu(T)\) is found so that the right hand side of Eq. (18) is equal to the left hand side (however, as Eq. (18) is solved incrementally, instead of an exact solution, the calculation actually stops when the right hand side of Eq. (18) is equal to or just greater than the left hand side). This complete procedure is followed at the beginning of each time step.

The sheet–sheet contact zone is taken identical with electrode–sheet contact area assuming a cylindrical current conducting zone within the sheet thickness. This consideration seems not far from reality as the ratio of electrode diameter to the sheet thickness normally being quite high, the current flow lines along the axial direction can be taken to be dominant.10,16)

2.3. Computation of Contact Resistance

The nature and variation of contact resistance is incorporated following the relationship,21)

\[ R_0(T) = \alpha R_0 \beta^{(T-T_0)/(T_0-T_p)} \] ..........................(20)

where, \(R_0(T)\) is the temperature dependent contact resistance, \(R_0\) the initial value of contact resistance at room temperature, \(\alpha\) and \(\beta\) factors depending on type of sheet metal, \(T_p\) the melting temperature of aluminium, \(T_0\) the ambient temperature and \(T\) the variable temperature. It was shown experimentally21) that \(\alpha\) and \(\beta\) can be taken as 1 and 25 respectively for aluminium alloys. Depending on the initial surface condition of sheets, several values of \(R_0\) are reported21) (e.g. 250 \(\mu\Omega\) in as-received condition; 550 \(\mu\Omega\) if pickled with 12% NaOH solution at 60°C for 60 s, 350 \(\mu\Omega\) if pickled with 12% NaOH solution at 60°C for 60 s and then washed; 100 \(\mu\Omega\) if pickled with 25% NaOH solution at 65°C for 60 s and then washed; 70 \(\mu\Omega\) for wire-brushed only) as sheet–sheet contact resistance. Similarly, three such values of \(R_0\) (0, 70 and 130 \(\mu\Omega\)) were reported for electrode–sheet interface resistance while the corresponding conditions were not explicitly mentioned.21) In the present work, calculations are carried out with \(R_0\) as 250, 350 and 550 \(\mu\Omega\) for sheet–sheet interface and 0 and 70 \(\mu\Omega\) for electrode–sheet interface.

A thin layer of elements (size 0.1 mm x 0.1 mm) is considered along the bottom surface (similar to along the top surface) to assume the sheet–sheet interface. Since the input to the contact elements should be in terms of resistivity for electrical analysis, contact resistivity due to contact resistance is further expressed as,

\[ (\rho) = (R_0(T) A/h) \] ..........................(21)

where, \((\rho)\) is the contact resistivity of the \(i\)-th element along the contact surface, \(A\) the cross-sectional area of sheet–sheet contact zone, \(A_i\) and \(h\) the cross-sectional area and height of \(i\)-th element respectively. The net resistivity of the \(i\)-th contact element \((\rho)\) is
\((\rho_i) = (\rho_b) + (\rho_r)\), \((\rho_r)\) is the temperature dependent bulk resistivity of \(i\)-th element) \(...(22)\)

3. Results and Discussions

The temperature dependent material properties are considered following Ref. 14). The properties are fairly in line\(^{21}\) for typical aluminium alloy AlMg\(_{0.4}\)Si\(_{1.2}\). Sheet thickness is 1.0 mm. The electrode is of the type A 13×25 (i.e. electrode diameter of 13.0 mm and the electrode face radius of 32.0 mm) as per the ISO/DIN 5184. The calculated isotherms in the sheet–electrode geometry can be plotted either for instantaneous temperature or for maximum temperature at a particular instant. The first one represents the temperature distribution prevailing at that particular instant while the second one refers to the maximum temperature the sheet–electrode geometry has been subjected to till that time instant. Therewith it is possible to depict the growth of nugget diameter and penetration with time. Figures 5 and 6 show the maximum and the instantaneous isotherms respectively at 18 kA weld current after 0.02 s (1st weld period). The region heated above 600°C is referred to as the fusion zone. Figure 5 shows that the nugget is already formed within 0.02 s while Fig. 6 manifests that the temperature of the fused zone has already reduced to 530°C. The initial sheet–sheet contact resistance dictates the formation of weld nugget at the faying surface while as the interface temperature increases the contact resistance drops drastically. Unlike steel, the increase in bulk resistivity of aluminium with temperature is not sufficient\(^{14,21}\) to carry the growth of fusion zone due to the intensive heat dissipation through the bulk material linked with very high thermal conductivity of aluminium. Figures 7 and 8 show the maximum and instantaneous isotherms respectively after 0.08 s for similar conditions. It is clear from Figs. 5 and 7 that the there is no further growth in nugget diameter and penetration beyond 0.02 s. This indirectly reflects that the dynamic resistance of aluminium has almost no significance on the growth of fusion zone and this is in line with the previous investigations.\(^{15,20}\) Figure 8 shows that the fusion zone is further cooled down. However, the extent of the 450°C contour in Figs. 5 and 7 shows that the maximum temperature experienced by the electrode face increases with time. Such high temperature can initiate melting of magnesium along electrode–sheet interface and subsequently causes alloying of electrode face by a magnesium oxide layer.\(^{14}\)

Figures 9–11 show the in-process growth of electrode–
sheet contact zone, nugget diameter and penetration with initial sheet–sheet contact resistance (S-S CR) of 250, 350 and 550 μΩ respectively. It is observed that for the combination of electrode and sheet thickness investigated, the development of nugget diameter and the penetration is almost completed by the first cycle. From Figs. 9–11, 18–19 kA appears to be the minimum required current to obtain a nugget diameter of approx. 3.0 mm (∼3√/t, where t is sheet thickness) irrespective of the sheet–sheet contact resistance and with nil contact resistance along electrode–sheet interface (E-S CR) for this typical electrode geometry and sheet thickness with 2.0 kN electrode force. A comparison of Figs. 9–11 does not highlight any significant change in nugget diameter and penetration for different values of initial sheet–sheet contact resistance at a particular weld current (except at 14 kA which can possibly be neglected since weld dimensions are very small). This appears still more distinct in Fig. 12 where some calculations of an ideal case (i.e. with nil sheet–sheet initial contact resistance) are added for comparison. Figure 13 shows a similar variation

Fig. 9. Variation of electrode–sheet contact diameter and weld dimensions with weld time for 250 μΩ (micro-ohm) sheet–sheet contact resistance.

Fig. 10. Variation of electrode–sheet contact diameter and weld dimensions with weld time for 350 μΩ (micro-ohm) sheet–sheet contact resistance.

Fig. 11. Variation of electrode–sheet contact diameter and weld dimensions with weld time for 550 μΩ (micro-ohm) sheet–sheet contact resistance.

Fig. 12. Variation of electrode–sheet contact diameter and weld dimensions with various sheet–sheet contact resistances at no electrode–sheet contact resistance.

Fig. 13. Variation of electrode–sheet contact diameter and weld dimensions with various sheet–sheet contact resistances at 70 μΩ electrode–sheet contact resistance.
with an initial electrode–sheet contact resistance of 70 $\mu$Ω. It is observed that satisfactory weld nugget and penetration form even at low current of 14 kA in contrary to the case with nil electrode–sheet contact resistance. At 14 kA, the nugget diameter changes from 3.5 mm to 5.04 mm respectively at 250 to 550 $\mu$Ω sheet–sheet contact resistance while at weld currents 19–23 kA, the weld dimensions are almost same irrespective of sheet–sheet contact resistance. A similar situation is observed with nil electrode–sheet contact resistance also while the nugget diameters are smaller in that case. The electrode–sheet contact zone always remained sufficiently higher compared to the nugget diameter irrespective of welding current or initial sheet–sheet contact resistance.

Figure 14 shows the influence of electrode force on weld dimensions and electrode–sheet contact zone. It appears that the electrode force has very little influence on weld nugget and penetration especially for welding currents 19–23 kA. However, it is to be noted that initial contact resistance data considered in the present work is independent of electrode force since no data were available. Although, contact resistance was reported to be insensitive to electrode force, more investigation is inevitably needed to look into this aspect since most of existing experiments were carried out with flat face electrodes with fixed face diameter. It is felt that corresponding experiments should also be done using curved face electrodes with varying electrode face curvature and electrode force to identify the influence of the electrode–sheet contact area and electrode force on contact resistance.

4. Conclusion

(a) In resistance spot welding of 1.0 mm aluminium alloy sheets, the formation of fusion zone can be completed as early as within 0.02 s i.e. the first cycle with a 50 Hz ac power supply. At a specific current, increase in weld time cannot further enhance the development of fusion zone.

(b) With the increase in weld time, the electrode face is subjected to higher temperature that may be detrimental for electrode life and should be avoided.

(c) The initial contact resistance along the sheet–sheet as well as the electrode–sheet interface greatly influences the formation of the fusion zone while variation in the magnitude of the former did not depict any significant change in weld dimensions. The electrode–sheet contact resistance should be anticipated or known for proper setting of welding current and also possibly for weld time.

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