Nugget Formation During Resistance Spot Welding Using Finite Element Model

Jawad Saleem*, Abdul Majid, Kent Bertilsson, Torbjörn Carlberg, Nazar Ul Islam

Abstract—Resistance spot welding process comprises of electric, thermal and mechanical phenomenon, which makes this process complex and highly non-linear and thus, it becomes difficult to model it. In order to obtain good weld nugget during spot welding, hit and trial welds are usually done which is very costly. Therefore the numerical simulation research has been conducted to understand the whole process. In this paper three different cases were analyzed by varying the tip contact area and it was observed that, with the variation of tip contact area the nugget formation at the faying surface is affected. The tip contact area of the welding electrode becomes large with long welding cycles. Therefore in order to maintain consistency of nugget formation during the welding process, the current compensation in control feedback is required. If the contact area of the welding electrode tip is reduced, a large amount of current flows through the faying surface, as a result of which sputtering occurs.

Keywords— Resistance spot welding, Finite element modeling, Nugget formation, Welding electrode, Numerical method simulation,

I. INTRODUCTION

RESISTANCE spot welding (RSW) is a widely used process of joining the metal sheets in automotive and aerospace industries. As the name implies, it is the resistance of the material to be welded, to the current flow that causes a localized heating in the part. A pressure is exerted during the process to hold the parts to be welded during welding time cycle. Current, force and time must be properly related in order to obtain a good weld. The total heat energy dissipated during the weld process [1-2] is given by the relation.

$$Q = I^2 R t \qquad (1)$$

Where I is welding current, R is resistance between the electrodes, t is the duration of the welding current and Q is total energy of the weld.

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In RSW process the welding nugget starts to form when sufficient heat has been generated at work-piece interface. The magnitude of the nugget formed is dependent on the resistance offered, the flow of current and the time during which the current flow as shown in Equation 1. The RSW is a complex process which involves electrical, thermal, mechanical and metallurgical phenomenon. This makes the whole process highly non-linear and difficult to model. The actual setting of the current, welding time in the control loop of the spot welding machine is determined by trial and error in most cases.

Finite Element Analysis (FEA) model have been developed [3]-[15] in order to get deeper understanding of the process and to get the best possible settings in terms of strength, residual stress in material and energy consumption. Greenwood in 1961, [3] made the first heat conduction model to simulate the RSW process. The first axisymmetric electro thermal model using a flat end electrode was developed in 1977 by A.F. Houchens at al [4]. The first 2D model considering both mechanical and thermal response was made by Nied in 1984, [5]. The model predicted deformation and stress as a function of temperature. The model was used for analyzing the squeeze and weld cycles to determine the electrical, thermal and mechanical responses. Gould in 1987, [6] proposed 1D heat transfer model using finite difference method to solve the nonlinear differential equations. The model demonstrated the radial heat transfer, which inhibits the calculation of nugget expansion. The predicted nugget size by the model was significantly larger than those observed experimentally. Temperature dependent material properties were considered. The developed model included the influence of the contact resistance on the faying surface.

Finite Element Analysis (FEA) model using simulation software such as ANSYS, JWRAIN, ABAQUS, DEFORM have been developed to model spot welding process. H.Huh and W.J. Kang [7] developed a 3D electro-thermal FEM model to study the quality of welding process. The finite element code developed simulates the welding process by varying process parameters such as electric current, contact resistance and material properties. The result from their research concludes that the shape of the electrode is an important factor in the current distribution and thus the heat generation. R.J Bowers and T.W Eager [8] studied the non-uniform distribution of the current density due to the electrode geometry. They concluded in their research that when the electrode sheet interface angles approaches 90°, there is

uniform distribution of current at the electrode tip. According to them, efficient electrode geometry can balance mechanical and thermal properties while maintaining a uniform current.

Electro-thermal-mechanical model developed are the most widely used models, enabling cost reduction of the weld quality test and to get the possible settings for welding schedules. MA. Ninshu and Murakawa [9] developed FEM program JWRIAN to study the welding nugget formation for two and three pieces of high strength steel sheets. ABAQUS commercial FEM program has been used in [10], [11]. The model developed by [10] predicted the nugget development during RSW of Al- alloys. The thermal history from thermal-electrical model was used as input data for the thermal-mechanical model analysis. The material properties for thermal-electrical analysis were artificially imposed in the simulation.

In the recent years ANSYS which is a commercial software has been used in most of the research [11], [12] have developed a coupled finite element model for RSW which is based on the thermal results from a sequential coupled thermo-elastic-plastic analysis. Stress and strain distributions in the welding process, deformation of the weld and electrode displacement were calculated. Thermo-electric-mechanical model using FEM code ANSYS is developed in both [13] and [14]. The phenomenon of nugget formation and effects of process parameter were studied. ANSYS software with advanced coupled field element PLANE223, to simulate the thermal characteristics to obtain the parameter to control the quality of the welding joint was used by [15].

In this paper COMSOL Multiphysics software [16], [17] has been used to model the RSW process. A transient thermo-electrical-mechanical model has been developed to model the RSW process. The structural mechanics module imposes a force and fixed boundary constrains on the modeled geometry. The electrode, work pieces and contact region are assumed to behave elasto-plastically. The AD/DC module controls the application of the required current density and is governed by the Maxwell's equations. An important output of this module is the Joule heat distribution as explained in Equation 1. The thermal module is governed by heat transfer module. The temperature evolution in the conducting body is governed by

$$\rho C_P \, \partial T \big/ \partial t = \nabla(k \nabla T) + Q_T \qquad (2)$$

Where C_P, ρ, k, Q_T are specific heat, density, thermal conductivity, and heat source term per unit volume. The surface of the electrode work piece interface is considered to be at constant temperature. The other material characteristic for both electrode and the work piece are taken as temperature dependent. The effect of enthalpy at the melting temperature has also been considered in the simulation.

II. RESISTANCE SPOT WELDING

Resistance spot welding process is a series of discrete time event as shown in the Fig. 1.

- Squeeze time.
- Weld time.
- Hold time.
- Off time.

During the squeeze time the welding electrodes move together and force is applied which press the work pieces together in order to build up necessary resistance during the heat generation.
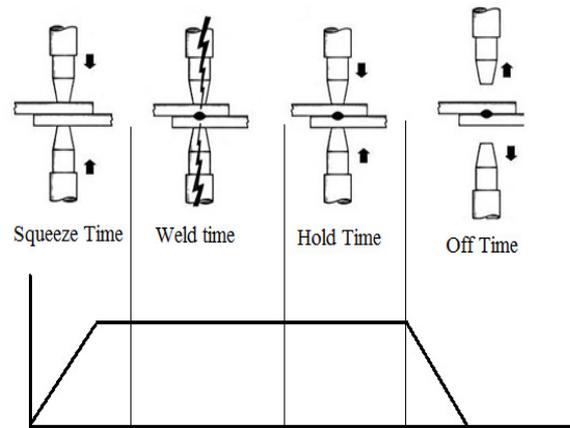

Fig. 1 Complete spot weld cycle

The applied force also counter balances the electrode magnetic forces which can misplace the welding joint during the welding cycle. The weld time is the time during which a set amount of current flows through the work pieces. During the hold time after the application of current, applied pressure is maintained, in order to form the welding nugget. Off time is time event when the pressure is released before doing the next weld. The welding nugget formation can be characterized as function of welding variables (welding time, current and electrode force). The contact resistance is a function of the applied pressure. The applied force is an important factor affecting the process especially in the early stages in the heating cycle [18]. With the application of high electrode force the contact resistance at metal to metal interface reduces which results in the reduction of joule heating effect. Welding current is the most significant factor for the nugget formation which is obvious from square relation of current given in Equation 1. The welding time is also very crucial if this time is prolonged, expulsion occurs, which means that the molten metal is expelled from welding nugget as shower of sparks. The shorter weld time results in cold weld in such cases no welding nugget is formed.

A. Simulation Model And Parameters

First of all 2D geometry has been developed using Comsol Multiphysics. The geometry allows 2D axial symmetry meaning, that a 2D model can describe a 3D problem with great accuracy. Another advantage of the COMSOL is that complex geometries can be developed in the CAD software and can be easily imported in the design. The geometry includes the welding electrodes and steel sheets. For the correct interpretation of the data in finite element analysis, it should be properly meshed. Comsol allows us to draw triangular, tetrahedral, quad meshes in the domains and on the boundaries. In the 2D simulation model we made physics controlled extremely fine mesh with 4438 elements for the solution as shown in the Fig. 2.

III. MATERIAL PROPERTIES

The process of RSW is a complex process involving physical, chemical and mechanical changes and relating lot of phenomenon such as, bulk joule heating, heat conduction, latent heat of fusion and phase change. The materials involved in the process are subjected to a wide range of temperature. The properties of the copper electrodes and the steel sheet such as thermal conductivity, coefficient of thermal expansion, specific heat, and resistivity are taken as temperature dependents [12].

IV. SIMULATION

The welding simulation runs for 18cycles which corresponds to 360ms with electro-thermal-mechanical physics. The squeeze time is 2cycles, weld time is 13 cycles and hold time is 3 cycles. The electro-thermal profile of the welding process and temperature changing history is shown in Fig. 3 and Fig. 4 and is comparable with research results of [12]. The temperature changing history shown in Fig. 4 is taken at the center of two steel sheets interface (point 1) and at the center of the electrode and work piece interface (point 2). The temperature at the center of the faying surface increases very fast as the melting process starts at this point and then the welding nugget is formed which expands in horizontal and vertical directions.
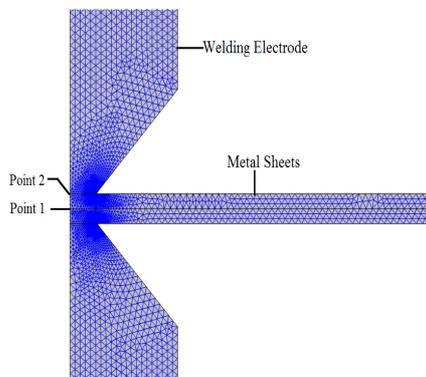

Fig. 2 Geometry meshing

VI. RESULTS (NUGGET FORMATION FOR DIFFERENT ELECTRODE CONTACT AREA)

The electrode shape and its tip contact area touching the work piece is an important parameter determining the shape and size of the welding nugget. The shape of the electrode is important in distribution of electric current and also the heat formation at the faying surface. The nugget formation is different for different electrodes with the same welding parameters such as current, time and pressure. When welding for longer periods, the tip contact area of the welding electrode has a tendency to become larger [19]. With the larger tip contact area if same amount of current is passed as with the previous welds, sometimes no nugget is formed. In the spot welding FEM model three electrodes are taken with the specification shown in Table I.

TABLE I
ELECTRODE DIMENSIONS

Electrode	Electrode Thickness (mm)	Tip Contact area (mm^2)	Electrode tip Diameter (mm)
No:1	14	50.26	6
No:2	14	113.09	4
No:3	14	201.06	8

A. Case 1:

In this case welding electrode No:1 is used with tip contact area of 50.26mm^2. Fig. 4 shows the temperature changing history at two different locations one at center of the nugget and the other at the center of the electrode and work piece interface. The welding current for this case is 12.2 kAmps.
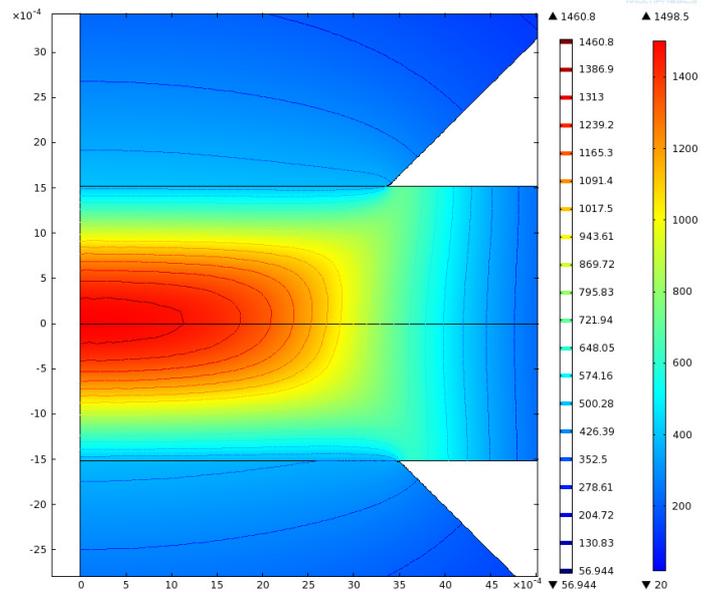

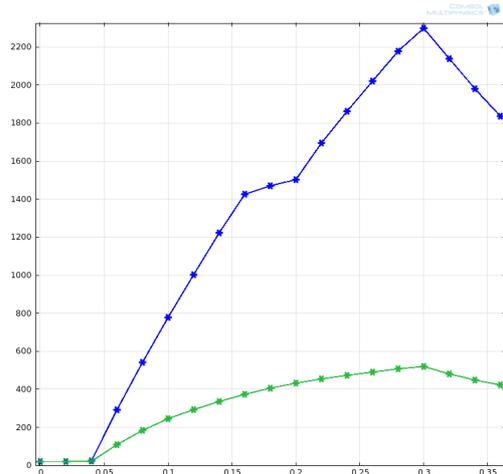Fig. 1 Thermal profile at faying surface

Fig. 4 Temperature changing history at point 1 and point 2
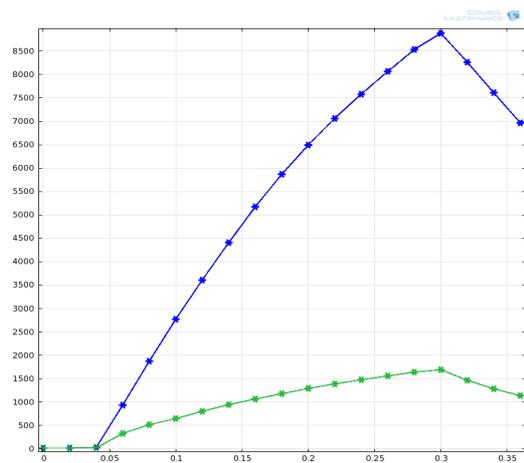for case :1 12.kAmps

Fig. 6 Temperature changing history at point 1 and point 2
for case: 2 12.kAmps

The Fig. 4 also shows the effect of enthalpy at the melting temperature 1450°C and shows that considering the enthalpy in the in FEM model causes to rise temperature slowly at the melting point. The nugget formation starts during the 6th welding cycle at around 0.18 sec. Due to enthalpy effect it takes few cycles for the process of melting. The nugget formation for the Case 1 is shown in the Fig. 5. The final nugget is formed at the end of hold time 0.36s.

B. Case 2:

In this case welding electrode No:2 is used with tip contact area of 113.09 mm^2. In this case all the welding parameters are similar to Case 1 except the electrode tip diameter which is changed from 6mm to 4mm. Fig. 6 shows the temperature changing history for the two points for Case 2. The melting temperature is reached during the 2nd welding cycle. It can be seen from Fig. 7 that during nugget formation, the temperature rises very quickly and sputtering may occur. The expulsion of molten metal from the joint can cause the injury to the operator and other equipment.

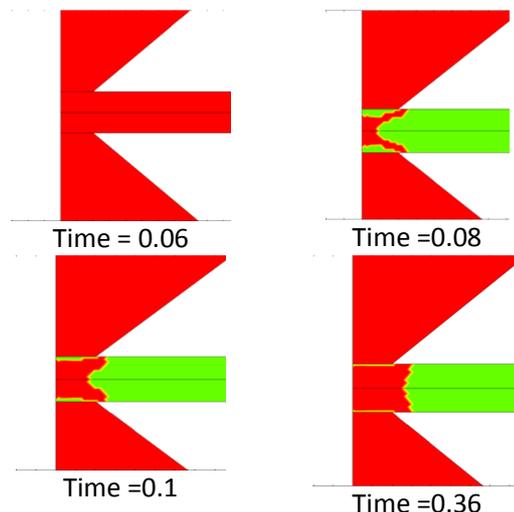
Fig. 7 Welding nugget formation for Case:2 (12.2kAmps)
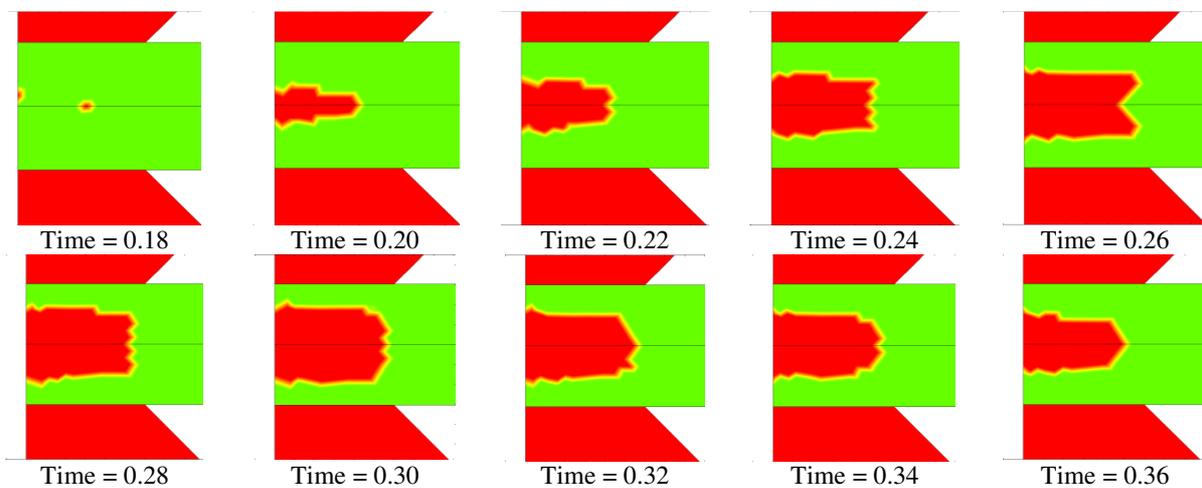with tip contact area 113.09 mm2

Fig. 5 Welding nugget formation for Case:1(12.kAmps) with tip area 50.26mm^2

In order to get the same temperature changing history as Case1, with this electrode the amount of current must be reduced. Fig. 8 shows the temperature changing history for Case2 when the current is reduced from 12.2 kAmps to 7 kAmps. The temperature changing history now resembles the results as in Case 1.The nugget growth with flow of 7 kAmps current is shown in Fig. 9.
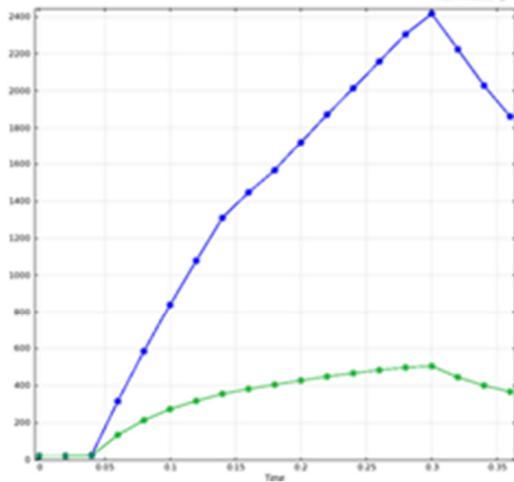

Fig. 8 Temperature changing history at two locations for Case :2 current 7.0kAmps

C. Case 3

In this case welding electrode No:3 is used with tip contact area of 201.06 mm^2 and tip diameter of 8mm. The tip diameter expansion can occur in RSW process due to longer welding periods. In this case if welding current of 12.2 kAmp is applied during the welding cycle no nugget is formed. The temperature changing history for Case 3 is shown in Fig. 10. The maximum temperature attained is around 800°C which is less than the melting temperature. In order to attain the same temperature changing history for this case like Case 1, the amount of welding current must be increased.
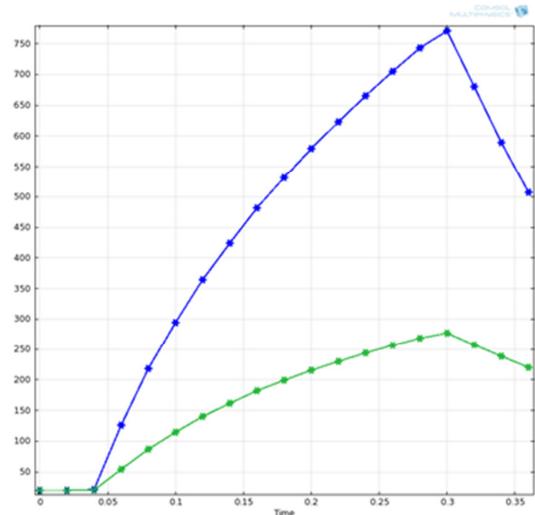

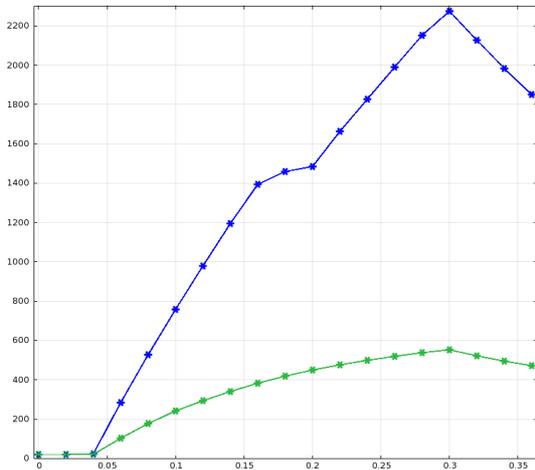Fig. 10 Temperature changing history at two locations for Case :3 current 12.2kAmps

Fig. 11 Temperature changing history at two locations for Case :3 current 19.2kAmps
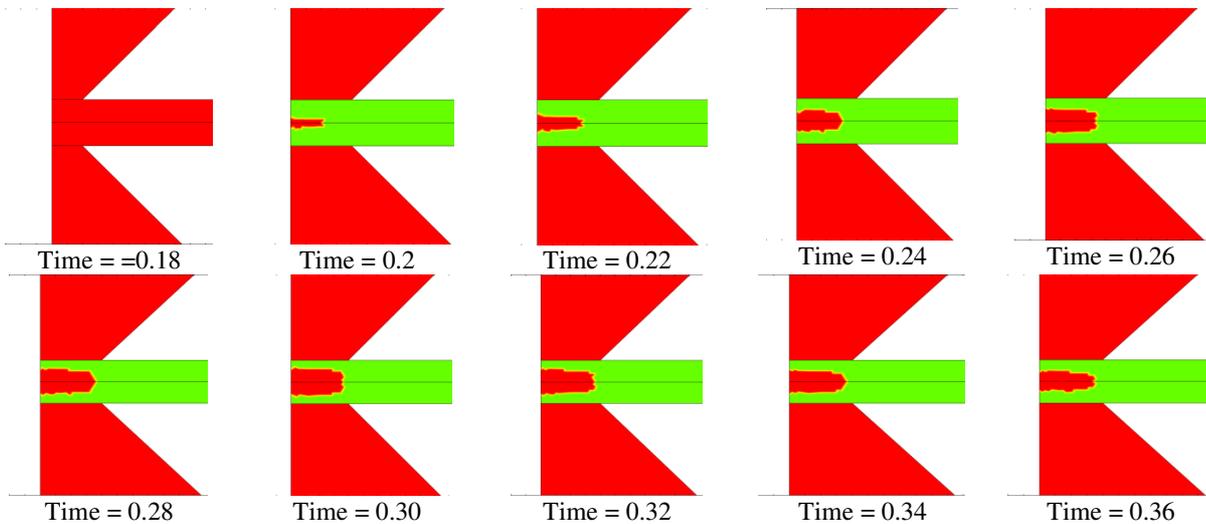

| Time = =0.18 | Time = 0.2 | Time = 0.22 | Time = 0.24 | Time = 0.26 |

| Time = 0.28 | Time = 0.30 | Time = 0.32 | Time = 0.34 | Time = 0.36 |

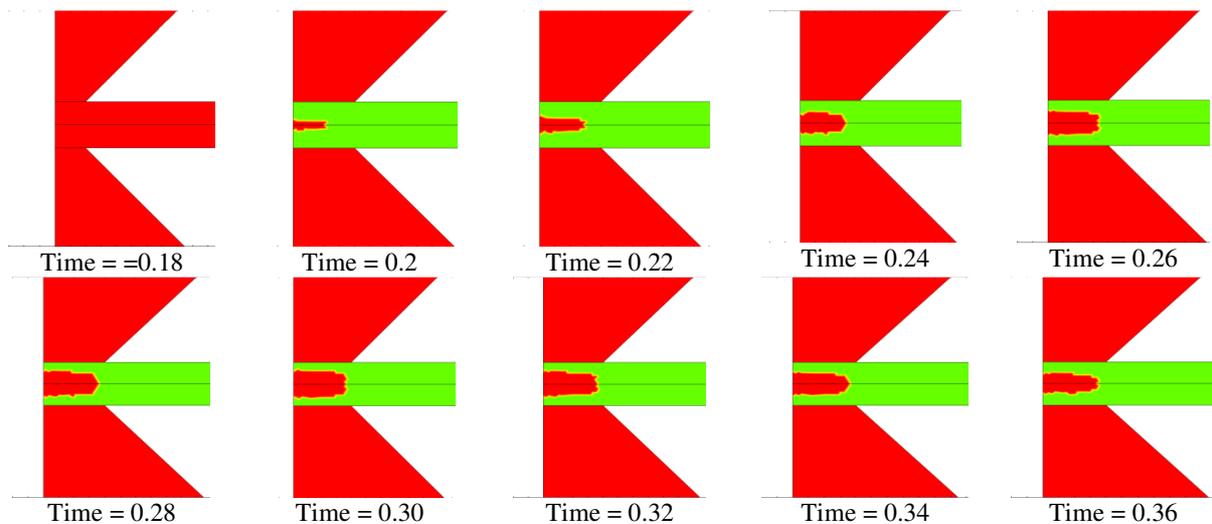Fig. 9 Welding nugget formation for Case:2 (7.0kAmps) with tip contact area 113.09 mm2

Fig. 12 Welding nugget formation for Case:3 (19.2kAmps) with tip contact area of 201.06 mm2

The welding current is increased from 12.2kAmps to 19.2 kAmps in order to achieve a good welding temperature profile like Case 1 as shown in Fig. 11. The nugget formation for the Case 3 with 19.2 kAmps of current is shown in Fig. 12.

V. CONCLUSIONS

In this paper a 2D axis symmetric FEM model for RSW process was made in order to analyze the electric, thermal and mechanical phenomenon involved in the process. Three different cases were analyzed with varying the tip contact area and it was observed that, with the variation of tip contact area the nugget formation at the faying surface is affected. The results of the Case 1 are compared with the published results [12]. In Case 2 when the tip contact area has reduced with the same welding parameters in the control system, the welding nugget forms so quickly that sputtering may occur. In order to get the same temperature rise the welding current has to be reduced. In case 3 when tip contact area is increased, which may occur during the welding process after having long welding cycles, no nugget will be formed if same welding parameters are maintain in the control system. In order to get the same temperature rise the welding current has to be increased.

Acknowledgements

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