Effect of plate placement on nugget shape in joining dissimilar thickness automotive steel thin sheets using resistance spot welding

Angita Kar, Sarfaraz Hussain, Ashad Seikh, Aatish Kumar, Bipul Das*

National Institute of Technology Silchar, Silchar, Assam, India

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FEM,
Dissimilar Thickness Joining.

ABSTRACT

The automotive products are adopting modern design dynamics to meet the market demands. One of the challenges that the automotive industries are facing is joining dissimilar thickness steel panels. The current study is an attempt to understand the formation of nugget shape during the resistance spot welding process in joining dissimilar thickness automotive steel AISI 4340. Steel plates with two different thickness of 2 mm and 1.5 mm are considered in the current investigation. The numerical simulation of the resistance spot welding process is carried out in FEM based commercially available software package. The study revealed that the temperature and the shape of the nugget is not same with the alteration of the positioning of the steel plates having dissimilar thickness. The shapes of the nuggets are different when the plate with higher thickness is at the top than the nugget formed when the plate is placed at the bottom.

1. Introduction

Resistance spot welding (RSW) is a popular joining process in the automotive industries. The RSW process is relatively a faster and flexible process compared to other joining processes. The RSW process can be effective in joining similar (Bi et al., 2022; Dingh et al., 2022) as well as dissimilar materials (Yu et al., 2021; Li et al., 2022). The change in the design dynamics in the automotive industries pushing the boundaries of RSW process for its effective applications. The current automotive industries are adapting to changes in sheet thickness to improve the strength of the superstructure in the automobile. In view of its widespread applications in automotive industries over other conventional joining processes, various research works have been carried out in the past to explore the RSW process for its improvement and innovations.

Gupta and De (1998) has performed a finite element modelling (FEM) of the resistance spot welding process. The base material was chosen to be low-carbon steel sheets of 1 mm and 2 mm thickness and HSLA steel sheet of 1 mm and an electrode of CuCrZr alloy (Cr—0.3 ~ 1.2 percent; Zr—0.03 ~ 0.3 percent and rest Cu) with spherical tip was chosen. Through this, the influence of welding current, weld time and electrode force on weld strength, nugget diameter and penetration studied by considering non-uniform current density. It was concluded that with increase in welding current, nugget diameter and penetration increases. Hashemi et al. (2012) has performed a 2-D axisymmetric finite element modelling incorporating thermo-electro-mechanical coupling of the resistance spot welding (RSW) using ANSYS. The base material was chosen to be AISI 1008 steel and electrode material was chosen to be copper. Choosing weld current was chosen to be50 Hz sine wave AC having 16 cycles of weld time. It was concluded that with increase in electrode force in a constant welding time, the nugget size both in diameter and height decreases; whereas with increase in weld current the nugget size increases. Nielsen et al. (2014) has performed three dimensional modeling of resistance spot welding using (SORPAS 3D). Two DC06 sheets of 0.8mm thickness and F1 electrode with tip diameter of 6mm were chosen. The numerical modeling was done considering the misalignment of electrode and tensile-shear test was also done to investigate the strength of the weld joint. It was concluded that though there would be uncontrolled electrode indentation into the sheet resulting in asymmetric nugget formation but the strength is not compromised due to

*Corresponding author E-mail: bipul@mech.nits.ac.in

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misalignment. De et al. (2013) has performed numerical modeling of resistance spot welding of aluminium alloy using in-house software based on FEM which is developed in Fortran 90. The base material and the electrode material were chosen to be aluminium alloy (AlMg0.4Si1.2) having sheet thickness of 1 mm, curved faced electrode of the type A 13×25 respectively. It was observed that for resistance spot welding of given aluminium alloy sheet, fusion zone is formed in the first cycle with a 50 Hz AC power supply i.e., within 0.02 s and no further development of fusion zone takes place on increasing weld time. It was also observed that the formation of fusion zone is greatly influenced by the initial sheet-sheet contact resistance and also electrode-sheet contact resistance; although changing the magnitude of initial sheet-sheet contact resistance does not impact the weld dimensions significantly. Li et al. (2011) has performed an axisymmetric finite element modelling (FEM) incorporating with heat and mass transport coupling of the resistance spot welding (RSW) process using commercial software ANSYS. The base material was chosen to be Mild steel (having thickness 1.5mm) and the electrode was chosen to be standard RWMA CLASS II electrode (MPE-25Z CMW®328) with a flat end having surface diameter of 6.25 mm. Induction of magnetic field due to the electric-field and their results were studied. Feulvarch et al. (2007) has performed a finite element method incorporating electro-thermal and thermal-metallurgical coupling of the resistance spot welding process by using SYSWELD. Two uncoated (XES) sheets, each having a thickness of 1.5 mm and electrodes with a tip diameter of 8 mm and a radius of curvature of 50 mm were chosen for the process. The width of the nugget was observed to be about 8.5 mm for the experimental one and 8 mm for the numerical simulation.

The aforementioned survey of recent available literature revealed that the studies are not emphasizing on the joining of dissimilar thickness materials using RSW process. Considering the current demand in the industries, the need for scientific analysis and understanding on the performance of dissimilar material joining using RSW process is realized and attempted in the current research work. In this current study, automotive steel AISI 4340 is considered as the base material with thickness as 2 mm and 1.5 mm. The electrode material is considered as copper. The objective of this work is to understand the effect of plate positioning in the formation of nugget. The shape and the size of the nugget in dissimilar material joining is analysed using numerical modelling. Commercially available FEM based software package is used for the numerical simulation in the current work.

2. Materials and Methodology

The current study considers automotive grade steel AISI 4340 as base the base material with thickness as 2 mm and 1.5 mm. The electrode material considered for this work is copper with a flat face

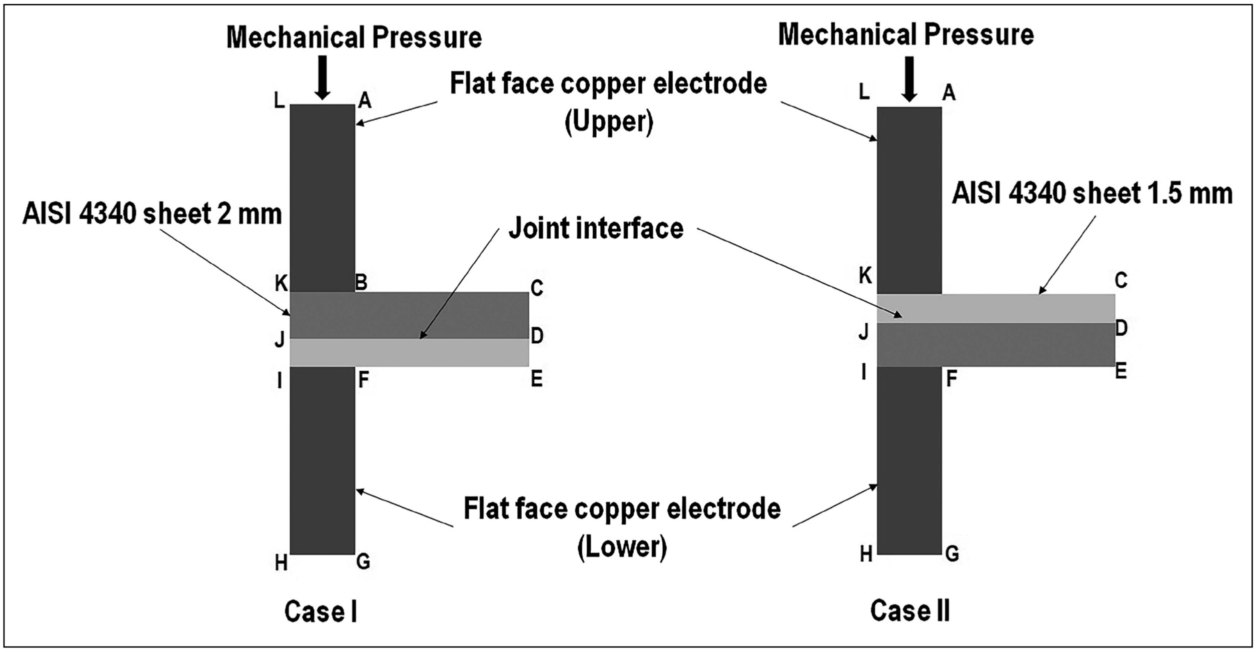


Fig. 1. Axisymmetric representation of the RSW process with the 2D axisymmetric view of the numerical model.

Table 1
Boundary conditions applied to the numerical model.

Boundary condition	Mathematical model (refer Fig. 1)
Thermal boundary condition	$-k_e\frac{\partial T}{\partial r}\Big\vert_{AB} = -k_e\frac{\partial T}{\partial r}\Big\vert_{FG} = h_e(T-T_o)$ $k_w\frac{\partial T}{\partial r}\Big\vert_{BC} = -k_w\frac{\partial T}{\partial r}\Big\vert_{EF} = h_w(T-T_0)$ $\frac{\partial T}{\partial r}\Big\vert_{KL} = \frac{\partial T}{\partial r}\Big\vert_{JK} = \frac{\partial T}{\partial r}\Big\vert_{JI} = \frac{\partial T}{\partial r}\Big\vert_{JH} = 0$ $\frac{\partial T}{\partial r}\Big\vert_{AL} = \frac{\partial T}{\partial r}\Big\vert_{GH} = T_{cw}$ $\frac{\partial T}{\partial r}\Big\vert_{CD} = \frac{\partial T}{\partial r}\Big\vert_{DE} = 0$
Electrical boundary condition	$J_{CD} = J_{DE} = J_{AB} = J_{FG} = J_{BC} = J_{EF} = 0$ $J_{AL} = J_{BK} = J_0 = I / A_e$ $J_{IF} = J_{JD}$ $V_{GH} = 0$
Mechanical boundary condition	$\sum F_{ext} = 0$ $\sum M_{ext} = 0$ $F_{ext} = F$ $u = 0, b = 0$

geometry. The positioning of the plates are altered and the numerical simulation using commercially available FEM based software package is done to estimate the temperature distribution and nugget formation during the RSW process. The setup is schematically represented in Fig. 1.

The numerical investigation is done using commercially available software package in order to understand the effect of plate positioning in the temperature generation and nugget formation during the joining of AISI 4340 steel plate having dissimilar thickness. In order to obtain the relevant results a few governing equations with various boundary conditions are applied to the computational domain to imitate the actual welding environment. The underlying physics governing the RSW process is relatively complex and it includes electro-thermo-mechanical coupling in the numerical domain. The mechanical model considered for the current investigation is presented in Eq. 1 and Eq. 2.

$$\nabla.(FS)^T + F_V = 0 \qquad \text{.................(1)}$$

$$F = I + \nabla u \qquad \text{..................(2)}$$

where, F is Deformation gradient which has the complete information about the local straining and rotation of the material.

The electrical model coupled with mechanical model is presented in Eq. (3) to Eq. (5).

$$J = \sigma E + J_e \qquad \text{.................(3)}$$

$$E = -\nabla V \qquad \text{.................(4)}$$

$$\nabla.J = Q_{j,v} \qquad \text{.................(5)}$$

where, σ is the electrical conductivity of the material (S/m), E is the electrical field (V/m), J_e is the external electric current density (A/m^2) and V is the electrostatic potential (volt).

The thermal model connected to the electrical and mechanical models is presented in Eq. (6) to Eq. (7).

$$\rho C_p \frac{\delta T}{\delta t} + \rho C_p u.\nabla T + \nabla.q = Q + Q_{ted} \qquad \text{......(6)}$$

Table 2
Assumptions incorporated in the numerical model of RSW.

Assumptions	Justification
The heat loss are assumed to prevail under conductive and convective losses	The assumption will simplify the numerical model eliminating the use of radiation heat transfer
No melting is considered in the nugget	The assumption will aid the numerical model to estimate the temperature without considering the effect of melting and latent heat in the thermal model of the RSW process
No phase change in the nugget	The assumption is made in order to keep the numerical model simplified to estimate the temperature change during the welding process
Heat generation at the interface	Heat generations at interfaces due to electrical contact resistance can be modelled as local volumetric heat sources

Table 3
Different cases considered for the numerical simulation.

#	Upper plate thickness (mm)	Lower plate thickness (mm)	Electrode diameter (mm)	Face of electrode
Case I	2.0	1.5	6	Flat
Case II	1.5	2.0	6	Flat

$$q = -k\nabla T \qquad \text{.............(7)}$$

where, ρ is the density (kg/m^3) of the work piece material, C_p is the specific heat capacity (J/kg K), T is the absolute temperature (K), u is the velocity vector (m/s), q is the heat flux due to conduction (W/m^2), k is the thermal conductivity (W/mK) and Q is the additional heat source (J) per unit volume and Q_{ted} is the heat (J) removed per unit volume from the electrode surface using external cooling system.

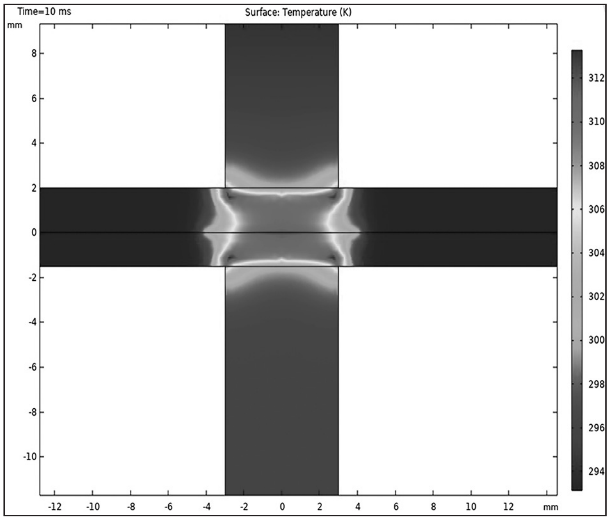
In order to solve the above governing equations over the computational domain selected as shown in Fig. 1, a series of relevant boundary conditions have been imposed in the model. The selected boundary conditions are presented in Table 1 for reference. In order to effectively model the physical process of RSW, a few assumptions have been incorporated in the model as listed in Table 2 for ready reference.

The numerical simulation of RSW process was performed by employing the FEM model to study the formation of nugget for sheets with dissimilar thickness. Three different cases were considered for our study. In the case I the thicknesses of the upper and lower plates were taken as 2 mm and 1.5 mm respectively while in the case II the thicknesses of the plates were reversed and the nature of the welding joints was studied and a comparative discussion has been drawn. The above mentioned cases are summarized in Table 3. The numerical models were developed in commercially available software package COMSOL Multi-physics software package to imitate the actual working environment of the RSW process. The numerical simulation was carried out with the current value of 3.5 kA and electrode force (F) of 6 kN and weld time of 500 ms.

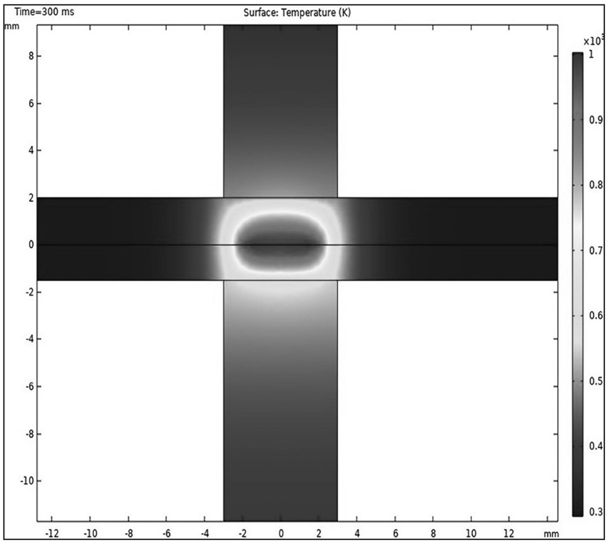
3. Results and Discussion

The current research work implements FEM in commercially available software package to extract the time temperature information of the nugget formation in the welding process. The results of the simulation for the case I is presented in the Fig. 2 and the same for the case II is shown in Fig. 3 against the various time steps to understand the nugget formation behaviour. It has been observed that the nugget grows its size over time and with the temperature increase. The final step considered in this investigation is 500 ms and the simulation result is shown in Fig. 4 against the cases considered in this investigation.

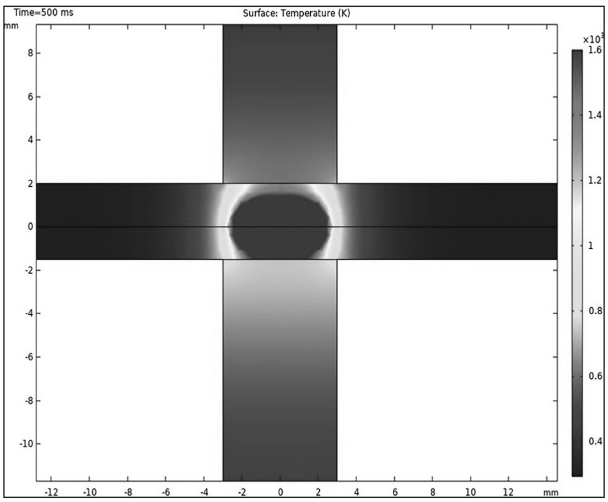
The simulation results shown in Fig. 2 and Fig. 3 reflects an interesting aspect that the shape of the nugget formed during the welding process



(a)

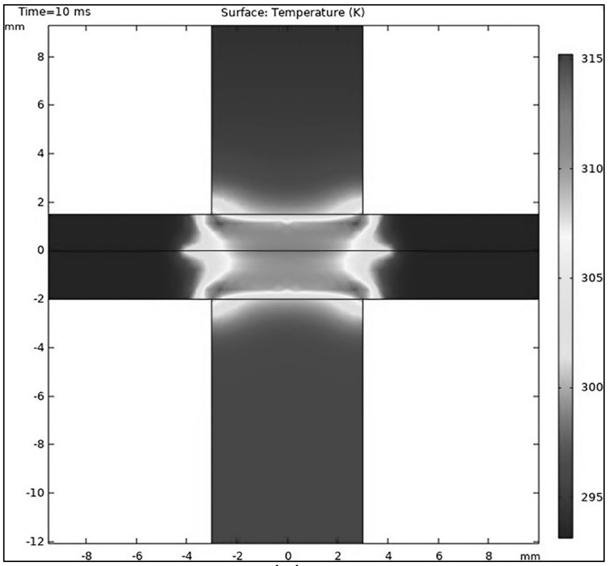


(b)

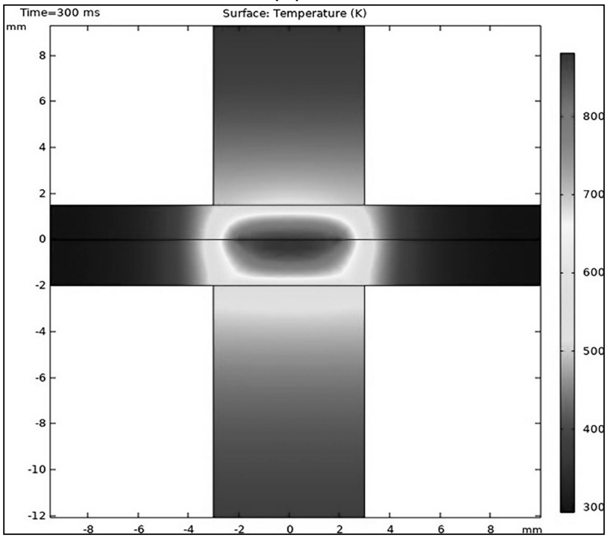


(c)

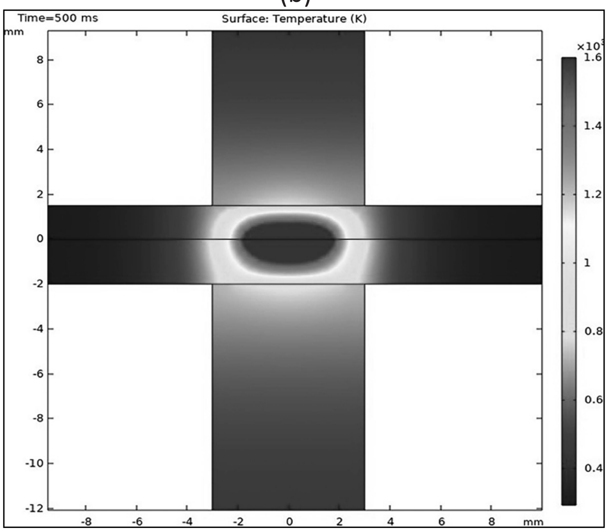
Fig. 2. Results of the simulation carried out against the experimental case I
(a) t = 10 ms (b) t = 300 ms (c) t = 500 ms.



(a)

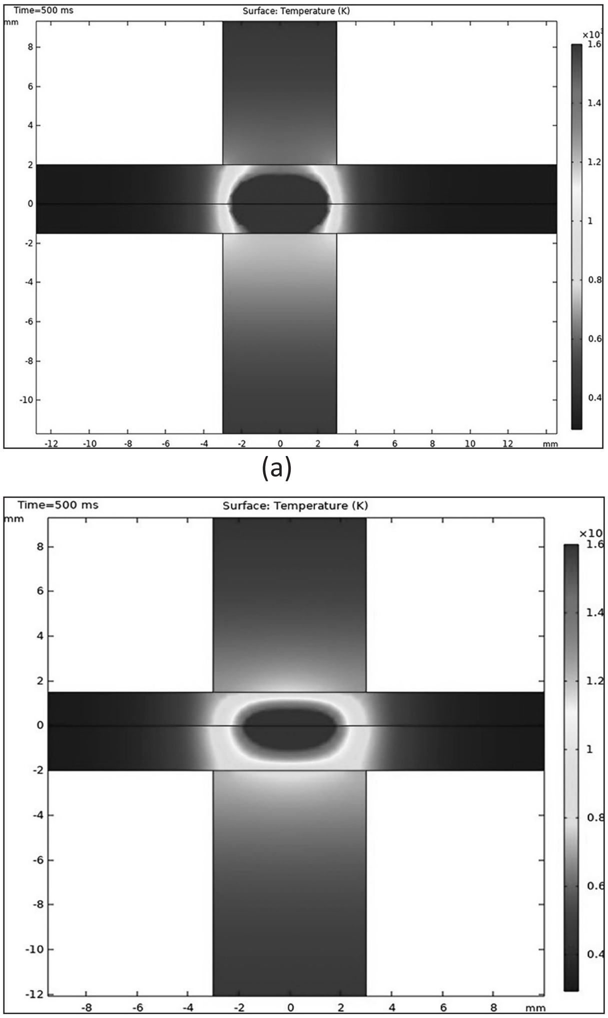


(b)



(c)

Fig. 3. Results of the simulation carried out against the experimental case II
(a) t = 10 ms (b) t = 300 ms (c) t = 500 ms.



(a)

(b)

Fig. 4. Shape of the nugget formed during the RSW process simulation at t = 500 ms against (a) case I and (b) case II.

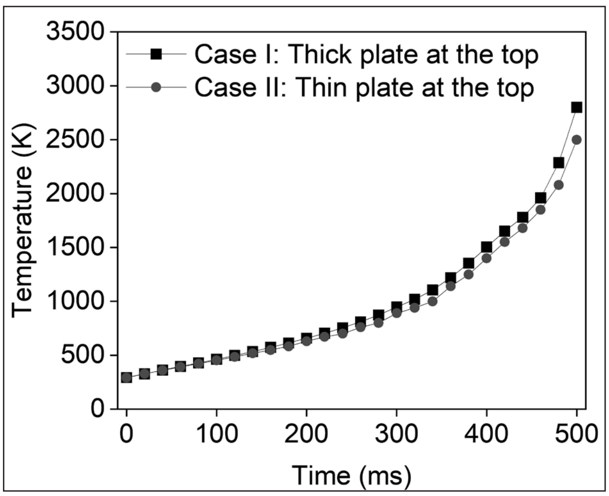


Fig. 5. Temperature invariability plot against the case I and case II during the nugget formation.

are different when the plates considered for joining is altered as per their thickness. The nugget shape obtained against the final time step of 500 ms is presented in the Fig. 4 for the comparison purpose. The figure reflects that at the same time step and with all the other process parameters remain the same, the shape of the nugget formed during the case I with higher thickness plate at the top results in a near circular shape as compared to the nugget formed in case II where an elliptical shape of the nugget can be observed. The nugget formed with the thin plate at the top is near elliptical shape as usually seen during the RSW process of joining steel material.

In order to understand the possible reason for the variation in the nugget shape with the alternation in plate positioning during the RSW process, an insight of the temperature distribution is extracted at the centre of the nugget from the numerical simulation results and the recorded temperature against both the cases are presented in Fig. 5. It has been clearly observed that the temperature at the end of the weld cycle of 500 ms does not result in same values. A variation of approximately 500 K is noticed in the maximum temperature of the nugget against both the considered cases as illustrated in Table 3. The change in the temperature variation is not very high to specifically comment on the variation of the nugget shape. However, it can be observed that the process dynamics is surely affected with the alteration in the plate positioning during the RSW process with dissimilar thickness plates. More scientific insight to this investigation is needed to explore the causes of nugget shape variation with experimental investigation.

4. Conclusions

The current investigation aims to probe the effect of plate positioning in the nugget formation during the resistance spot welding process. Numerical simulation using FEM is performed over selective process parameters and temperature information is extracted. The temperature contour obtained shows promising results in terms of nugget formation. It has been observed that the shape of the nugget varies if the thick plate is placed at the top. The shape of the nugget tends to form a circular shape. On the other hand, when the thin plate is placed at the top, the shape of the nugget is observed to be of elliptical shape, as expected during the RSW process. The temperature at the centre of the nugget in both the conditions are measured and it has been observed that the temperature does not vary appreciably with the change in the plate positioning. The results obtained in the current research work will be useful for the industrial applications to select the proper plate orientation during the robotic welding of various parts using RSW process with more detailed investigation as the future scope of the current work.

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Angita Kar received her B.Tech degree in Mechanical Engineering from National Institute of Technology Silchar, Silchar, India in the year 2022. Currently, she is working as Grade A Officer in Marketing Division of Indian Oil Corporation Limited.
(E-mail: angita_ug@mech.nits.ac.in)

Sarfaraz Hussain received his B.Tech degree in Mechanical Engineering from National Institute of Technology Silchar, Silchar, India in the year 2022. Currently, he is working as Graduate Engineer Trainee at Alstom and currently posted in Hyderabad, India.
(E-mail: sarfaraz_ug@mech.nits.ac.in)

Ashad Seikh received his B.Tech degree in Mechanical Engineering from National Institute of Technology Silchar, Silchar, India in the year 2022. Currently, he is working Advanced Application Engineer Analyst at Accenture, Kolkata, India.
(E-mail: ashad_ug@mech.nits.ac.in)

Aatish Kumar received his B.Tech degree in Mechanical Engineering from National Institute of Technology Silchar, Silchar, India in the year 2022. Currently, he is preparing for competitive examination in India.
(E-mail: aatish_ug@mech.nits.ac.in)

Dr. Bipul Das is working as Assistant Professor in the Department of Mechanical Engineering at the National Institute of Technology Silchar, Silchar, India since July 2018. He received his Ph.D degree from Indian Institute of Technology Guwahati in the year 2017. His research areas include advanced welding processes, condition monitoring of manufacturing processes, non-traditional manufacturing processes, laser based material deposition, natural material processing. He has published more than 40 research articles in international journals, conferences and edited book volumes. He is supervising 4 externally funded research projects as Principal Investigator and 1 research project as Co-Principal Investigator from various funding agencies under Government of India. He is currently supervising 4 Ph.D scholars and guided more than 20 M.Tech and B.Tech scholars.