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Karima Tahar-Chaouch, Philippe Rogeon

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Development of weld nugget in dissymmetric assemblies

K. TAHAR CHAOUCHa, Ph. ROGEONb
a.Laboratoire des Matériaux et Traitements de surface (LMATS), Université Saad Dahlab, BP.270 Route de Soumaa 09100, Blida Algérie
b.Université de Bretagne Sud, Centre de Recherche, LIMATB, F-56321, Lorient, France
karimachaouch@yahoo.fr

Abstract:
Quite recently, new families of high strength steel have been introduced in the design of body-in-white automobile. New configurations of assemblies, including up to three sheets with unequal thicknesses and different steel grade combinations may be defined to meet the new standards of, corrosion resistance, resistance to impact safety and light weighting for reducing energy consumption. These new assemblies (number of sheets, nature, and thickness) and the presence of the coating are all factors those causing weldability problems and difficulties to the optimization of the process parameter setting. Modeling and simulation could help to better understand the origin of difficulties of weldability. It is in this objective that it is oriented this work. For this study, we considered sheets of coated steel (ESG10/10 and DP6G10/10). A 2D- axisymmetric finite element model incorporating coupling phenomena electro-thermo-metallurgical (ETM) in the material and at the interfaces, implemented on commercial software Sysweld®, was used to simulate numerically the welding phase. The phenomenon of the expansion of the electrothermal contact surfaces and thermomechanical phenomena associated (fusion, expulsion, and solidification) are not directly integrated into the model. Contact radius electrode- sheet (rc(E/S) and sheet–sheet (rc(S/S)) are considered constant (flat tip electrodes welding). For the effect of zinc on electrothermal contact conditions are taken into account using surface contact parameters (electrical contact resistance ECR and thermal contact resistance TCR, the partition coefficient of heat flow α). The ETM model was validated by comparing the calculated kinetics of nugget development with experimental micrographs obtained from welded two and three sheets asymmetric assemblies (ESG10/10 and DP6G10/10). The model gives good trends comparing with the experience, both in terms of location and time of appearance of the nugget, the shape of the nugget.

Key words: Resistance spot welding (RSW), dissimilar weld, galvanized steel, contact resistance, coupled analysis

1 Introduction
In automotive industry, increasing demands regarding weight and performance of safety in impacts, has led to introduction of new configuration assemblies. Two and three sheets of different material and unequal thicknesses may need to be combined, forming heterogeneous assemblies. These new configurations raises weldability problems (default positioning of weld nugget in the assembly, setting operating parameters,…). The process is further complicated by introducing high-strength steels. In this paper a numerical study was developed to understand the mechanisms of heating, location, and development of weld nugget in dissymmetric assemblies of two and three sheets of unequal thickness and different material. Very few previous studies exist on this subject matter [1-5,7-8], and most of these studies focus on experimental nugget growth cross sectioning. In this work, we are particularly interested in the influence of the parameters responsible for the asymmetry of the nugget (the properties of materials, sheet thickness, and properties of interfaces).

2 Numerical model, configuration and welding conditions
In this study, a coupled of electro-thermal-metallurgical (ETM) model implemented in the finite element code SYSWELD is used [6,10] for simulation RSW of coated sheets assemblies. In this model, it is assumed a constant contact surfaces at Electrode- Sheet (E/S) and Sheet-Sheet (S/S) which eliminates the mechanical coupling problem. Here, the values considered for contact radius at interfaces E/S and S/S are rc(E/S) = 3 mm and rc(S/S)= 3.6 mm corresponding respectively to radius of flat tip electrode and radius of current flow including the contribution of the molten zinc accumulated at the periphery of faying interface during the early cycles of welding [10]. The parameters of the ETM model are the electrical and thermal properties of the materials considered, the operating schedules and electro-thermal contact conditions. Two coated steels grades are considered in this study
(industrial choice): zinc coated mild steel (ESG) and dual phase steel (DP6G). The properties of this materials are temperature dependent and are issued from literature [10,11]. The contact conditions (Electrical Contact Resistance (ECR), Thermal Contact Resistance (TCR)) are determined in LIMATB from experimental investigation device designed specially to measure these contact resistances ECR and TCR according to the temperature (up to 550 °C) and pressure (up to 80 MPA) [9]. For all configurations assemblies studied, the welding time is fixed at 0.26 s (13 cycles, AC current 50HZ) and the welding current intensity is adjusted according to the configuration to allow the formation and development of the weld. The welding force is involved in the values of contact resistances measured as function of temperature at constant pressure [9].

3 Numerical results and discussion

3.1 Analysis of weld nugget development in two identical sheets

In the case of spot welding of two identical sheets (grade and thickness) the initiation of the heating and the peak temperature occurs at the interface. And the melting is, first, takes place at the interface (S/S) and then propagates symmetrically into the plates (Fig.1(a)). This can be accounted for in terms of resistive heating: at low temperature (T<350°C), the electrical contact resistance ECR(S/S) is greater than the bulk material resistance, and so greater resistive heating takes place at the interface S/S, when approaching the melting point of the coating (~420°C), the electrical contact resistance(S/S) collapses, and the sheet resistance that increase with temperature, becomes dominant (Fig.A1). There are two consecutive heating regimes: first, at the beginning of welding, a rapid heating by ECR(S/S) to 0.02 s (1 cycle), then a slower heating by electrical resistance of the material sheet (Fig.1(b)).

3.2 Influence of thickness ratio

The study of the influence of the asymmetry in thickness, defined as the ratio of thickness e (e = thick plate / thin plate), on the initiating of the heating, nugget shape and location of the nugget is carried out on an assemblage of two ESG sheets of an equal thicknesses. Thickness of the top workpiece: e1= 0.8 mm and thickness of the bottom workpiece varied from, e2 =0.8 to 4mm.

In the all configurations, the initiation of the heating occurs at the interface (S/S) resulting from a high initial contact resistance (ECR(S/S)). When ECR (S/S) collapses (~420°C), the heating process is identical to that of symmetrical sheets. It is characterized by two different regimes: a rapid heating at the beginning of welding due to ECR (S/S), followed by a slow heating induced by self-heating of the material (heat generated from bulk resistivity). Changes of thickness ratio, will affect both the rate of local heating and the rate of local heat conduction away from faying interfaces, local heating rate decreases with increasing thickness ratio (Fig.2.a).

According to the value of the thickness ration (for example: e = 2.5/0.8), the maximum temperature is shifted toward the thick plate. In fact, melting first occurs at a point closer the interface in the thick plate. As time progresses, the peak temperature is seen shifting further away from the interface and tends to locate at the center of the whole thickness of two sheets. The weld nugget in the workpieces at last was asymmetric and migrated (Fig.2.b) and its shape is strongly influenced by the effect of important heat flow which diffuses in the thickness of the thick plate (micrograph Fig 2(b)). Indeed, the distance d, which indicates the shift of the nugget, presents a parabolic
form passing through a maximum for a value of the ratio \( e \approx 3 \) (Fig. 3). However, the depth of the nugget in the thin sheet \( (e_{N1}) \) is decreasing function of \( e \). This nugget migration phenomenon is conditioned by the balance between the mechanisms of heat gains and losses.

![Fig. 2 - The effect of dissymmetry in thickness on temperature evolution](image)

![Fig. 3 - Effect of thickness ration on weld nugget position](image)

### 3.3 Welding of dissimilar material

In the case of an assembly of two sheets of equal thickness but in nature are different (ESG0.8 mm/DP6G0.8mm), the heating is initiated at the interface S/S due to high values of ECR(S/S) at temperature below 400°C. As time progress, the overheating is shifted in the more resistive sheet (DP6G) and melting occurred at close proximity to sheet/sheet interface in the resistive sheet (Fig 4). Towards the end of welding, the peak temperature comes back to the interface and the weld nugget appears in the center of the assembly. Indeed, beyond the austenization temperature, the thermophysical properties of the two materials are almost identical; the asymmetry in nature fades, so the nugget is repositioned at the interface. Despite everything, the formed nugget has an asymmetric shape such that fusion zone size and penetration depth of DP6G side are larger than those of galvanized mild steel (ESG) side at the end of welding such also observed experimentally (Fig. 4).

![Fig. 4 - the effect of dissymmetry in nature on the heating and nugget position.](image)

(The dashes lines represents the position of maximum temperature)
3.4 The combined effect: thickness ratio and dissymmetry in nature

In an assembly asymmetrical in nature and thickness, the two effects (thickness ratio and nature of the materials) are combined and influence the position of the nugget, the final size and shape of the spot weld. Two situations were examined here. When the thickest sheet is also the most resistive electrically and thermally, the highest dissipation associated with a lower thermal diffusion in the thickness of this sheet tends to locate the heating and refocus the molten material towards the plane of symmetry of the workpieces. The nugget reaches in this case a large volume with a more regular shape and a diameter almost constant along the thickness (Fig 5.b). In the case where the thin sheet is the most resistive one, the nugget comes near to the interface (S/S) in the thick plate side which is the more conductive sheet, and its shape is modified by the heat flows in the thick plate (Fig.5.a).

![Fig.5 - Heating of an assembly of two different material sheets and unequal thickness](image)

(The dashes lines represent the position of maximum temperature)

3.5 Analysis of weld nugget development in three sheets configuration

The nugget formation kinetics in the case of similar three-sheets joining (ESG0.8/ESG0.8/ESG0.8 mm), the first hot zones appear at the interfaces (S/S) but the weld nugget start forming at the center of middle sheet and finally hooking the outer sheets and appears symmetric. For this configuration, of three coated sheets the results again show that the contact resistances disappear very quickly and the assembly behaves a single piece. This explains the appearance of the weld nugget in the center of the assembly (Fig.6).

![Fig.6 -Weld nugget development in three similar sheets: ESG 0.8/ESG0.8/ESG0.8 mm](image)

Differences in thickness obviously lead to a breakdown of the symmetry. In the configurations shown in the Fig A.2, thin/thin/thick and thin/thick/thick, even if the materials would be similar (galvanized mild steel, ESG) (Fig.A.2), the challenge to create a spot weld between the thin sheet on the outside with the middle sheet would be complicated, as the distance between the interface between these two sheets and the water cooled electrode is so small that most heat is conducted away, making it hard to accumulate heat. If the sheets to be joined are of dissimilar materials, as is the usual case, the location of the onset of melting becomes more complex. This suggests that the combined effects of thickness ratio and difference in thermal conductivity are responsible of the bad hooking of thin sheet (Fig.A.2). Fig.7 shows the modeling results with one ESG (0.8mm) and two DP6G (2.5mm) joint. The weld nugget on the faying interface of DP6G forms earlier than that on the other interface of DP6G/ESG. It is due to the fact that the greater contact resistance and greater bulk resistivity of the DP600G, would lead of quicker heat development in the thick sheet of DP6G than the ESG.
5 Conclusion

In this paper, our goal has been to clarify the various physical phenomena and the main factors determining the position and development of the weld nugget in the assembly of two and three sheets asymmetrical in nature and unequal thickness, using a model two-dimensional axisymmetric numerical integrating coupled physical phenomena electro-thermo-metallurgical in materials and interfaces.

The main conclusions that can be drawn from the present investigation are as follows:

- If the heating is always initiated at the interface S/S seat of high heat dissipation at the early periods of welding phase, for a limit value of thickness ratio $e < 3$ ($e = \text{thick plate/thin plate}$, the weld nugget start to form in the thick sheet between the interface and plane of symmetry of the assembly. For a large value of ratio $e > 3$, the nugget appears and develop at the faying interface.
- In welding dissimilar material of identical or different thickness, the weld nugget starts to form in the material with high electrical resistivity coefficient and low thermal conductivity coefficient.
- In case of welding three sheets, if all sheets are similar materials then the symmetry in the configuration will lead to the start of melting in the middle sheet, or on the interfaces between the outer sheets and he middle sheet. The exact location is dependent upon the distance to the water cooled electrodes and the thickness of the sheets, as these factors determine how much heat is conducted away. If the contact resistance between the sheets is high enough to overcome the shorter distance of the interface between sheets to the electrodes compared to the distance between the center of middle sheet and the electrodes, then melting will start at the interfaces. If the sheets to be welded are of dissimilar materials then this lead to a breakdown the symmetry and to create a joint between the thin sheet and the middle sheet becomes more complex.

Reference


Fig. A.1- Contact resistance evolution with function temperature measured at constant pression 80Mpa:
(a) Electrical contact resistance (Sheet/Sheet) and (Electrode/Sheet) - comparaison with material resistance (0.8mm)
(b) Thermal contact resistance (Sheet/Sheet) and (Electrode/Sheet)

Fig. A.2 - Nugget development in three dissimilar sheets joints: t=13~, new rounded tip electrode welding $\Phi$6mm