Resistive Spot Welding Simulations Using LS-DYNA

Pierre L'Eplattenier[1], Iñaki Çaldichoury[1], Sarah Bateau-Meyer[1], Tobias Loose[2], Uwe Reisgen[3]

[1]LSTC, Livermore, USA
[2]DynaWeld GmbH & Co. KG, Germany
[3]ISF - Welding and Joining Institute, RWTH - Aachen University, Germany

1 Introduction

Resistance Spot Welding (RSW) is a very important welding process for thin sheet metals with many applications, in particular in the automotive industry. In this method, the contacting metal surfaces are joined by the heat obtained by Joule heating of an electrical current flowing through resistances. These resistances are composed of the bulk resistance of the parts being welded, and of the contact resistances at the interfaces between the electrodes and the sheets, and between the sheets.

The amount of Joule heating energy delivered to the spot is determined by the magnitude and duration of the current and the values of the resistances. The resistances usually depend on the geometry, material properties and temperature: the bulk resistance of the metals is temperature dependent, and the contact resistances depend on the local contact pressures and temperature. The electrical conductivities of the materials and the yield stress are also used in some models to predict the contact resistance.

The current flow then depends on the local values of the bulk and contact resistances. It is thus very important to have a model which captures all these phenomena.

Recently, the contact resistance model in the EM solver of LS-DYNA has been extended to allow RSW simulations, where the user can define a local contact resistance as a function of different local contact parameters, using a `*DEFINE_FUNCTION`. The EM solver has also been adapted so that the current flow takes into account the local contact resistances. The local Joule heating is added to the thermal solver, and temperature dependent electrical conductivities can be taken into account via EM EOS's.

The model will be presented, then we will show how to set up a RSW case, and will present some results and benchmarks with experiments.

2 Resistive spot welding

2.1 Contact resistance

When two solids are in contact, at the microscopic level, the roughness of the contact surfaces limits the flow of the current from one side to the other. The current needs to flow through a set of contact spots, making the actual contact surface much smaller than the apparent one. This constriction of the current gives rise to an electrical contact resistance. The phenomenon is pictured on Figure 1.

At the macroscopic level, like in the numerical models of such contacts, one cannot describe the individual contract spots, and the contact is described with a much smoother surface with an added contact resistance.
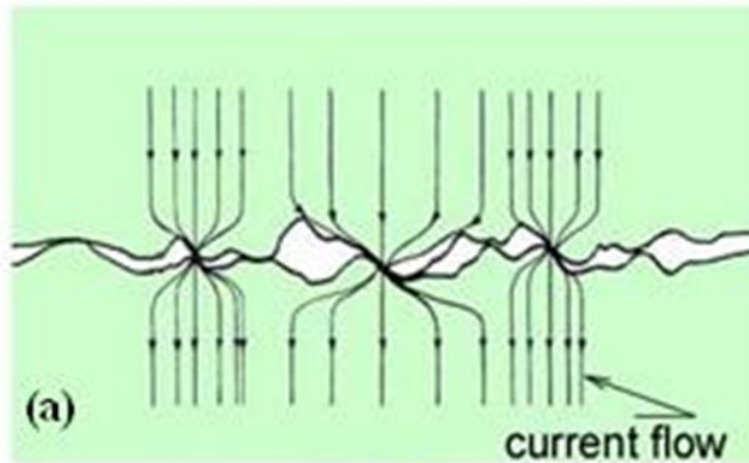
Fig.1:   Illustration of the current flow at the contact of 2 materials at a microscopic level

From Figure 1, one can intuitively understand that the number of contact spots as well as their individual areas, and thus the contact resistance, locally depends on the pressure, softness, temperature, electrical conductivity, … , of the two materials in contact. We thus developed a new contact resistance capability allowing the user to have a contact resistance which locally depends on a set of parameters. This dependence is done through a `*DEFINE_FUNCTION`.

2.2   Resistive spot welding process

Resistive spot welding is a process where 2 electrodes are used to both apply some pressure and pass an electric current through the workpieces to be welded. This current flowing through the bulk and contact resistances generates Joule heating which creates a melted "nugget" between the 2 parts, where the weld occurs. Figure 2 shows the different steps involved in the process.
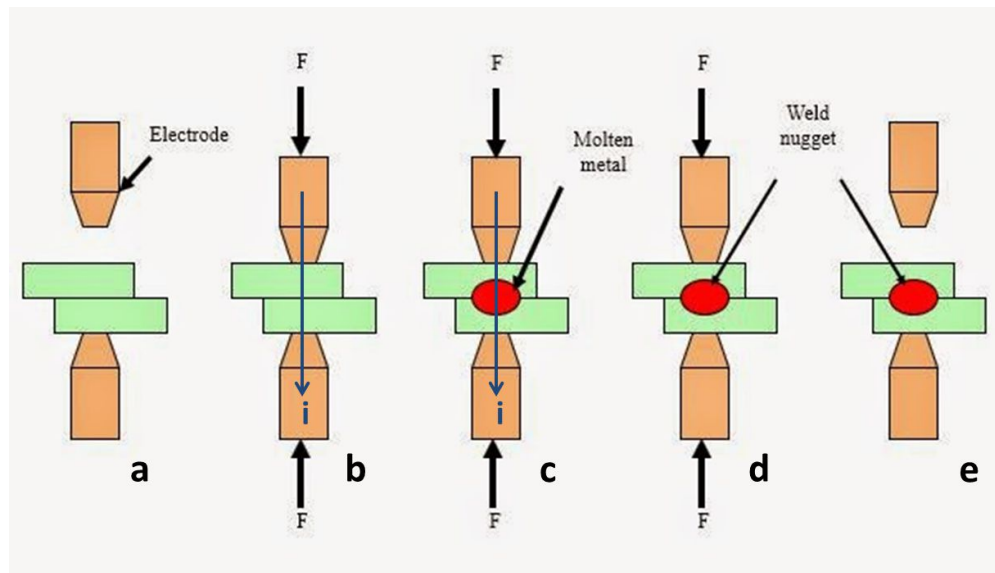

Fig.2:   Steps of the resistive spot welding process: a) The 2 electrodes are placed on each side of the sheets to be welded. b) A force is applied on the 2 electrodes in order to create a pressure at the contact, and a current is sent through the electrodes. c) The joule heating due to the current flowing through the contact resistance creates a hot "nugget" volume at the contact. d) The pressure is applied for a short while to get a good weld. e) The electrodes are removed.

3 Presentation of the LS-DYNA electromagnetic model

3.1 Resistive heating model

The RSW simulations is based on the so called "resistive heating" EM solver, where the inductive effects are considered negligible [1]. The main variable of this solver is the scalar potential, φ , from which the electric field is defined as

$$\vec{E} = -\vec{\nabla}\varphi \tag{1}$$

So that voltage between two point just is the difference between the scalar potential at these points:

$$V_{12} = \varphi_2 - \varphi_1 \tag{2}$$

Then, from the Ohm's law, the current density is equal to

$$\vec{j} = -\sigma\vec{\nabla}\varphi \tag{3}$$

where σ is the electrical conductivity, and the volumic joule heating power is defined as

$$P_j = \frac{j^2}{\sigma} \tag{4}$$

Since there cannot be any charge accumulation, we must have

$$\nabla \bullet \vec{j} = \nabla \bullet (-\sigma\vec{\nabla}\varphi) = 0 \tag{5}$$

except where the conductors are connected to an external current source.

In our finite element representation, φ has nodal degrees of freedom forming a nodal vector Φ , and equation (5) reads :

$$S(\sigma) * \Phi = 0 \tag{6}$$

Where $S(\sigma)$ is the node to node matrix representing the Laplace operator.

It is interesting to note that in our finite element representation [1], $(S(\sigma)*\Phi)_i$, the ith component of the nodal vector $(S(\sigma)*\Phi)$ represents the total current entering node i (if positive) or exciting node i (if negative). This can be used to set a non-zero right hand side to equation (5) at the nodes where the model is connected to a current source.

From the nodal vector Φ , we can get an edge-based current density J by

$$J = T(\sigma) * \Phi \tag{7}$$

where T is a node to edge matrix representing the gradient times the conductivity.

3.2 EM contact and contact resistance

A new contact resistance model was introduced in LS-DYNA to deal with RSW where the contact resistance can locally depend on miscellaneous mechanical, thermal and EM parameters. The user accesses these parameters through a ***DEFINE_FUNCTION** and can define locally the contact resistance using any function of these parameters. The parameters available are given in table 1 below.

Let's consider as an example the contact between 2 parts described in Figure 3.
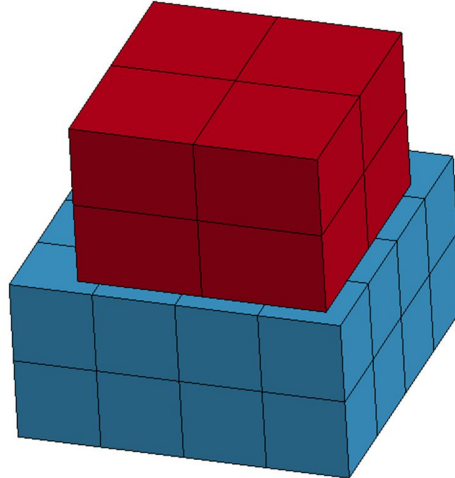
Fig.3:   Example of a contact between 2 parts

An algorithm allows getting the couples of faces in contact, and the total contact is divided into a sum of n local areas, each local area corresponding to a couple of faces in contact:

$$A = a_1 + a_2 + ... + a_n \tag{8}$$

as showed in Figure 4. For each of these couple k, we retrieve the parameters entering the ***DEFINE_FUNCTION**, from the faces or the elements on each side and compute a local contact resistance r_k^f . The actual resistance used for area a_k is

$$r_k = r_k^f \bullet \frac{A}{a_k} \tag{9}$$

The total contact resistance is then the sum of n resistances in parallel:

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + ... + \frac{1}{r_n} \tag{10}$$

We use convention (9) so that if the user defines r_k^f as uniform: $r_1^f = r_2^f = ... = r_n^f \equiv r_0$, then the total resistance R of the contact is equal to

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + ... + \frac{1}{r_n} = \frac{a_1}{A}\frac{1}{r_0} + \frac{a_2}{A}\frac{1}{r_0} + ... + \frac{a_n}{A}\frac{1}{r_0} = \frac{1}{r_0} \text{ , hence}$$

$$R = r_0$$

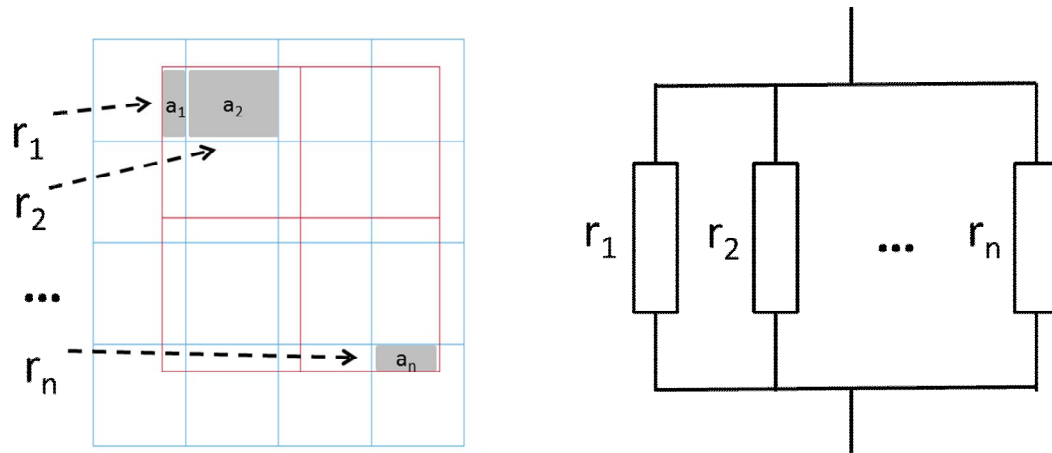Figure 4 illustrates this on the simple contact shown on Figure (3).

Fig.4:   Illustration of contact resistance on the whole contact as a sum of n resistances in parallel

3.3   Implementation of the local contact resistances in the EM resistive solver

Instead of using constraint methods, which are not always very stable, the contact resistance are directly introduced in the linear system (6) by adding entries to the matrix $S(\sigma)$, corresponding to resistive connections between one node on the master side and one node on the slave side of the contact. The algorithm is such that each node on the master side lying inside the contact area is connected to one node on the slave side. These nodal resistances r_{kl}^{n} from node k on one side of the contact to node l on the other side are of course computed from the local area resistances r_{j} defined in the previous section, in order to represent as best as possible the user defined local resistances. Figure 5 illustrates these resistances.

Since the algorithm ensures that all the nodes in the master side are taken into account, it is best to choose the master side of the EM contact as the one with the thinner mesh.

3.4   Addition of the contact resistance joule heating

The method described in section 3.2 allows a very simple way to add the extra joule heating coming from the contact resistance to the thermal solver. As illustrated on Figure (5), for each couple of nodes (N_{k}, N_{l}) connected by a nodal contact resistance r_{kl}^{n}, the current flowing from one node to the other is equal to:

$$i_{k,l} = (S(\sigma) * \Phi)_{k} = -(S(\sigma) * \Phi)_{l}$$

The ohm heating power is thus equal to

$$P_{kl} = r_{kl} \bullet i_{kl}^{2}$$

This heating power is evenly spread as an extra heat term between nodes N_{k} and N_{l} and added to the thermal solver.
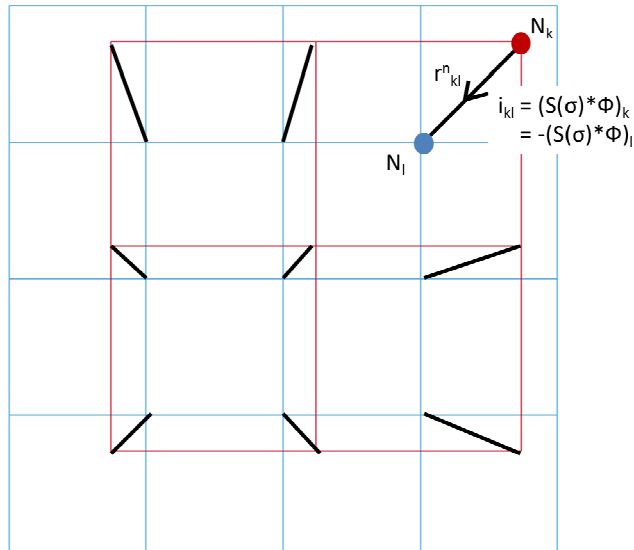
Fig.5: Illustration of the local node to node resistances used to connect the 2 parts using the contact resistances locally defined by the ***DEFINED_FUNCTION**

4 Implementation of a RSW case in LS-DYNA

Let us now show how to set up the EM contacts for a typical RSW case as presented in Figure 6.
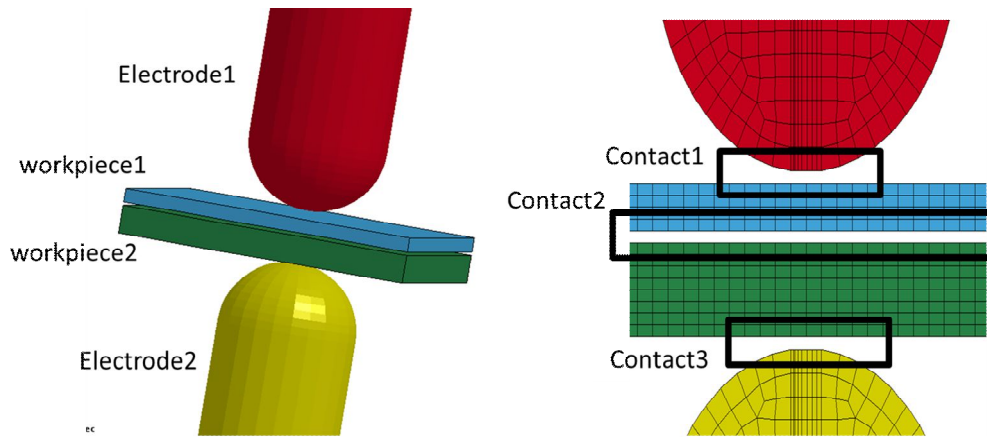

Fig.6: Typical RSW case

You will first need to turn on the EM contact by the card.

*EM_CONTROL_CONTACT

EMCT	CCONLY		COTYPE	EPS1	EPS2	EPS3	D0
1	1						

Where you might as well to use CCONLY=1, since you will most likely need to define the contact parameters for each contact separately (electrode1/workpiece1), (workpiece1/workpiece2), (workpiece2/electrode2).

Then you will probably need to define 3 ***EM_CONTACT** since the ***DEFINE_FUNCTION** may be different for contact1, contact2 and contact3 showed in Figure 6. Each of the ***EM_CONTACT** card will look like:

*EM_CONTACT

CONTID	COTYPE	PSIDM	PSIDS	EPS1	EPS2	EPS3	D0
18	1	1	2	0.3	0.3	0.3	

Again, please use the master side as the one with the finer mesh.
You can then attach a contact resistance to each of these contacts by using the card ***EM_CONTACT_RESISTANCE**, where the CONTID should be the same as the CONTID in the ***EM_CONTACT** card. Also, the CTYPE should be equal to 1 (contact resistance defined by load curve), and LCID should be the id of a ***DEFINE_FUNC**TION (instead of a load curve).

*EM_CONTACT_RESISTANCE

CRID	CONTID	CTYPE	CIRCID	JHRTYPE		D0
12	18	1		1		

LCID		D0
14		

*DEFINE_FUNCTION

FID
14

Where the parameters currently available in the ***DEFINE_FUNCTION** are:

time	Simulation time
area_glo	Global contact area A (see equation (8))
area_loc	Local contact area A (see equation (8))
dist_ct	Distance between the 2 faces in contact
ctpress_mst	Contact pressure on master side
ctpress_slv	Contact pressure on slave side
temp_mst	Contact temperature on master side
temp_slv	Contact temperature on slave side
cond_mst	Electrical conductivity on master side
cond_slv	Electrical conductivity on slave side
vmstress_mst	Von mises stress on master side
vmstress_slv	Von mises stress on slave side

Table 1: Parameters available in the ***DEFINE_FUNCTION** *defining the local contact resistance.*

5 Application

The mechanism of heat generation during resistance spot welding is as follows: At the beginning the contact resistance starting at room temperature is high. This initializes the first joule heating in the contact zone and the attached material. The increasing temperature decreases the contact resistance, but increases the bulk resistance of the material. The heat generation now moves forward from the contact zone into the inside of the material.

Galler et. al. [3] describe a method to obtain the temperature dependency of the contact resistance by reverse engineering. This means the spot weld is performed as experiment and simulation. The contact function then is adjusted during some simulation iterations until the nugget evolution matches with the experiment result.
Kaars [3,4] extended the method from temperature dependent function to temperature and pressure dependent function for the contact resistance. The calibration follows two tests. A static test with low current and no significant heat generation and a dynamic test with a pulse current leading to nugget generation. Both tests are performed at several force levels. As the contact pressure distribution

cannot be measured, an approach to calibrate the Jonny-Kaars-Model (Eq. 11) by FE calculation was developed [3,4]

$$r(T,P) = r_0 \left(\frac{p - p_k}{p_0 - p_k} \right)^{\varepsilon_p} \cdot \left(\frac{T - T_{\lim} + (293,15 \ K - T) \cdot 2^{-\frac{1}{\varepsilon_T}}}{293,15 \ K - T_{\lim}} \right)^{\varepsilon_T} \tag{11}$$

r_0 specifies the basic resistance. The first term is the scaling function for contact pressure. Its parameters including r_0 are calibrated by the static test. The second term is the scaling function for temperature. Its parameters are calibrated by the dynamic test. This model represents the shape of pressure and temperature dependent electrical contact resistance. It does not describe the real physics, but it is an equivalent approach considering the major relevant parameters.

Figure 7 shows the shape of this function on the left side for constant temperature and increasing pressure and on the right side for constant pressure and increasing temperature. Increasing temperature and increasing pressure lead to decreasing contact resistance.
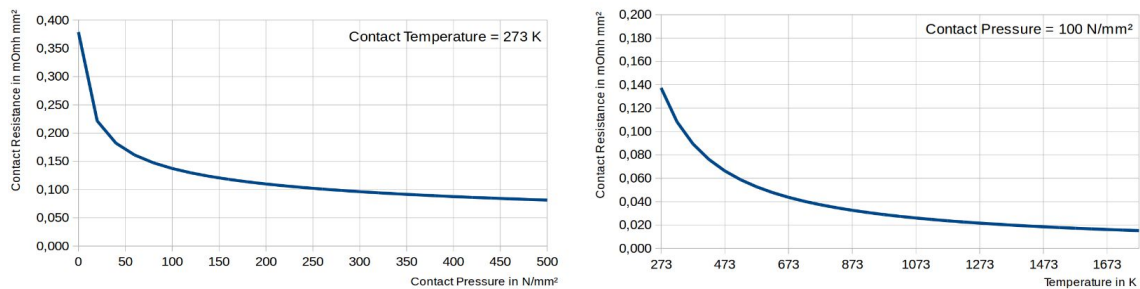

Fig.7:   Example electrical contact resistance according Jonny-Kaars-Model
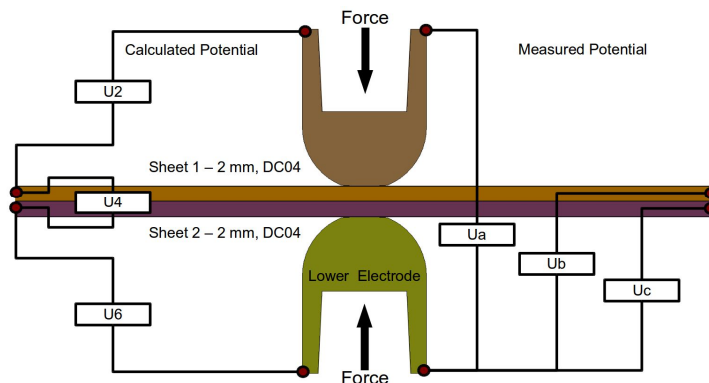

Fig.8:   Experiment and location of measured and calculated potential differences

The joint shown in Figure 8 with 2 sheets made of steel grade DC04, wall thickness 2 mm and 0,01 mm zinc coating shall give an example how to get the electrical contact resistance for spot welding. The Welding and Joining Institute of RWTH - Aachen performs the experiments. The current and the electrical potential are measured between lower electrode and sheet 1 (Uc), sheet 2 (Ub) and upper electrode (Ua). The potential difference is calculated for:

lower electrode - sheet 1 (E-S): U6 = Uc
sheet 1 - sheet 2 (S-S):   U4 = Ub - Uc
upper electrode - sheet 2 (E-S) U2 = Ua – Ub

The potential differences U2, U4 and U6 take place at the sum of contact resistance and bulk resistance within the effects of surface pollution and coating. The bulk resistance of the material is a known quantity. The contact resistance is the unknown parameter to be adjusted. The simulation model for the adjustment was set up with DynaWeld. The scalar potential was extracted at the same points as in the experiment. The model also considers the coating with one layer flat solids and own material properties of zinc.

In the first 10 ms the Force is applied. The static test is driven with a current ramp from 0 A to 6800 A in 70 ms for two forces of 3,5 kN and 4,5 kN. The measured potential versus calculated potential with calibrated resistance model according to Jonny Kaars is shown in Figure 9. All load stages are calculated with the same parameters, which indicates that the impact of pressure is included correctly by the resistance model.
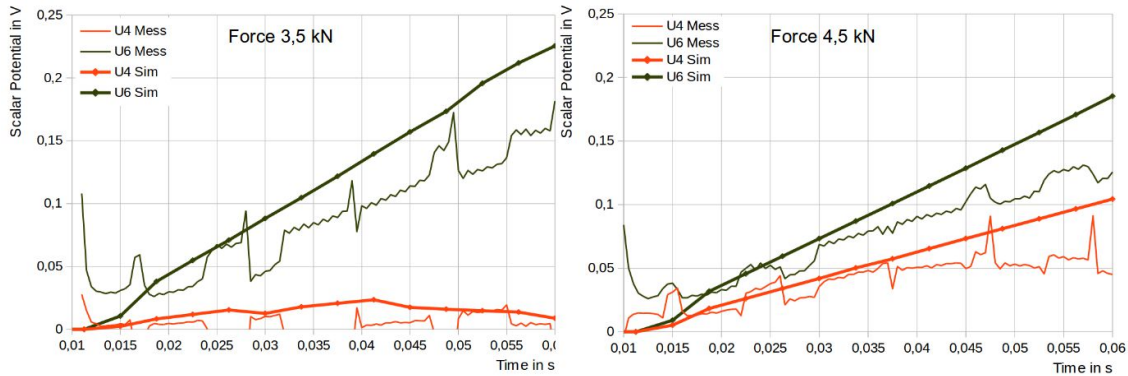

Fig.9: static resistance test

The dynamic test is performed with constant current at 8710 A. The measured potential differences are plotted versus calculated potential differences in Figure 10. The nearly constant level comes from the compensation of increasing bulk resistance and decreasing contact resistance by increasing temperature. The dynamic test generates a nugget (Figure 11). Its diameter can also be used for calibration of the simulation model
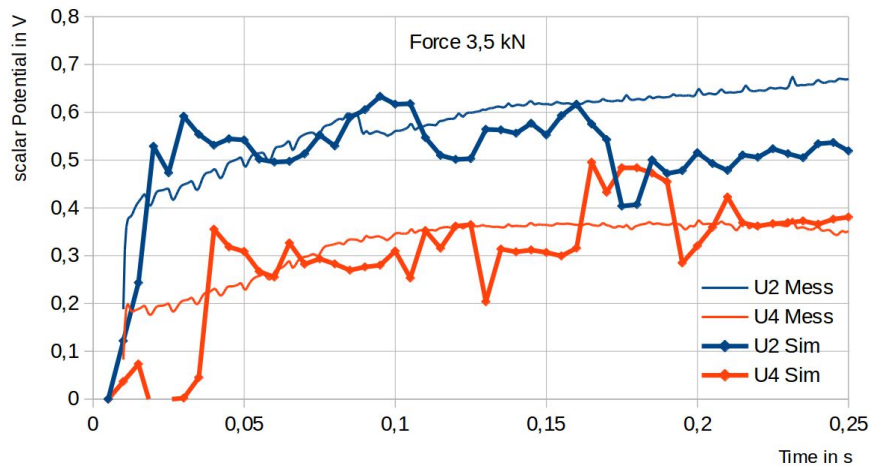

Fig.10: dynamic resistance test

The new LS-DYNA contact functions support a lot of parameters, not only temperature and pressure. So, apart from the Jonny-Kaars-Model, other contact resistance models may be developed or applied for resistance spot welding simulation using this contact function.
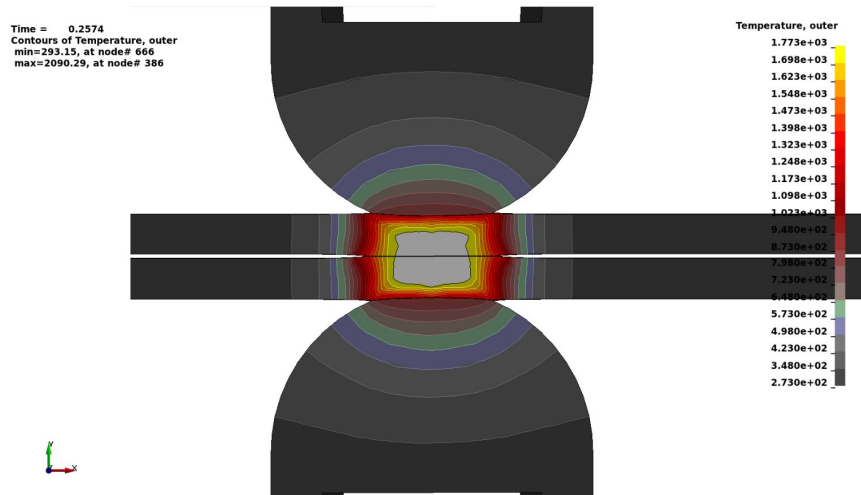
Fig.11: Weld nugget at dynamic test

6 Summary

Resistance Spot Welding (RSW) is a very important welding process for thin sheet metals. Recently, the contact resistance model in the EM solver of LS-DYNA has been extended to allow 3D - coupled mechanical/thermal/EM - RSW simulations. The user can define a local contact resistance as a function of different local contact parameters, using a *DEFINE_FUNCTION, which gives a lot of flexibility. The model was presented as well as a first benchmark with experimental results.
Future work includes the extension of the model to 2D axisymmetric simulations.

7 Literature

[1]   L'Eplattenier, P, Çaldichoury, I : "LS-DYNA EM theory manual", LSTC, 2012, pages
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