Resistance Spot Welding in LS-DYNA®: An Overview of Current Capabilities.

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Abstract

Resistance spot welding is perhaps the most frequently encountered joining method for steel sheet in the automotive industry. It is accomplished by passing an electrical current through metal sheets via electrodes. The sheets are held together under the pressure exerted by the electrodes and heat is induced by the electrical current which generates a molten nugget between the sheets. The molten nugget then solidifies to form a bond. During the spot welding process, important changes occur in mechanical and metallurgical properties of the spot welded areas and heat affected zones appear. Although routinely used by the industry, the physics involved in the process are far from trivial, and generally involve a combination of electrical, mechanical, thermal, and metallurgical fields. In particular, the contact area between electrode and workpiece generates an additional electric contact resistance dependent on the models parameters. This contact resistance will have a decisive impact on the shape and size of the nugget and therefore the weld's quality. Furthermore, the development of new materials such as advanced high strength steels or the replacement of steel by aluminum in certain automotive parts further increases the complexity of the process. Numerical tools and finite element analysis (FEA) can on the other hand offer a crucial assistance in the comprehension of the phenomena involved.

Numerically, setting up the RSW model consists in a challenging and highly non-linear problem where solid mechanics, thermal and EM quantities interact with each other. The interface area is especially critical, a robust electric contact algorithm is needed to accurately distribute the local extra resistance to the faces that are in contact with one another so that the correct heating can be calculated and passed on to the thermal solver, even in complex cases with different density meshes and shapes. Over the years, several developments have been introduced in LS-DYNA in order to tackle this problem and in this paper, an overview of the current capabilities will be given along with some example description so that potential users can gain a better understanding of what to expect.

The Electromagnetic problem behind the RSW process

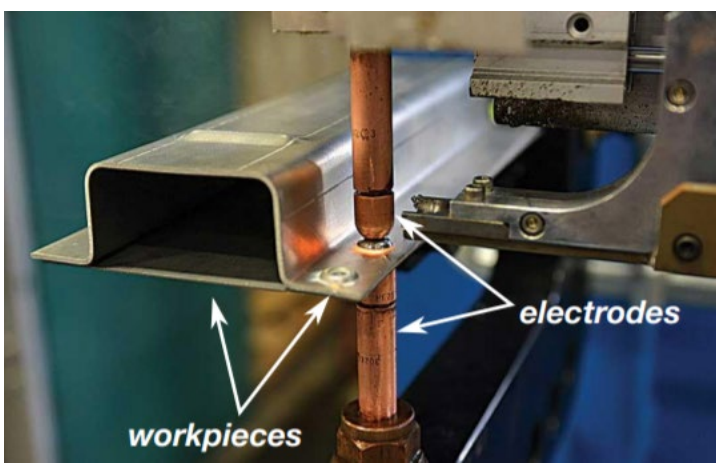

Figure 1 Picture showing the RSW process

Resistance spot welding (RSW) shown in Figure 1 is a process in which contacting metal surface points are joined by the heat obtained from resistance to electric current (Joule heating) flowing through them. The work-pieces are held together under pressure exerted by electrodes. Figure 2 shows the four main steps occurring during the process.

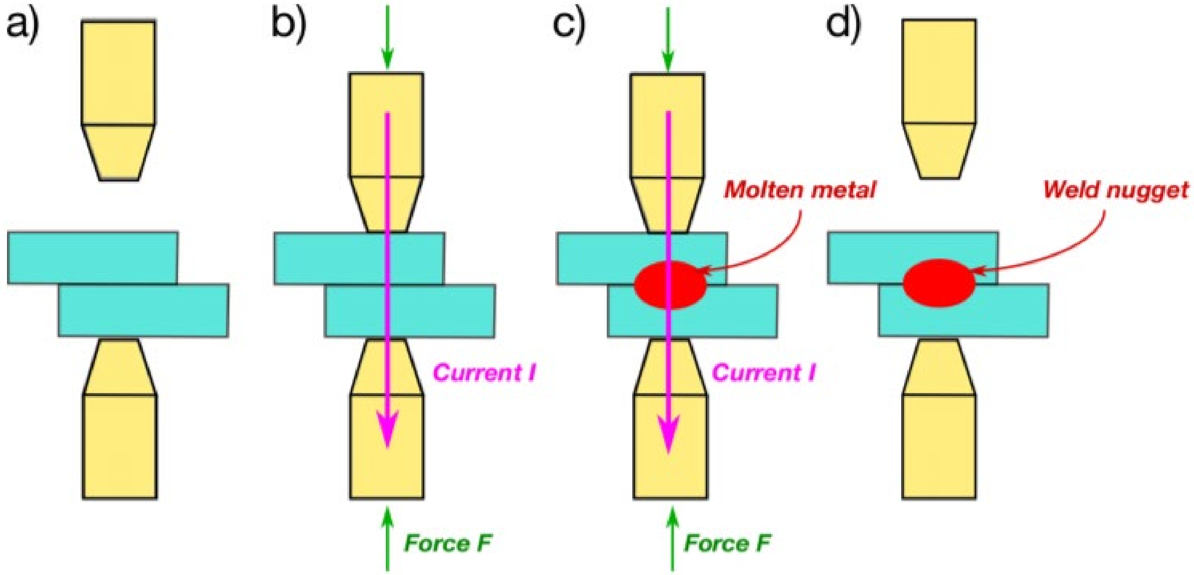

Figure 2 a) The two electrodes are placed on each side of the sheets to be welded, b) A force is applied on the two electrodes in order to apply pressure on the contact area and current is sent through the electrodes. c) The Joule heating due to the current flowing through the contact resistance creates a hot 'nugget' zone between the two workpieces. d) After applying pressure for a short while, a weld nugget is formed and the electrodes are removed.

The difficulty lays in capturing the correct Joule heating in the contact area between the electrodes and the workpiece. At the microscopic level, the roughness of the contact area limits the flow of current from one side to the other, rather, it flows through a set of contact spots, making the actual contact surface much smaller than the apparent one as described in Figure 3. This added constriction of the current gives rise to an electrical contact resistance. This contact resistance has a decisive influence on the final heat distribution and must therefore be taken into account in the numerical simulation. At the macroscopic level, the local and individual contact spots cannot be correctly described. Rather, the contact is described with a much smoother surface but an added contact resistance is added usually based on experimentally measurable quantities (temperature, current intensity, applied force on the electrodes etc).

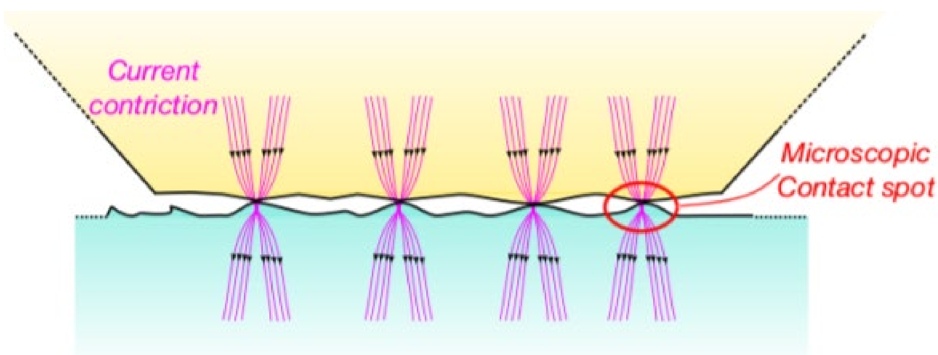

Figure 3 Electrical contact resistance arising from current constriction

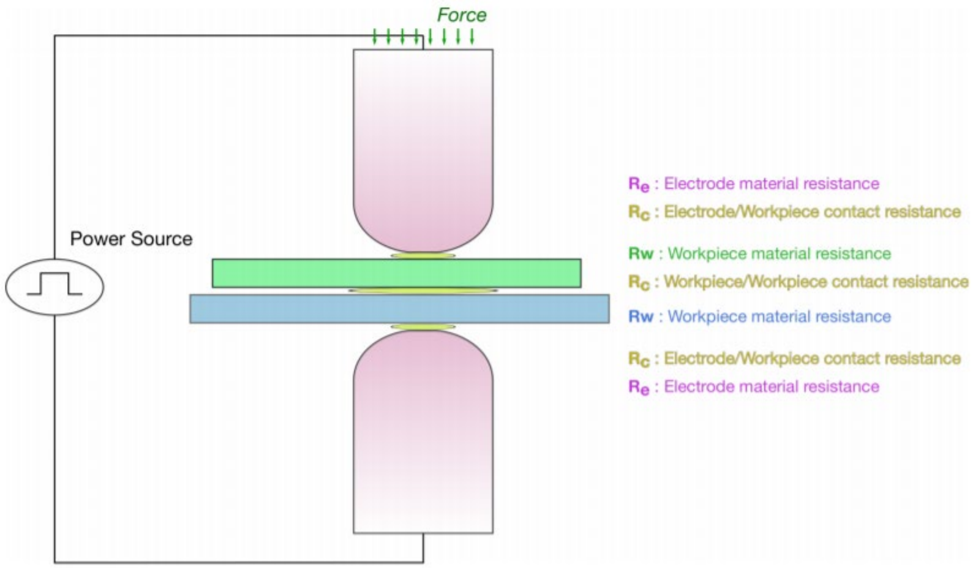

Figure 4 The RSW process: a series of electric resistances

The Resistance Spot Welding process can therefore be viewed as a circuit of different electrical resistances in series : Electrode and Workpiece 'bulk' or material resistances and the additional Contact Resistances between electrodes and workpieces (See Figure 4). Each of those resistances will contribute to the overall heating. The material resistance is dependent on the Electrode/workpiece configuration and geometry as well as the various materials' electrical conductivities. Those are also often function of temperature and in general, the total material resistance is expected to raise during the RSW process. The contact resistance on the other hand is usually an order of magnitude higher than the material resistance during the beginning of the process but will rapidly decrease (See Figure 5). On top of being strongly dependent of temperature, it can also depend on the contact force and other parameters.

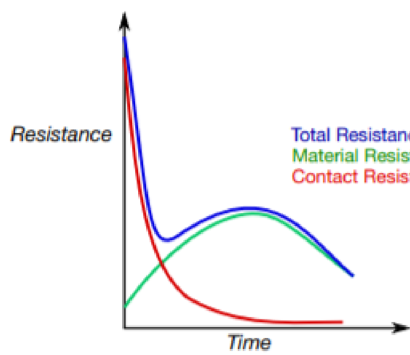

Figure 5 Typical Spot Welding Resistance behaviors

Contact Resistance laws

Describing the electric contact resistance behavior is usually a challenge which requires experimental calibration or a combination of experimental tests and simulations to capture the temperature dependency and other dependencies (contact force, conductivity) (See [1] and [2]). To calibrate such a model, experiments need to be carried out and can be combined with FE simulations, for example by joining two sheets with variation of electrode force and current and then measuring the apparent resistance. The contact resistance model can subsequently be validated by comparison between experimental and simulated nugget dimensions. Figure 6 shows a typical behavior of a general Temperature and contact force dependent resistance law.

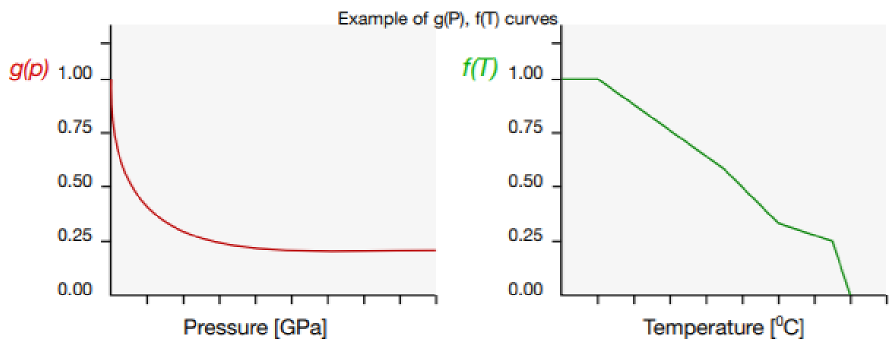

Figure 6 Contact resistance law defined as the product of a temperature dependent function and a contact pressure dependent function time a base resistance value: $r(T,P) = r_0 f(T) g(P)$

Some laws are directly made available in the literature and can be applied for certain materials. The Jonny Kaars model (See [3]) for example described the contact resistance function of temperature and contact pressure:

$$\mathrm{r(T,P)} = r_0 \left(\frac{p - p_k}{p_0 - p_k}\right)^{\varepsilon_p} \left(\frac{T - T_{lim} + (293.15 - T)^{1/\varepsilon_T}}{293.15 - T_{lim}}\right)^{\varepsilon_T} \quad (1)$$

with r_0 the base resistance value to be calibrated, p_k a corrective pressure with no physical meaning, p_0 the reference pressure, T_{lim} the half value temperature and ε_T and ε_p the temperature and pressure exponents respectfully.

Another common law encountered in literature, Wanheim and Bay's (See [5]) model:

$$\mathrm{r(\sigma,P,\rho)} = 0.33 \frac{P}{\sigma\rho} \quad (2)$$

with σ the stress of the softer material of the two in contact and ρ an average resistivity value function of the two material resistivities, ρ_1, ρ_1 as well as a contaminants resistivity ρ_c and a factor γ to be determined by contact resistance adjustment so that $\rho = \frac{1}{2}(\rho_1 + \rho_2) + \gamma\rho_c$.

Contact Resistance numerical implementation

The LS-DYNA resistance spot welding capabilities have been described in [6]. This paper provides an opportunity to further introduce the latest developments and offer a summary of the current capabilities.

The EM resistive heating solves the Laplace equation for the electric potential (σ is the electrical conductivity from now on):

$$\nabla.\left(\sigma\vec{\nabla}\varphi\right) = 0. \quad (3)$$

From which current can be calculated:

$$\vec{j} = -\overrightarrow{\sigma\nabla}\varphi \quad (4)$$

And therefore Joule heating:

$$J_{heat} = \frac{j^2}{\sigma} \quad (5)$$

From a linear algebra stand point, the system solved can be expressed as:

$$\begin{gathered} S_0(\sigma)\Phi = f \\ C\Phi = g \end{gathered} \quad (6)$$

with $S_0(\sigma)$the stiffness matrix dependent on conductivity and Φ the scalar potential i.e the unknowns. The constraint matrix and vector C, g as well as the RHS f will be built thanks to the boundary conditions on the scalar potential or current that the user will define.

The contact algorithm is essential a Robin Boundary condition without right hand side term, where a local stiffness matrix D_0 between the nodes in contact will be build and added to the system such as the modified system reads:

$$(S_0(\sigma) + D_0(r_0))\Phi = f \quad (7)$$

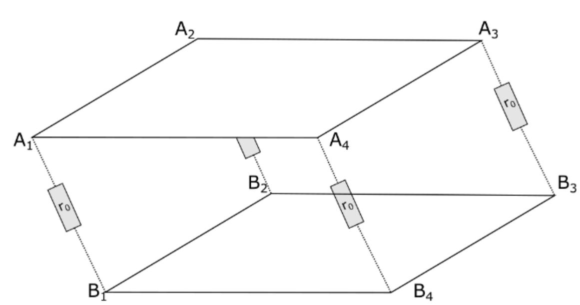

Figure 7 Node to node contact. Each pair of node in contact gets added the local matrix $D_0\left(r_0\right) = 1/r_0$

The most basic form of penalty contact consist in connecting all pairs of nodes coming in contact and adding the local contact resistance to each of them (See Figure 7). However, this approach can yield inaccurate results in highly non-conforming meshes which can be of critical importance in Resistance Spot Welding configurations. For this reason a mortar contact [8] was implemented which essentially reconstructs the intersection polygon between the faces in contact and assigns weight coefficients to nodes that are in contact (See Figure 8). This approach has the potential to yield more accurate results and should be considered as the default approach for Resistance Spot Welding applications.

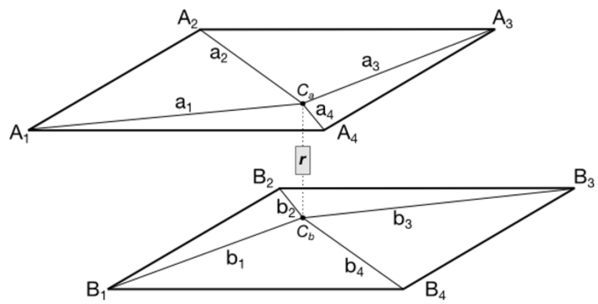

Figure 8 Mortar contact, a local stiffness matrix is build connecting the two faces and assigning weights a_1, a_2, a_3, a_4 and b, b_2, b_3, b_4 on the intersection surface area

LS-DYNA Model

Numerically, setting up the RSW model consists of a challenging and highly non-linear problem where solid mechanics, thermal and EM quantities interact with each other (See Figure 9). Two options are available to the user. Either the full 3D model can be set up (usually only a slice is used) or the 2D axisymmetric solver can be used for a faster solve. When setting up a 3D slice of the model, it is important to set the correct symmetry conditions for the solid mechanics problem by defining a local coordinate system and applying the correct boundary conditions (See Figure 10). Due to the duration of the process (around 1 second), the implicit solver is often used for the solid mechanics part of the analysis (See *CONTROL_IMPLICIT keywords). In conjunction with the implicit solver, mortar contact is often used for the mechanical contact (See *CONTACT_..._MORTAR). For the accuracy of the solid/EM/thermal coupled analysis, it is important to avoid big penetrations between the electrodes and the metal sheets. The thermal contact can be activated by adding the suffix _THERMAL in the contact keyword. Using a mortar contact will also increase the accuracy of the heat transfer at the contact zone. The effects of water cooling and air cooling on the different parts is usually taken into account by a convection boundary condition (See *BOUNDARY_CONVECTION).

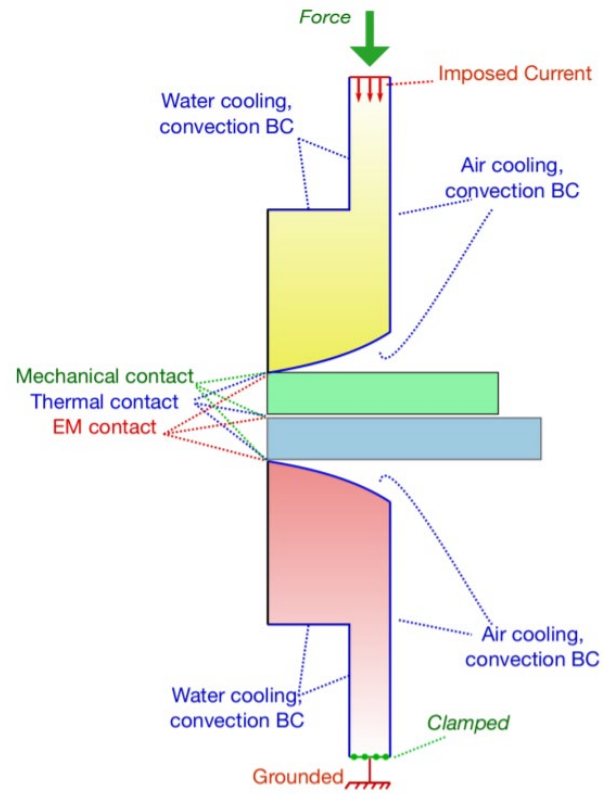

Figure 9 Sketch showing the RSW problem set up with contact and boundary conditions

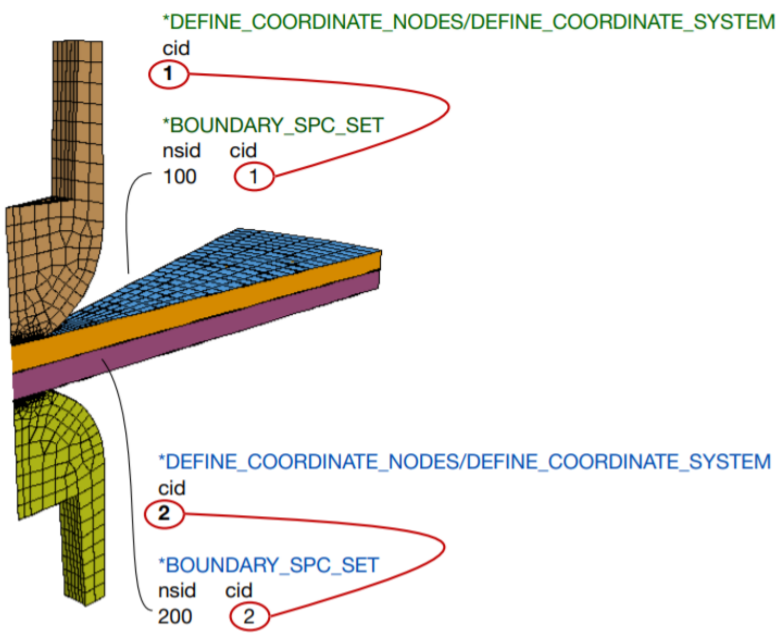

Figure 10 3D axi problem: mechanical symmetry conditions set up

For the EM part, after setting up the resistive heating solver (See *EM_CONTROL), the materials' electrical conductivities (See *EM_MAT_) and the correct boundary conditions (See *EM_ISOPOTENTIAL, *EM_ISOPOTENTIAL_CONNECT or *EM_BOUNDARY_PRESCRIBED), the EM contact detection can be turned on by:

***EM_CONTROL_CONTACT**

EMCT	CCONLY	CSOLVE

The flag of main interest here is CSOLVE which allows the user to control the EM contact algorithm. CSOLVE=-1 triggers a constraint based contact which can only be used to describe a 'perfect' electrical contact with no contact resistance and is consequently of no interest for the present application. CSOLVE=0 is the classic legacy contact described in Figure 7. Its accuracy depends on the mesh conformity on both sides of the contact. CSOLVE=1 and CSOLVE=2 are two similar mortar contact implementations that are available in R12 and Post R12 LS-DYNA versions and which are recommended, especially in highly non-conforming mesh cases.

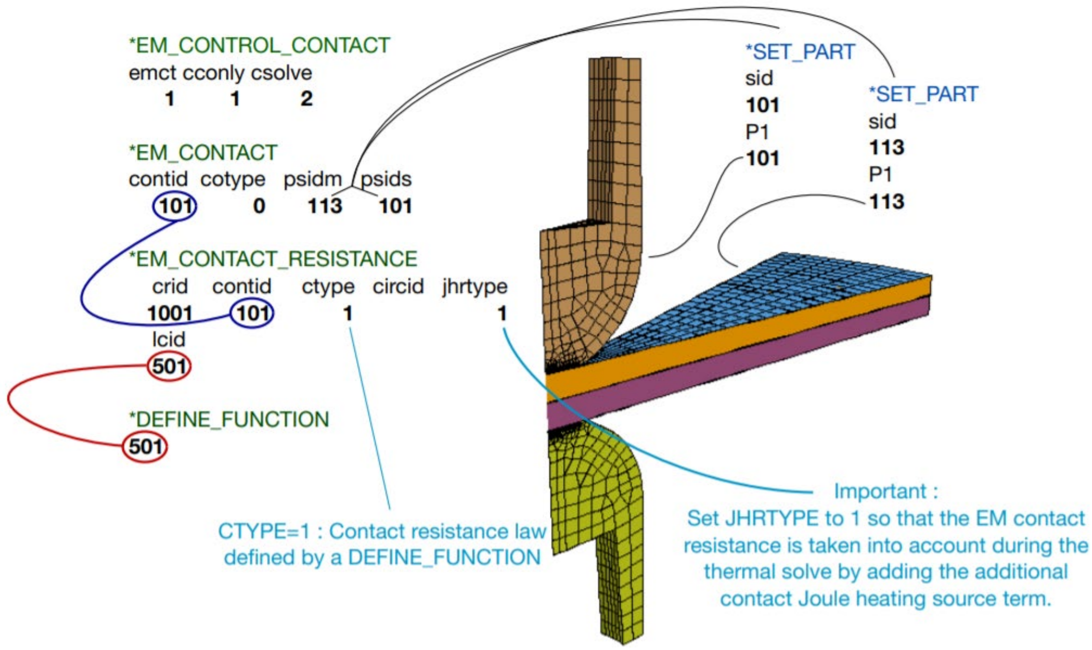

Figure 11 3D axi problem: EM contact resistance keywords set up

The contact resistance law is defined through the combination of the *EM_CONTACT and *EM_CONTACT_RESISTANCE keywords. It is based on a *DEFINE_FUNCTION where the choice of which law to use is left to the user. Figure 11 shows an example of keyword definition while Figure 12 shows a snippet of keyword organization for a specific contact resistance law.

```
*DEFINE_FUNCTION (Jonny Kaars type example)
     501
float r501(float time,float emdt, float arealoc, float areatot, float ctdist,
  float rho_mst, float rho_slv, float cond_mst,float cond_slv,float ctpress_mst,
 float ctpress_slv,float temp_mst, float temp_slv,float vmstress_mst,
 float vmstress_slv, float press_mst, float press_slv)
{
float f,t,ct;
float tlim,t0;
float p0,pk;
float epsP,epsT;
float r0;

r0=2.7823;
p0=20.001;
pk=-0.001;
epsP=-1./3.;
epsT=-1./1.;
tlim=415.;
t0=293.15;
t=(temp_mst+temp_slv)/2;
ct=(press_mst+press_slv)/2;
f = 1.0E-6;
f=r0*
(((abs(ct))-(pk))/(p0-(pk)))**epsP*
((t-tlim+(t0-t)*2**(-1/epsT))
/(t0-tlim))**epsT;
if (f <= 0.0) {
  f = 1.0E-6;  return f;}
```

Accepted parameters for the define function. Those include the contact pressure (ctpress), the element pressure (press), the von misses stress (vmstress), the element density (rho), temperature (temp), electrical conductivity (cond), contact distance (ctdist) and local/total areas (arealoc,areatot). The _mslv and _mst suffix indicate the master and slave PIDs defined in EM_CONTACT.

Base Resistance in Ohm.m²

Avoids negative values and divisions by zero

*Figure 12 *DEFINE_FUNCTION example for * EM_CONTACT_RESISTANCE.*

As mentioned previously, for a faster solve, the 2D axisymmetric solver (around the Y axis) can be used along with shell elements. To activate the solid mechanics and thermal axisymmetric solvers, *SECTION_SHELL type 14 and 15 may be used. The contact keywords now become *CONTACT_2D and have slightly different options available when compared to the 3D problem. Some are not yet available in MPP. On the EM side, *EM_MAT_004 will replace *EM_MAT_001 and the 2D axisymmetric solver can be activated via DIMTYPE=3 in *EM_CONTROL. Figure 14 shows a comparison of the 3D and 2D cases with the formation of the nugget.

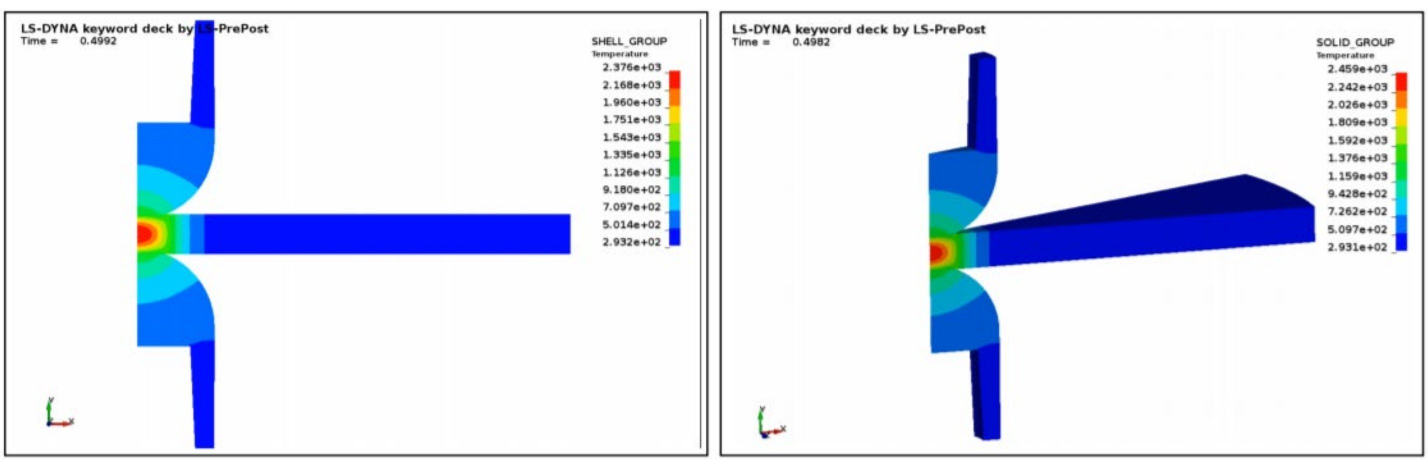

Figure 13 3D axi and 2D axi temperature comparison

Conclusion and future developments

All the numerical tools needed for the simulation of the RSW process have been developed within the commercial code LS-DYNA which consists in a complex coupled EM-thermal and solid mechanics process. Naturally and in the accordance with the general nature of the LS-DYNA software, while all capabilities are made available, the challenge for the engineer remains to correctly characterize his inputs, especially the choice of material model and properties and, in this case, the electric contact law. On the other hand, this offers the unique opportunity when combining experimental tests with numerical calibration to gain a deep understanding of the physics involved, especially when new materials or processes are being tested and investigated (See [7]).

Besides the implementation of the few missing features in the 2D solver, future developments will most likely concentrate on assisting the engineer with his workflow, where he would wish to apply and scale the results of one RSW simulation to a complete metal sheet model with hundreds or thousands of spot welds. In order to tackle this future challenge, feedback to the developer team is crucial and therefore strongly encouraged.

References

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