Abstract: The paper summarizes the latest developments in numerical simulation and optimization of resistance welding as well as new developments in 3D simulation. Resistance welding simulation can be applied for the prediction of weld nugget sizes in various material combinations, and for the optimization and planning of welding process parameters. Weld quality can be modelled in terms of microstructural phase changes, resulting hardness distribution and strength under specified loading conditions. New developments for 3D simulation of complex joints allow for modelling strength testing and special effects such as shunting. Furthermore, projection welding often needs 3D simulation. 3D simulation of a new, lightweight, sandwich material is presented in the paper.

Keywords: resistance welding, numerical 3D simulation, welding parameters

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results with specified materials, electrodes and welding process parameters. This is the fundamental function for more advanced functions such as optimization and welding process planning.

Automatic procedures have been developed for preparing input data, speeding up the simulations with more convenient graphical user interface and displaying weld results. After simulation, the dynamic process parameter curves can be displayed as functions of time, which include the process curves of voltage, current, power, resistance, force, displacement of electrode and evolution of the weld nugget size etc. The distributions of temperature, current, voltage, stress and strain in all materials can be visualized in animation throughout the welding process.

Figure 1 shows an example of the process simulation for spot welding of 1.0 mm mild steel sheets. Figure 1a shows the graphical user interface for preparing the input data with materials and welding process parameters. Figure 1b shows the report of simulation with the input conditions and the simulation results including a process parameter curve and the final weld nugget sizes.

Expulsion (or splash) is simulated by predicting the starting time of the splash during the welding process and also the intensity of splashes at three levels: low, medium and high. Figure 2a shows the dynamic resistance curve with the indication of the splash starting time and intensity. Figure 2b shows the final weld nugget with the indication of the splash intensity.
Process optimization

Based on the results of process simulations, automated procedures have been developed for the optimization of the resistance welding process parameters. The weldability analyses and optimizations of resistance welding are presented in the international standard ISO 14327:2004 with two diagrams, including the weld growth curve and the weldability lobe. Both diagrams can be simulated automatically with SORPAS® with predicted expulsion (splash) limits and process window.

The weld growth curve can be produced by running a series of welding tests with increasing weld current and measuring the resulted weld nugget sizes. This is a tedious job with high costs of time and materials. It can now be simulated with an automated procedure for running simulations of all welds along the weld growth curve with the prediction of splashes.

The weldability lobes can be similarly simulated by running simulations of all welds in the specified ranges of weld current and weld force with the prediction of the welding process window. Two types of weldability lobes can be simulated with two varying process parameters. The first type is with varying weld current and time but constant weld force. The second type is with varying weld current and force but constant weld time.

Figure 3 shows the process optimizations for spot welding of 1.0 mm mild steel sheets.

Figure 3a shows the simulated weld growth curve with weld nugget diameter as a function of weld current. It is seen that the weld nugget starts to form at a certain weld current and then grows with increasing weld current. The black (or square) points mean no weld or an undersized weld. The red (or triangular) points indicate expulsions (or splashes). The green (or round) points in the middle are good welds, which indicate the welding process window with the working range of weld current. Figure 3b shows the weldability lobe with current and weld force as the two varying parameters at a constant weld time. The black (or square) points are no weld or undersized welds. The red (or triangular) points are expulsion (splash) welds. The green (or round) points indicate good welds and the welding process window.

Weld planning automated for spot welding of steel and aluminium

After predicting the welding process window with the optimization procedures, a further demand of the industry is to determine the weld schedule specifications with optimal welding process parameters. The new function Weld Planning has been developed based on optimization procedures to predict the optimal welding parameters with specific current, force and time for a specific weld task. With the newly released SORPAS® 2D version 12, the weld planning works with a lot of improvements for spot welding.
welding of steels and also extended to work as well for spot welding of aluminium alloys.

Figure 4a shows the graphical user interface of the Weld Planning function for preparing the Weld Task Description (WTD) with information of the sheets, electrodes and welding machine. A special algorithm has been developed to automatically analyse the combination of sheet material and thickness, determine the weld force and weld time, and then obtain the welding process window. Thereby the optimal weld current, force and time can be obtained. Figure 4b shows the Weld Planning Report with the input data for the weld task description (WTD); the graphical display of the optimal welding process parameters; the Weld Schedule Specifications (WSS) with optimal weld current, force, weld time and hold time together with the welding process window; and the welding results obtained with the optimal welding process parameters.

Based on the simulated optimal welding process parameters, users can quickly determine the starting welding process parameters.

**Weld properties after welding**

The weld properties, in terms of microstructural phase changes and the hardness distribution, are calculated in SORPAS® for typical automotive steel grades. Furthermore, in SORPAS® 3D, it is possible to simulate strength testing based on the predicted hardness distribution and thereby predict the strength of a weld under a giving loading condition.

During heating, the calculation of austenitization is based on the Ac1 and Ac3 temperatures independent from the heating rate. Full austenitization is assumed when the process peak temperature is above the Ac3 temperature; zero austenite formation is assumed when the process peak temperature is below the Ac1 temperature; and linear interpolation is applied in between the Ac1 and Ac3 temperatures. Transformation of the predicted austenite upon subsequent cooling is based on critical cooling rates in continuous cooling transformation (CTT) diagrams. Following the formulas presented by Blondeau et al. [12], the critical cooling rates for the formation of martensite, bainite and ferrite/pearlite are estimated by the chemical compositions. Formulas for the hardness of each phase are provided by Maynier et al. [13] with the dependency of chemical composition. The total hardness is predicted based on volume mixing of the hardness of each individual phase.

Figure 5a shows an example of the predicted hardness distribution in spot welding of two 1mm thick sheets. The upper sheet is a low carbon DC06 deep drawing steel and the lower sheet is a dual phase high strength steel DP600. The figure shows the hardness of the base material around the nugget and the hardness due to austenitization and the formation of subsequent phases during cooling in the weld nugget.
and in the heat affected zone (HAZ). The HAZ shows the difference between the two sheets. A large amount of martensite is formed in the DP600 steel with the resulting increase of hardness, while almost no martensite was formed in the HAZ of the DC06 where the hardness remained almost unchanged. In the nugget, volume mixing results in the formation of phases due to the mixed chemical composition. In this case some martensite was formed and an increase of hardness compared to both of the base materials. Figure 5b shows an example of cross-tension strength testing [14]. The simulation shows the localization of damage outside the nugget in agreement with the experimental observation of plug failure. Load-elongation curves for tensile-shear, cross-tension and peel strength testing are given in the references. Further details on the metallurgical changes, hardness prediction and damage implementation are given elsewhere [15].

3D simulation of new, sandwich material

A new application of simulation by SORPAS® 3D is spot welding involving new, lightweight, sandwich materials such as LITECOR®. For more details of the LITECOR® sandwich material see [16-17]. Figure 6 shows an example of two DC06 sheets being spot welded to a centre layer of LITECOR®, where an additional shunt tool is included in the setup in comparison to traditional spot welding. In the initial stage of the process, the current flows as schematically illustrated in Figure 7a through the outer sheets and the shunt tool without passing through the weld zone. This current flow results in heating and softening of the polymer layer in the LITECOR® and in combination with the applied electrode force this leads to squeezing out of the polymer in the weld zone to reach metal-metal contact and a current flow as illustrated in Figure 7b. The current passing through the four metal layers produces a spot weld joining the three sheets.

Sagüés Tanco et al. [18] have presented experiments and simulations by SORPAS® 3D of the case outlined in Figures 6 and 7. Some of these results are presented as follows. The simulated current density before squeezing out the polymer (corresponding to Figure 7a) is shown in Figure 8a at a selected time step. It is visible how the current flows through the outer sheets and the shunt tool while not passing the polymer layer of the LITECOR®. Figure 8b shows the current density during a selected time step.
after the polymer has been squeezed out and the current can pass through the spot to form a weld. Part of the current still passes the shunt tool. An example of a simulated weld nugget is presented in Figure 9a with comparison to the corresponding experiment in Figure 9b. The simulated nugget size measured at the interface between the DC06 sheet and the BH220 layer of the sandwich material was 5.05mm, which is in good agreement with the 5.11mm nugget size measured in the experiment. Further comparisons over the entire range of a weldability lobe can be found in [18].

**Conclusions**

Numerical simulation of resistance welding has been applied in industry for evaluations of the weldability of new materials and optimizations of welding process parameters. Two automated procedures have been developed for the optimization of welding process parameters with weld growth curves and weldability lobes. The new Weld Planning function is developed for predicting optimal welding process parameters to support welding production applications. The new developments in 3D simulations have made it possible to simulate more complex welding cases, whereas the 2D simulations are more suitable for simulation and optimization of spot welding and simple projection welding cases.

**References**


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