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Design and Implementation of Software for Resistance Welding Process Simulations

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ABSTRACT

Based on long time engineering research and dedicated collaborations with industry, a new welding software, SORPAS, has been developed for **s**imulation **o**f **r**esistance **p**rojection **a**nd **s**pot welding processes applying the powerful finite element method (FEM).

In order to make the software directly usable by engineers and technicians in industry, all of the important parameters in resistance welding are considered and automatically implemented into the software. With the specially designed graphic user interface for Windows, engineers (even without prior knowledge of FEM) can quickly learn and easily operate and utilize the software. All industrial users, including welding engineers from DaimlerChrysler, Volkswangen, PSA Peugeot Citroen, VOLVO, Siemens, ABB and so on, have started using the software just after taking a one-day training course.

With the user-friendly facilities for flexible geometric design of work pieces and electrodes as well as process parameter settings similar to real machine settings, the software has been readily applied in industry for supporting product development and process optimization. After simulation, the dynamic process parameters are graphically displayed. The distributions of temperature, current, stress and deformation in the materials are displayed in color, which can be animated like slow-motion video. The software has been extensively verified and today applied in various industries including automotive, electronics and other metal processing industries as well as welding equipment manufacturers.

INTRODUCTION

Resistance welding including spot welding of metal sheets and projection welding of more complex components has been widely applied in various industries, e.g. automotive, aerospace, rail, electronics, electrical, radiator, container and other metal working industries for joining similar as well as dissimilar metals (e.g. carbon steel, high strength steel, stainless steel, copper, silver, nickel, aluminum and titanium alloys etc.).

Due to influence of a great number of variables such as geometry and materials of products and electrodes as well as the dynamic characteristics of process and welding machines, resistance welding is difficult to apply and hard to manage in industrial production especially when joining complex geometries and new metal combinations. The development of new products and optimization of process parameter settings in industry are greatly dependent on the personal experience of the welding engineers relying on a method of trial-and-error. This often involves a great number of running-in experiments with actual welding, destructive tests and metallographic studies. These increase the costs and delay the time-to-market of new products. Both costs and time-to-market must be reduced continuously for the company to be competitive on the market.

Computer simulation (or modeling) has been applied for solving various engineering problems in many sectors of industry. By using scientific theories and numerical methods, the engineering processes or problems can be simulated on a computer, where solutions of the practical problems are obtained virtually by computations without performing the engineering processes in reality. This is a very advantageous technique that not only can save costs, time, materials and equipment, but also can provide information that is often difficult or impossible to obtain otherwise.

The advantage of applying numerical simulations for the resistance welding processes is thus obvious especially for joining new and innovative products of complex geometries and metal combinations. A number of studies have been carried out on numerical modeling of resistance welding in the recent years. However, most of the published work dealt only with the temperature development in spot welding of similar metals and arbitrary assumptions were made on the contact resistance. The numerical methods applied include analytical methods (Refs. 1-2) and the finite difference method (Refs. 3-5). Although commercial FEM code for general purposes had been used for modeling of spot welding in some publications (Refs. 6-7), in general, most of the available FEM software systems have been designed for structural analysis, and none of them is directly suitable for engineers to use in industry for simulation of resistance welding processes at an industrial relevant level. This is due to the fact that resistance welding is a very complex process to analyze, which involves interactions of electrical, thermal, metallurgical and mechanical phenomena, which are further affected by the dynamic characteristics of the welding machines or welding guns and the process parameters.

The great demand of both the theoretical background and the engineering expertise makes the development of such a numerical system difficult and requires close co-operation between the software developers and the industrial end-users. The ideal way would be that the software developers should be engineers themselves and they should talk the same language as the welding engineers in industry.

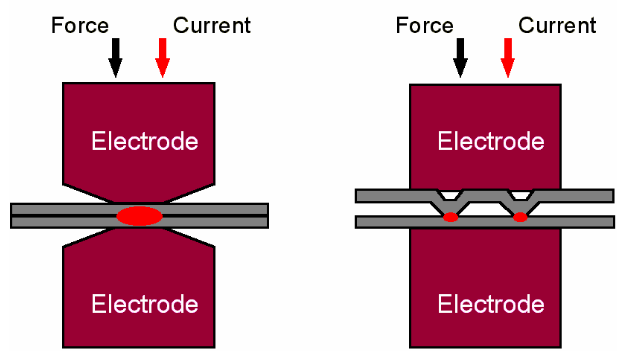
Since 1994, the development of a completely new software system with fully coupled FEM modeling of the electrical, thermal, metallurgical and mechanical aspects integrating with the engineering expertise in resistance welding has been carried out directly by mechanical and welding engineers at the Department of Manufacturing Engineering, Technical University of Denmark in close collaborations with industry (Refs. 8-15). The new software, SORPAS, has now been widely applied in many companies in Europe including DaimlerChrysler, Volkswagen, PSA Peugeot Citroen, VOLVO, Siemens, ABB and so on. The development is further continued with the spin-off private company, SWANTEC. The present paper introduces the unique concept and professional design of the software and how it has been applied in industry.

UNDERSTANDING OF RESISTANCE WELDING

In order to develop the professional welding software that can be used directly by engineers and technicians, the process of resistance welding should be understood in an engineering way and the parameters involved in resistance welding should be considered completely.

PRINCIPLE OF RESISTANCE WELDING

The principle of resistance welding is Joule heating based on the resistance of the materials to be welded. During welding the metallic work pieces are pressed together between two electrodes, and then a high current is led through the materials. Heat then develops in the work pieces due to the resistance of the materials and the contact resistances in the interfaces due to the welding current working during the weld time. Finally the materials around the weld interface are melted thus a weld nugget is formed. Among resistance welding processes spot welding and projection welding are the most common ones as illustrated in Fig. 1.



(a) Spot welding *(b) Projection welding*

Fig. 1: Process variants of resistance welding.

PROCESS STAGES OF RESISTANCE WELDING

In order to properly utilize resistance welding, it is very important to understand the process completely. Considering the process parameters and the behaviors of materials, the process of resistance welding can be divided into three stages, which are *squeezing stage*, *welding stage* and *holding stage*.

In squeezing stage, the metals to be welded are brought into contact by applying a welding force to the joint. The contacting work pieces may be plastically deformed especially in projection welding, but the welding current is not applied in this stage. The squeezing stage is usually completed when the welding force is fully built up to the specified level.

In welding stage, the welding current is applied to the joint and heat is generated at the contact interfaces and in the work pieces and electrodes while the welding force is applied. Due to increase of temperature, the material properties are changed and deformation of the materials is accelerated. If the welding time is long enough, melting occurs in the work pieces and the weld nugget is formed. The welding stage is stopped when the weld nugget has reached the sufficient size.

In holding stage, the current is switched off thus heat generation is stopped, but the welding force is still applied to maintain the weld. As temperature decreases due to heat transfer and heat losses, the melted metal returns to solid state. The welding force will be released when there is no risk of damaging the welds.

PARAMETERS IN RESISTANCE WELDING

In order to make realistic simulations, all of the important parameters in resistance welding have to be considered. Fig. 2 illustrates the system of parameters in resistance welding, which is classified into five groups, namely the work pieces, the electrodes, the contact interfaces, the machine characteristics and the process features.

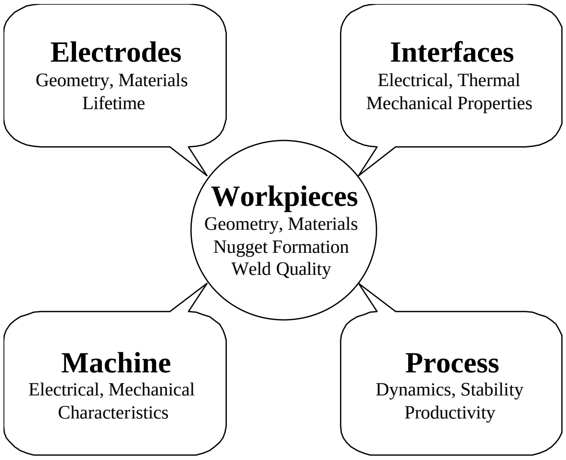


Fig. 2: System of parameters in resistance welding.

The *work pieces* are the products to be manufactured applying resistance welding. Parameters related to the work pieces include the geometry and the material properties, the weld nugget formation and the resulting weld quality. The *electrodes* are applied to conduct the welding current to the work pieces to be welded. Parameters related to the electrodes include the geometry and the material properties, the cooling passage and the lifetime. The electrodes influence the heat development and eventually the nugget formation in the work pieces. The lifetime of electrodes has a vital importance in production especially in automatic production lines. Another important group of parameters is the *contact interfaces* between the work pieces and between the work pieces and the electrodes. Parameters related to the interfaces are the electrical contact resistivity, the thermal contact conductivity and the friction if relative movement (sliding) occurs at the interface. All these parameters are dynamic and dependent on many other factors. These make the contact properties very difficult to model in theory and to handle in practice. However, they have great influence on the weld nugget formation and the weld quality.

Besides the parameters directly in connection with the work pieces, parameters related to the welding machine and the process are also important. The *welding machine* decides how the energy is delivered to the electrodes and the work pieces. For example, alternating current (AC) welding machines will have different energy delivery comparing to capacitor discharge (CD) welding machines. Furthermore, each individual welding machine will have its own electrical and mechanical characteristics including its dynamic response to a rapid current variance and a sudden mechanical movement.

The dynamic characteristics of the *process* parameters such as the welding current and the welding force are very important, too. Stability of the process indicates how sensitive the weld quality is to the variation in the process parameters, since the process parameters may be disturbed by many factors in industrial production. Productivity is another factor. A low welding current and a long welding time may result in a similar welding result as a high current and a short time. For stability reason the former case may be preferred but for productivity reason the latter case is preferable. The varying properties of the electrodes along with the number of welds have also great influence to the dynamic behaviors of the welding machines and processes.

The many parameters involved in resistance welding imply that a lot of welding experiments are necessary to achieve understanding of resistance welding. Because the evaluation of the weld quality normally has to be made by metallurgical micrographs or destructive tests, the engineering work is expensive and time-consuming. With support of the computer simulation, the development time can be substantially reduced and weld quality and stability of production can be considerably improved.

DEVELOPMENT OF NUMERICAL MODELS

In order to facilitate industrial applications of resistance welding and to support product development and process optimization as well as advance education and training, a unique and professional software tool, SORPAS, has been developed applying the finite element method (FEM). Based on understanding of the physical processes occurring in resistance welding and the basic parameters, resistance welding is simulated with four numerical models: an electrical, a thermal, a metallurgical and a mechanical model.

ELECTRICAL MODEL

The *electrical model* calculates the distributions of the voltage and the current as well as the heat generation in materials and electrodes.

The governing differential equation for the potential (Φ) field is:

$$\frac{\partial}{\partial x}\left(s_x \frac{\partial \Phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(s_y \frac{\partial \Phi}{\partial y}\right)=0 \qquad (1)$$

where s is the electric conductivity.

There are usually two types of boundary conditions for determining the potential field, these are:

$$\Phi = \Phi_0 \qquad (2)$$

on boundaries contacting the electrodes with given potential (Φ_0), and

$$\frac{\partial \Phi}{\partial n} = 0 \qquad (3)$$

on free surfaces with no potential gradient.

Applying the techniques for FEM formulations, the system equations of the electrical model are obtained:

$$[A]\{\Phi\} = \{F\} \tag{4}$$

where [A] is the electrical conductance matrix, {Φ} is the unknown potential field array, {F} is the array of boundary conditions. The potential field will be obtained with this equation. After obtaining the distribution of the potential field, the current distribution and the heat generation will be calculated.

THERMAL MODEL AND METALLURGICAL MODEL

The *thermal model* calculates the heat transfer and the temperature distribution. The *metallurgical model* calculates the phase transformation and the material properties dependent on temperature.

The governing differential equation for transient heat transfer with internal heat source ($\dot{Q}$) is:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \dot{Q} = rC\frac{\partial T}{\partial t} \tag{5}$$

where k is the thermal conductivity, r is the mass density and C is the heat capacity.

There are usually three types of boundary conditions for determining the temperature field, these are:

$$T = T_0 \tag{6}$$

on boundaries with given temperature (T_0),

$$\frac{\partial T}{\partial n} = 0 \tag{7}$$

on boundaries without heat transfer such as symmetry lines, and

$$-k\frac{\partial T}{\partial n} = h(T - T_e) \tag{8}$$

on free boundaries with heat losses.

Applying the techniques for FEM formulations, the system equations of the thermal model are obtained:

$$[A]\{T\} + [C]\left\{\frac{\partial T}{\partial t}\right\} = \{F\} \tag{9}$$

where [A] is the thermal conductivity matrix, [C] is the heat capacity matrix, {T} is the unknown temperature field array, {F} is the array of boundary conditions and heat sources. After obtaining the temperature field, the metallurgical models are applied to determine the material properties dependent on the temperature.

MECHANICAL MODEL

The *mechanical model* calculates the deformation and geometry of materials, the stress and strain distribution and the contact areas at interfaces.

The governing equation for plastic deformation is the functional of the potential energy:

$$p = \int_V \bar{s}\dot{\bar{e}}\,dV - \int_S Fv\,dS \tag{10}$$

The first term on the right hand side is the potential energy of the bulk deformation. The second term is the boundary conditions due to external load or velocity and friction etc.

In addition to the friction losses, there are usually two types of boundary conditions in the mechanical model:

$$v_i = v_0 \tag{11}$$

on boundaries with known movement, and

$$F_i = F_0 \tag{12}$$

on boundaries with known forces.

Applying the variational approach, the solution of eqn. (10) is obtained when its first derivative vanishes:

$$\frac{\partial p}{\partial v} = 0 \tag{13}$$

This yields a series of nonlinear equations. Newton-Raphson method is applied for linearization of the equations. Applying the FEM formulations, the following system equations are obtained:

$$[K]\{\Delta v\} = \{F\} \tag{14}$$

Where [K] is the stiffness matrix, {F} if the nodal force vector, {Δv} is the variation of the velocity. Based on the initial velocity field, the deformation of materials will be solved incrementally with eqn. (14).

Since large plastic deformation is modeled in the software, SORPAS can thereby be applied for spot welding as well as projection welding.

CONTACT RESISTANCE MODEL

In the simulations the contact resistivity $r_{contact}$ at the interfaces is calculated according to Wanheim and Bay's friction theory for the real contact areas (Ref. 16):

$$r_{contact} = 3\left(\frac{s_{s\_soft}}{s_n}\right)\left(\frac{r_1 + r_2}{2} + r_{contaminants}\right) \qquad (15)$$

where s_{s_soft} is the flow stress of the softer metal, s_n is the contact normal pressure at the interface, and the subscripts 1 and 2 indicate the two base metals in contact. An extra term $r_{contaminants}$ is introduced in the model to include the influence of surface contaminants such as oxides, oil, water and dirt etc.

COUPLING OF THE NUMERICAL MODELS

All the models are strongly interrelated to each other and they are all influenced by the dynamic behaviors of the materials, the interfaces, the machines and the processes. The mechanical model calculates the deformation and the stress and strain in the materials but needs the temperature field to determine the material properties. The thermal model calculates the heat transfer and the temperature field but needs the heat generation source from the electrical model and the deformed geometry from the mechanical model. The electrical model calculates the current distribution and the heat generation source but needs the temperature field to determine the materials properties and the deformed geometry from the mechanical model. The metallurgical model calculates the material properties based on the temperature field from the thermal model.

In order to make efficient simulations, a simultaneous coupling is made for electrical, thermal and metallurgical models, whereas the mechanical model is coupled stepwise with the others, see Fig. 3. In this way, convergence of the models can be easily achieved while the accuracy of solutions is maintained.

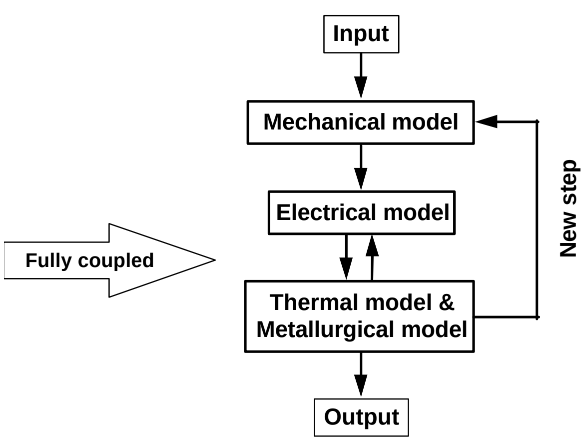


Fig. 3: Algorithm for coupling of the numerical models.

PROFESSIONAL DESIGN OF SORPAS FOR WELDING ENGINEERS

With the objective to develop a professional welding software suitable for engineers to apply in industry for their daily development work, great efforts have been concentrated on making the software not only theoretically reliable but also practically usable, for which a lot of expertise in resistance welding have been integrated with the numerical models.

Considering engineers and technicians as direct end users, an engineering language well known to engineers has been applied in designing the graphic user interface of the software, whereas most of the numerical variables have been translated into engineering parameters, which makes the terms on the software user interface familiar and easy to understand by engineers.

PREPARATION OF SIMULATIONS

There are basically two groups of input parameters to be prepared for simulations. One group is for definition of the geometry and materials of the work pieces and the electrodes, the other group is for machine parameter settings.

Fig. 4 shows the graphic user interface for designing the geometries of work pieces and electrodes in nearly any arbitrary shapes. The pre-defined material database is directly connected to the user interface that makes it easy to select material for any part of the geometries. Mesh is generated with user-defined number of elements and density distribution.

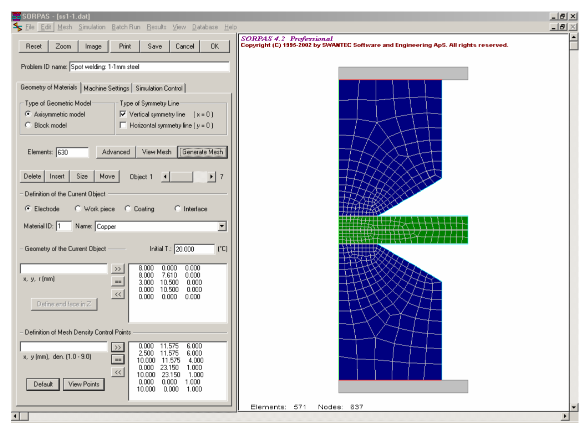


Fig. 4: Graphic user interface for geometric design.

Fig. 5 shows the graphic user interface for machine parameter settings and mounting of electrodes in the welding machine. Both the welding force and the current can be defined with slope up (building up) and slope down or in any profile as a function of time. All types of current can be defined including AC, DC (also MFDC or inverter) and capacitor discharge (CD) etc.

RUNNING SIMULATIONS

After preparation of the input parameters, the simulation can be easily started and the progress can be dynamically monitored and controlled with stopping and resuming at any time. A special function of running batch simulations makes the parametric studies and optimizations very easy and efficient.

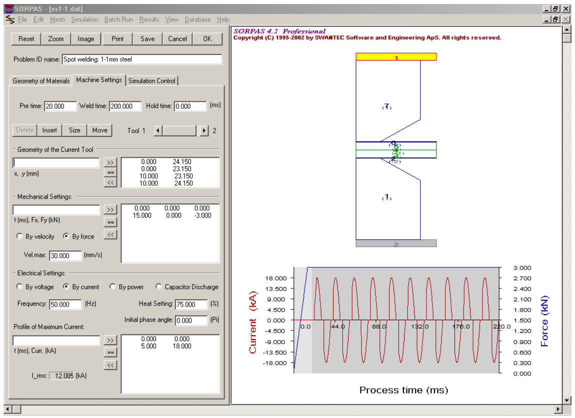


Fig. 5: Graphic user interface for machine settings.

DISPLAY OF SIMULATION RESULTS

A post-processor has been developed and integrated in SORPAS for displaying simulated process parameters and distributions of electric current, temperature, stress and strain in both work pieces and electrodes.

After simulation, the process parameter curves can be displayed as function of weld time, which include voltage, current, power, total resistance, force, displacement of electrode and size of weld nugget. Fig. 6 is an example for the curve of the welding current.

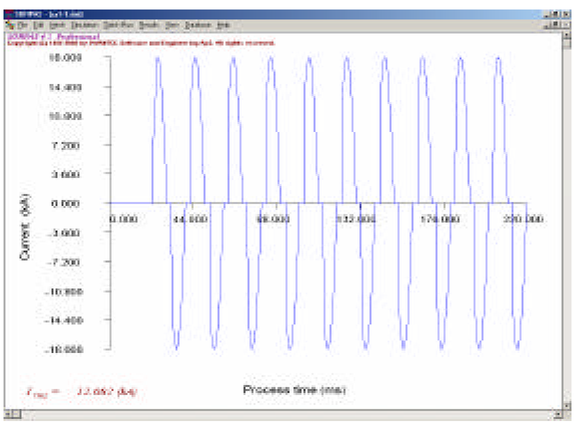


Fig. 6 Parameter curves displayed as function of time after simulation.

More important for understanding of the process and the parametric influence to the weld quality, the animated display of distributions of temperature, current, voltage, stress and strain can be dynamically visualized throughout the welding process, see Fig. 7.

INTEGRATED DATABASES IN SORPAS

In order to facilitate the industrial applications of SORPAS directly by engineers, a number of databases have been established and integrated with the user interface of SORPAS. So far, four databases have been established including material database for material properties, interface database for contact interface properties, electrode database for standard and user defined forms of electrodes, work piece database for pre-defined and frequently applied product designs. All databases have user interface for editing existing data and adding new data. Another database for machine properties is now under development. With support of the databases, the preparation for simulations becomes very easy and efficient. This has made SORPAS much more relevant to industrial applications directly by engineers and technicians.

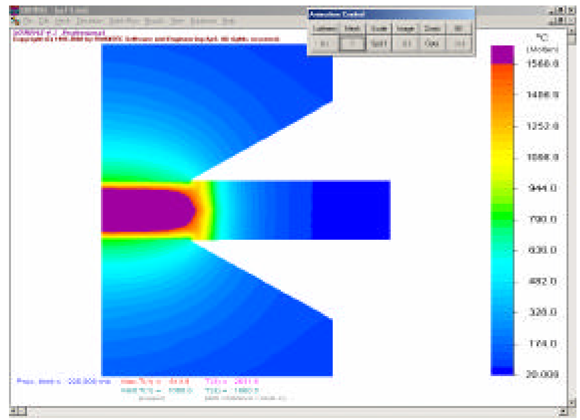


Fig. 7 Animated display of temperature distribution (also possible for current, deformation and other variables).

VERIFICATIONS OF SORPAS

In the past eight years, SORPAS has been developed and verified continuously with scientific research at universities and practical applications in industry. Fig. 8 shows the result of simulation with SORPAS for the weld nugget formation in spot welding of 2 mm stainless steel sheet to 2 mm mild steel sheet. The result of simulation is almost identical to the experimental observation.

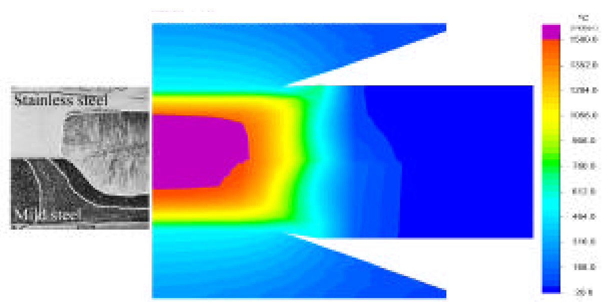


Fig. 8 Comparison of simulated and experimental weld nugget formation in spot welding of stainless steel to steel (both with thickness of 2 mm).

APPLICATIONS OF SORPAS

Since year 2000, SORPAS has been commercialized and applied in various industries, including automotive, electronics and welding equipment manufacturers. According to the feedback of industrial users, SORPAS has been supporting engineers in the following applications.

PRODUCT DESIGN

With the graphic user interface in SORPAS, it is easy to draw the geometries of the work pieces and to select materials for each part of the geometries from the integrated material database by simply clicking on the name of the materials. This makes the evaluations of different weld designs easier, especially for design of the joints with projection welding or evaluating the welding results for spot welding of multi-layer sheets with new materials and complex thickness combinations.

Fig. 9 shows the simulation of spot welding of three steel sheets with thickness of 1-2-2 mm. The welding process was carried out with welding current of 11.6 KA and force of 6.2 kN for welding time of 300 ms. The results of simulation show the weld nugget formation. The size of the weld nugget and the penetration of the weld nugget into each layer of the steel sheet as well as the indentation of electrodes into the materials can be predicted. The deformation of the work pieces due to indentation of the electrodes is also simulated.

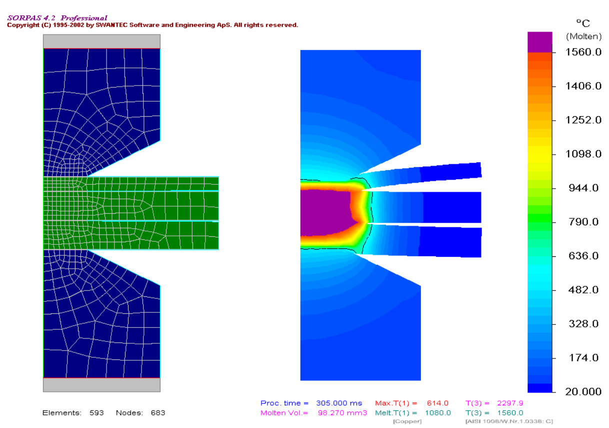


Fig. 9 Simulation of spot welding of three steel sheets with thickness 1-2-2 mm.

ELECTRODE DESIGN

The electrodes are simulated in SORPAS as materials similar to the work pieces, thus the design of the forms and selection of materials for the electrodes can be easily done just like designing the work pieces.

Fig. 10 shows the simulation results for spot welding of steel sheets of 1 mm with ISO 5821 standard electrode type A with a curvature radius of 40 mm. The welding current was 10 KA, the force was 3 kN, and the weld time was 100 ms.

Fig. 11 shows the simulation results for spot welding of steel sheets of 1 mm with ISO 5821 standard electrode type B with tip diameter of ϕ6 mm. The welding current was 10 kA, the force was 3 kN, and the weld time was 200 ms.

Comparison of Fig. 10 and Fig. 11 shows that the forms of the electrodes have great influence on the weld nugget formation and the weld quality. With the same welding current and force, electrode type A (R=40 mm) resulted in deeper penetration of the weld nugget into materials.

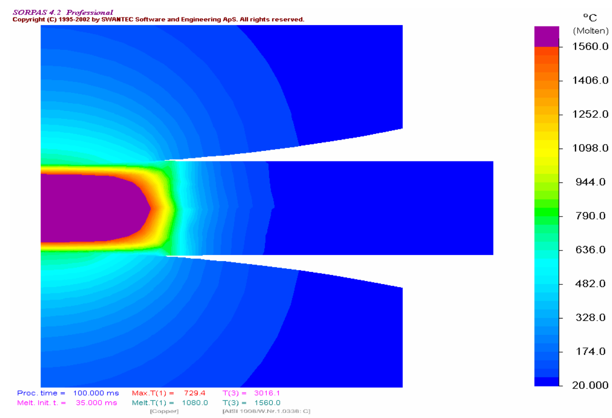


Fig. 10 Simulated temperature distribution and weld nugget formation for spot welding of 1 mm steel sheets with electrode type A. I_{rms} = 10 kA, F = 3 kN, t = 100 ms.

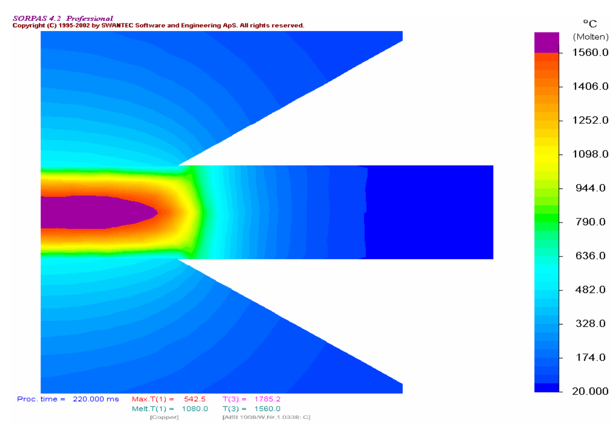


Fig. 11 Simulated temperature distribution and weld nugget formation for spot welding of 1 mm steel sheets with electrode type B. I_{rms} = 10 kA, F = 3 kN, t = 200 ms.

OPTIMIZATION OF PROCESS SETTINGS

A tedious job of welding engineers doing everyday in industry is to optimize the welding parameter settings for a specified weld combination. In many cases the products or the joints have been specified by preceding production steps, which leaves the welding engineers only the possibilities for selecting the form and materials of the electrodes and optimizing the welding machine parameters. With support of simulations, it has also been helpful to feedback the unreasonable design of the joints to earlier production steps.

For an efficient production operation, optimization of the welding process settings should be done after optimization of the design of the joints (work pieces) and the electrodes. Sometimes, the optimization of the joint and electrode design has to be carried out together with the optimization of the welding parameter settings in order to achieve the largest area of the weld lobe for a more reliable weld quality and better production stability.

Fig. 12 shows the results of simulation for spot welding of 1 mm steel sheets in conditions similar to Fig. 11 but with welding current of 12 kA instead of 10 kA. It is found that the weld nugget in Fig. 12 is much larger especially with deeper penetration into the materials.

Fig. 13 shows the results of simulation for spot welding of 1 mm steel sheets in conditions similar to Fig. 12 but with welding force of 5 kN instead of 3 kN. It is found that the weld nugget in Fig. 13 is smaller than that in Fig. 12. This is due to that the larger welding force has lowered the contact resistance at the weld interface thus reduced the heat generation with same welding current.

By simulations with different welding current, force and time, it is possible to find out the optimal process parameter settings. Using the batch simulation function in SORPAS, a series of simulations with different process parameter settings can be done automatically.

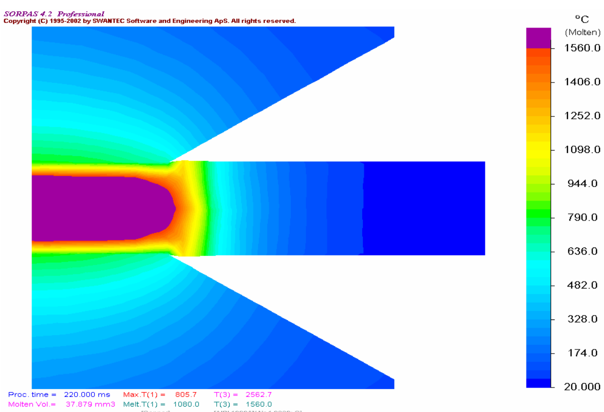


Fig. 12 Simulated temperature distribution and weld nugget formation for spot welding of 1 mm steel sheets with electrode type B. I_{rms} = 12 kA, F = 3 kN, t = 200 ms.

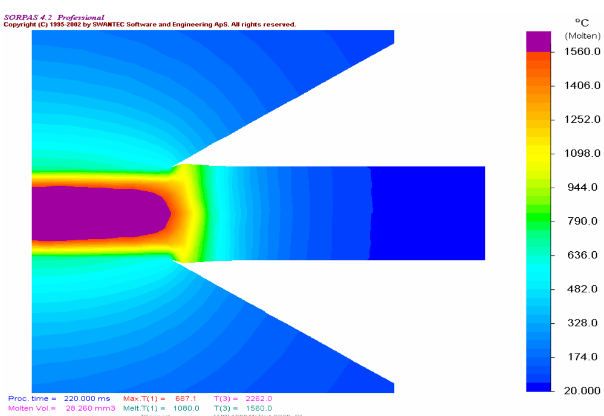


Fig. 13 Simulated temperature distribution and weld nugget formation for spot welding of 1 mm steel sheets with electrode type B. I_{rms} = 12 kA, F = 5 kN, t = 200 ms.

TROUBLE SHOOTING

In addition to the obvious advantages in supporting new product design and process optimizations, SORPAS has also been frequently applied for trouble shooting in existing or running production lines applying resistance welding.

By duplicating the design of the work pieces, the electrodes and the machine parameter settings in SORPAS, the welding process can be simulated, whereas the development of the weld nugget is illustrated graphically on the computer throughout the complete welding process. In this way, it would be possible to identify problems in the productions, to understand why the problem comes and when the problem occurs in the process. This could help the welding engineers to diagnose and solve the problems by running and evaluating some new simulations with alternative conditions.

Fig. 14 shows an example of the projection welding of stainless steel sheets with two embossed projections. The problem was that the results of welding showed that the weld of one projection is worse than the other. Simulation was made for the welding process with one projection contacted earlier than the other. The results of simulation illustrated the reason for the welding problem. This had also helped the engineers to find the solution to improve the weld quality.

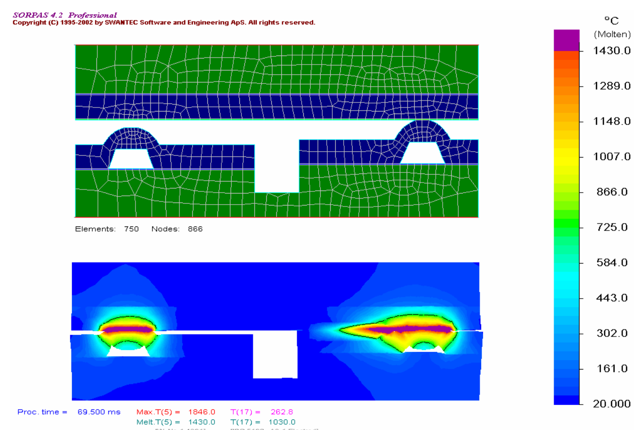


Fig. 14 Simulation of projection welding of stainless steel with one projection contacted earlier than the other.

EDUCATION AND TRAINING

As SORPAS has been designed with professional expertise in resistance welding, especially equipped with graphical illustrations of the whole welding process, it has also been applied to support training inexperienced welding engineers. In several companies, SORPAS has been used to educate newly recruited engineers to get into the welding job within a few days only, which has usually to be done in months with the traditional personal teaching by following experienced engineers.

CONCLUSIONS

Resistance welding involves many parameters that have great importance for the quality of the weld. In order to develop new products and optimize process settings as well as to understand the welding process and influence of various parameters, a lot of practical welding experiments are usually needed that increases the costs and time to market of new products.

The professional software, SORPAS, is specially developed for industrial applications of resistance welding, which makes it possible to simulate the process and show the influence of different parameters e.g. materials and geometry of work pieces and electrodes, welding current and electrode force etc. Using SORPAS it is possible to see what happens inside the weld zone through the welding process, thus to understand the importance of the parameters, and to support the product development and process optimization. This new way of working will reduce development time and improve weld quality as well as advance education and training in resistance welding.

Finally, as a unique feature, SORPAS is specialized in resistance welding and has been applied in various industries in Europe and directly used by welding engineers at manufacturing companies.

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