Resistance welding is an important industrial joining method in the fields of automotive engineering, among others, or in the electronic industries and other economic sectors. The method features a good adaptability to mechanisation and a high process stability. Among the welding parameters which exert considerable influence on the heat balance are: the electrode force, the welding current and the current time, Fig. 1.

Other, less important parameters are the set-up time and the post-weld hold time, and other boundary conditions, for example, the electrode geometry, the cooling water volume...
flow, the materials and the mechanodynamical properties of the force generation system may also exert a fundamental influence on the welding.

If the process is to be adapted to altered requirements there is, on the one hand, the possibility of the iterative approach. Parameters and boundary conditions are, based on the user's experience, altered insofar that the result, for example, nugget diameter or the width of the heat affected zone complies with the demands. The validation of the result must in this event, however, be carried out in the form of metallurgical sections which makes the validation of the iterative approach most time-consuming.

There are on the other hand, different software products available which assist the user in examining the selected parameters and in calculating them in dependence on the required result, for example of the nugget diameter. The computer simulation programs are based on substitute models which are simulating the sequences of the welding process.

The first model of a resistance spot welding process has been created by Gelmann in 1949 in the form of a differential equation system of the electric potential and the thermal conduction. The two-dimensional temperature distribution has been determined numerically by Greenwood for steel and by Ruge and Hildebrand for aluminium; Tschakalew developed the axially symmetric model based on the numerical solution of the differential equation for the thermal conduction. The deformation of the welded workpieces has been considered by Nied using the finite element (FE) method. Wei and Ho used the instationary model of thermal conduction for examining the weld nugget dimensions with different types of currents, electrodes or plates with different thicknesses. Nowadays, many institutes and companies are researching simulation software for resistance welding.

The Swantec company has been established in 1999 as a spin-off of the Technical University of Denmark. One of their main fields of activity is development and marketing of the simulation software “Sorpas” which is applied in resistance welding.

Sorpas addresses the industry and also the fields of research and development. The software is suitable for the simulation of stack spot welding, projection welding, pressure butt welding and micro resistance welding. It is possible to predict the weld result for pre-determined parameters and also to carry out parameter selection and optimisation for a desired result. Sorpas provides a graphic user interface which allows a simplified input on the supposition of standard boundary conditions. The network which is required for the FE simulation is, in spot welding, either automatically generated or defined by the user. The electric model calculates the current density and heat generation in dependence on the current intensity and the material properties. The thermometallurgical model acquires the heat flow, the development of temperature, the alteration of the material properties via the temperature and also the nugget formation.

The mechanical model calculates the mechanical sequences during a welding, among those are the deformation of the joining parts, the change of the contact surfaces and also stress and strain. The simulation results include the animation of the development of different variables, for example, temperature and deformation or the nugget form and size. The most important boundary conditions and results are summed up in a report, Fig. 2.

Sorpas contains three data bases, one for the materials which are most used, one for standard electrode tips in accordance with ISO 5821 and a workpiece database which contains the most important types of joining parts. The user is able to change or extend the contents, this applies to all three data bases.

Sorpas also allows the automatic generation of welding ranges, in accordance with ISO 14327: On the one hand, through variation of current time and welding current where a constant electrode force is maintained; on the other hand through variation of welding current and electrode force where a constant current time is maintained.

Sorpas is, by now, used by many different companies from the industry.

The software package “SpotSIM” is a simulation program for resistance spot welding which includes a material data base with data about thermophysical and thermomechanical properties of the steels and also a welding machine and electrodes data base. SpotSIM has been developed in a cooperation between the ComHighTech-Institute, University of Tula/Russia and the ISF - Welding and Joining Institute, RWTH Aachen University, Aachen/Germany. The mathematical process model consists of a system of differential equations for the calculation of the electric potential, the thermal energy and also of the equation for the plastic deformation of the metal under elect-
trode force and the time variations of the welding current. The simulation software allows the determination of the weld nugget dimensions, the electrode indentation, the gap width between the plates, the occurrence of weld spatters and the preparing of welding range diagrams.

The material data base contains data about enthalpy, thermal conductivity, density, specific resistance and resistance to deformation of steels. The input of the steel properties is possible for six arbitrarily selectable steps for temperatures from 20 up to approx. 2000°C. The data for the AC machines include power, short-circuit current, power factor, setting range of the electrode force and also the open-circuit voltage class of the transformer. Data about MF DC machines have, in addition, been implemented. In the event of standardised electrode tips, the dimensions of the tips and also the material can be entered; it is, moreover, possible to define invented electrode types/shapes. Also a shunt of one or two welding spots can be considered in the calculation. The model calculates the values of the welding current at the moment, of the temperature, the weld nugget diameter, the resistance, the gap width and the contact diameter between the workpieces, dependent on the selected steels, plate thicknesses, electrode geometry, electrode material, machine data and the welding parameters. In addition, backward optimisation based on the required nugget geometry is possible. The simulation results are comprised in a summary, Fig. 3.

Proceeding from the works carried out within the scope of a publicly sponsored research project, the simulation program “Spotwelder” has been developed by the MPA of the Stuttgart University/Germany on the basis of the finite element program “ANSYS”.

Using a two-dimensional axially symmetric model, the calculation steps of the electrothermal calculation and of the mechanical calculation are carried out separately and sequentially alternating. For the coupling between the mechanical and the electrothermal calculation, the calculated deformations are after each time step of the mechanical calculation transferred to the electrothermal model. After each time step of the electrothermal calculation, the calculated temperature distribution is, in return, transferred to the mechanical model. Through the sufficiently marginal selection of the time steps (1 ms) a sequential mechano-electrothermal coupling is, this way, achieved.

In the first program step, the deformations of the electrode and the joining parts during the electrodes' approach are calculated. Further program steps then establish the instationary temperature field in the region of electrodes and joining members during the heating and cooling phase. Non-linear material properties and a model approach for the specification of the contact resistance are, in this event, considered. It is possible to integrate user-defined material parameters and process data.

Stress distribution, deformation, temperature, current density or potential fields are displayed graphically in the form of sections. The development of several process parameters, for example a local temperature, can be displayed in a chronological sequence, Fig. 4.

The Nottingham Trent University/UK has also developed a simulation tool which is based on “ANSYS”. The model carries out two types of calculation: a structural and a thermo-electric calculation. The structural calculation considers the developing stresses during the set-up time and the thermo-electric calculation determines the nugget growth during the current time. The material properties of copper and carbon steel are used for the model; the model considers the elasticity modulus, Poisson's ratio, resistance, thermal conductivity, specific heat and the enthalpy.

The Laboratory for Heat Transfer in Material Processing of the University of South Carolina/USA has created a model for the prediction of nugget growth in resistance spot welding of aluminium. The model contains a coupled thermo-electro-mechanical calculation and also data bases for phase conversions and convective processes in the weld pool. The contact areas and force distributions are acquired via a coupled thermo-mechanical model which considers time-variable contact resistances. This is sup-

![Fig. 3 Graphical user interface, SpotSIM](image-url)

![Fig. 4 Visualisation of the weld results, Spotwelder](image-url)
posed to be the basis of the exact calculation of the heat development at the interfaces. The model is usable for the prediction of the influence of the welding parameters and the electrode shape on the nugget development. In tests about the validation of the simulation results it has been established that the influence of the convection in the weld pool does not exert significant influence on the formation of the weld nugget. The maximum speed has been established to be $2 \times 10^{-5}$ m/s.

The Technical University of Berlin/Germany has, in a cooperation with the Mechanical Engineering Department of the IIT Bombay/India, developed a simulation model for resistance welding of aluminium alloys\textsuperscript{16}. For this purpose, the electrothermal and the mechanical model have been coupled. A software which was based on the FE method for the prediction of the nugget growth, the penetration depth and the contact area electrode/plate, in dependence on welding current, current time and electrode force had been developed. Non-linear, temperature-independent and thermophysical material properties and also the enthalpies of melting and solidification have been considered. The influence of different surface properties on the contact resistance at the start of the weld had been considered using an exponential attenuator. The simulation of the welding of the aluminium alloy of the type AlMg\textsubscript{0}, 4Si, 2 with a plate thickness of 1 mm showed that the development of the weld nugget, under the prerequisite of a 50 Hz-AC welding unit had been concluded within the first cycle, the welding currents were, at that, between 14 and 23 kA. It had, moreover, been established that the original contact resistances between the plates and between the electrode and the plate exerted a great influence on the development of the joining zone; the contact resistance electrode-plate should be calculated beforehand or its value should be known in order to be able to select welding current and current time.

The Joining and Welding Institute of the Osaka University/Japan has developed a FE model for the numerical simulation of resistance spot welding and of seam welding\textsuperscript{18}. For modelling resistance welding, three calculations are carried out: One calculation of the electric field, one of the thermal conductivity and one of the occurring deformations. The validation of the simulation results showed that the formation of the weld nugget and the occurrence of spatters are closely connected to electrode follow-up which, for that reason, may also be used for controlling the welding current. If continuous AC current had been used in seam welding, non-uniform nugget formation had been found. This is to be ascribed to the instable contact ratios; if higher current-off times between the welding impulses occurred, this negative phenomenon did, due to more stable contact conditions, no longer appear.

The Massachusetts Institute of Technology/USA has developed a simulation program for the visualisation of the processes in resistance spot welding\textsuperscript{17}. The system consists of two parts and is therefore termed a "hybrid simulation": The sensor part which acquires the process data during the welding and the numerical part which processes those process data as input data and, thereof, calculates the nugget growth. Two approaches are pursued: One approach using a net structure which, for example, calculates the temperature distribution in the workpieces and the electrode tips and also the current distribution. The other approach is a reduced system which is much faster and is therefore suitable for the inline control of the welding process, however, it predicts just temperature and nugget diameter. Both models dispense with the calculation of the viscoelastic/plastic contact situation through resistance acquisition during the welding. Therefore, the calculation of the contact situation is not required and some hard-to-determine material data, for example flow stresses at high temperatures in the vicinity of the melting point, may be dispensed with. The validation of the simulation showed that the alteration of the electrode contact area through wear had a strong influence on the simulation result and that, for the simulation, it should not be proceeded from a constant form.

The simulation programs which have been presented here have, for the most part, been developed in the environment of universities; just the programs Sorpas and SpotSIM have, so far, been promoted and commercialised. The challenge of all simulation programs is the support of the material data bases and the consideration of altered boundary conditions, for example, new electrode force systems. The validation which goes along with a data base extension in order to allow for all those developments is absolutely indispensable; the simulation meets, in this event, its limitations if applied for development and research. The programs do, however, allow deep insight into the highly-transient processes of resistance welding which, by means of pure measurement, is impossible due to the process sequence.

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