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Numerical Analyses in the Modelling of Spot Resistance Welding Processes

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Abstract: The article presents the basics of the modelling of spot resistance welding processes, describes mechanisms to be taken into consideration in relation to numerical analyses of the above-named processes, briefly describes their mutual correlations and presents a simple example of the two-sided single spot welding of two steel plates demonstrating the vast range of analyses offered by a Sysweld state-of-the-art software programme. The foregoing is of great importance during production where, e.g. because of manufacturing continuity, it is not possible to perform related tests. This article aims to present the new possibilities addressed to design engineers and technologists and offered by the cutting-edge FEM-based software programme for numerical analyses of welding processes and heat treatment.

Keywords: spot resistance welding, weld nugget, electrode shape, modelling, numerical analyses

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Introduction

For many years, spot resistance welding has been an important and popular joining technology, primarily in the automotive industry. Because of its properties, the technology ensures the obtainment of high-quality joints in a short time, significantly increasing the efficiency of production. Because of their complexity, welded structures obtained, e.g. in the automotive industry, are usually viewed through the prism of distributions of global stresses and strains. In addition to addressing the above-named issue, numerical analyses make it possible to determine dimensions and shapes of welds, significantly affecting the quality and strength of welded joints. The use of advanced computational tools significantly reduces prototyping costs and eliminates expensive tests, which, because of production continuity, are often difficult or even impossible to carry out.

Although the process appears to be simple, it actually combines many phenomena. When analysing the course of the process it is necessary to take into consideration electrical, thermal, metallurgical and mechanical phenomena taking place during the process. In general, the entire process is divided into three primary phases, i.e. squeezing, welding current flow (weld nugget formation) and the forging of a weld during cooling (Fig. 1). The method described above is usually used when joining

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sheets having thicknesses restricted within the range of 0.5 to 3 mm. In typical spot resistance welding, two copper alloy electrodes supply electric current and exert squeezing force on elements being welded. The above-named process leads to the formation of a spot weld resulting from the melting of the material at the interface of elements being joined. A heat input to a joint depends on the value of current flowing through the welding area and on the time of current flow. These two parameters are adjusted in relation to a material being welded, thicknesses of sheets and types of electrodes used in the process.

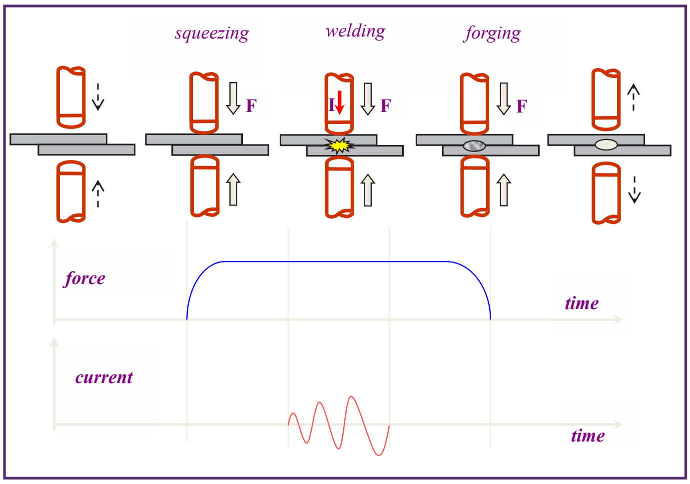


Fig. 1. Individual phases of the spot resistance welding process [1]

The quality of the above joints depends primarily on the electrode (squeezing) force and the time of welding current flow. Recently, numerical analyses have become very popular with engineers facing various challenges when developing state-of-the-art technologies without compromising economical aspects [2,3]. The use of the above-named analyses makes it possible to precisely determine the effect of the squeezing force and welding current flow time on the distribution of temperature during the entire process. In addition, the observation of the effect of the remaining parameters, including material properties or fixing manner, can be used to identify their effect on the distribution of stresses and strains as well as on the resistance of a spot welded joint.

Spot Resistance Welding in Numerical Analyses

The above-named phenomena occurring during the process are strictly combined (Fig. 2). Therefore, similar to numerical analyses of welding processes, it is necessary to perform both thermo-metallurgical and mechanical calculations. In accordance with the scheme presented in Figure 2, the four primary phenomena, previously mentioned in relation to the spot resistance welding process, taken into consideration by the SYSWELD software along with their correlations are the following issues:

- electrokinetic,
- related to the transport of heat,
- concerning metallurgical transformations occurring during the heating and cooling of elements being welded,
- related to stresses and strain in elements being welded.

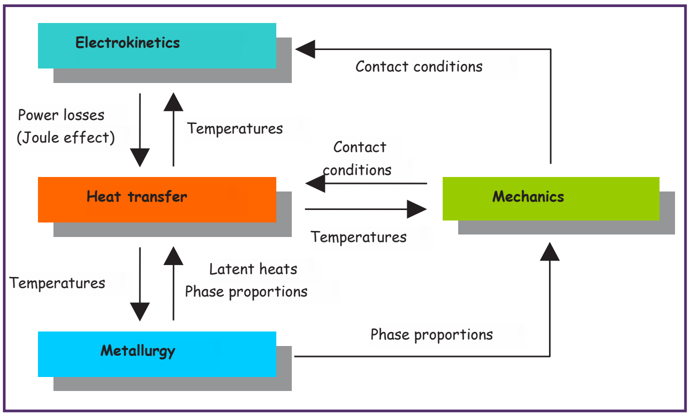


Fig. 2. Correlations between electrokinetic phenomena, transport of heat, metallurgical and mechanical phenomena in spot resistance welding [1 ,4, 5]

Electric phenomena and the transfer of heat in analysed limited area $\partial\Omega$ is combined by the phenomenon of energy dissipation through the Joule effect and can be described using an electrokinetic model (assuming that the frequency of current powering the circuit will amount to approximately 50 Hz) [4,6]:

$$div(\mu \cdot \overrightarrow{grad}(V)) = 0 \tag{1}$$

where μ stands for electric conductivity.

Taking into consideration the Dirichlet (superimposed potential) or Neuman (superimposed current density 'j') boundary condition and the heat conduction described by the Fourier law, the transfer of heat in a homogenous material is determined by the heat conduction equation containing the Joule effect as an internal heat source [1, 4]:

$$div(\lambda \cdot \overrightarrow{grad}(T)) + \overrightarrow{grad}(V) \cdot \mu \cdot \overrightarrow{grad}(V) = \frac{\partial H}{\partial t} \tag{2}$$

where 'λ' – heat conductivity and 'H' – volumetric enthalpy. It should also be noted that electric conductivity μ depends on temperature.

If a material being welded undergoes metallurgical transformations (typical when welding steel sheets), it is also necessary to allow for correlations between the transport of heat and metallurgical transformations. The above-named correlations are the following:

- metallurgical transformations depending on the so-called thermal history (previous changes in temperature),
- material properties (including thermal properties) depending on individual metallurgical phases,
- metallurgical transformations accompanied by latent heat, significantly changing distributions of temperature fields.

In terms of numerical analyses, distributions of metallurgical phases constitute additional state variables, the changes of which can be described using differential equations in time [1].

The identification of correlations between metallurgical transformations and material properties (thermal conductivity, density, enthalpy) involves the use of linear equations for each phase separately [4, 5]. The emission of heat resulting from plastic (non-elastic) dissipation can be ignored because of very low values of the above-named welding process-induced transformation factors, particularly in comparison with,. e.g. Joule effect-triggered energy losses [4, 5, 7]. In the thermo-metallurgical analysis, the convection of liquid metal in the weld nugget is ignored and replaced (artificially) by an increase in thermal conductivity.

Similar to the modelling of welding processes, the analysis of the kinetics of isothermal transformations usually involves the use of the Johnson-Mehl-Avramie equation [8].

However, as regards typical welding processes, characterised by significant heating and cooling rates, it is also possible to use the model proposed by Leblond and Devaux [4, 5, 9] expressed as the following dependence (in relation to a given transformation – where 'p' is the ratio of the formed phase):

$$\dot{p} = \frac{\overline{p}(T) - p}{\tau(T)} \tag{3}$$

where $\overline{p}(T)$ and $\tau(T)$ are parameters which, at given temperature 'T', represent phase ratios after infinite time and time delay. For each transformation, the above-named values are corrected to match the CCT-W diagram.

In relation to a diffusionless transformation, i.e. martensitic transformation, similar to analyses of welding processes, the Koistinen-Marburger equation is used [1, 4, 5, 10]:

$$p(T) = p_A(1\text{-}\exp(\text{-}b\,(Ms\text{-}T))) \text{ for } T \leq Ms \quad (4),$$

where p_A – amount of transformed austenite, p_A – temperature at the beginning of the martensitic transformation, b – parameter corresponding to transformation taking place along with changing temperature.

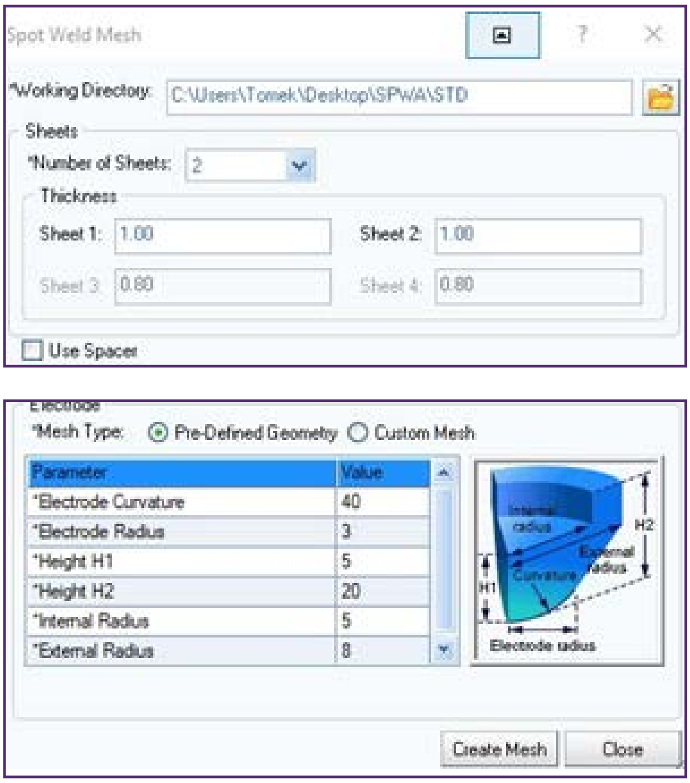
Correlations between thermal and mechanical issues are of great importance in modelling, as it is necessary to allow for thermal stresses, metallurgical transformation-induced changes in volume, metallurgical transformation-triggered plasticity etc. The mechanical analysis is based on standard equations describing the static equilibrium. Interestingly, when modelling the welding process performed using flat tip electrodes, the above-named analysis can be separated from thermo-metallurgical analyses. This results from the fact that in the thermo-metallurgical analysis, the contact area between electrodes and the material being welded is the same as the mechanical contact area in the mechanical analysis. The analysis of the process involving the use of rounded electrode tips is different as the change in the contact area between the electrode and materials being welded has a significant effect on the weld nugget formation. Therefore, in the latter case it is highly necessary to strictly combine the two types of aforesaid analyses [4, 5, 6].

Exemplary Numerical Analysis of the Spot Resistance Welding Process

The Sysweld modules of *Spot Weld Mesh* and *Spot Weld Advisor* are used to prepare and define the computational model. The first module contains a very comfortable tool enabling the creation of parametric models of welded joints, significantly quickening the creation of a computational model. In this module, the user must provide the number of sheets/plates to be welded as well as their thicknesses. The user can decide whether to use the predefined geometry of electrodes or create the geometrical model of their own (Fig. 3).

To demonstrate possibilities offered by modern analytical software, the Sysweld software programme was used to create an axisymmetric 2D model of two steel sheets subjected to spot resistance welding (Fig. 4). Both 1.0 mm thick sheets were made of cold-rolled low carbon steel DC04 (EN 10130). The analysis involved two variants, i.e. welding performed using electrodes with rounded tips and those having flat work surface (Fig. 4). In the former case, the surface curvature radius was long in order to obtain flat-like surface. In the latter case, the radius was 20 mm long, representing the round shape of the electrode tip. Both variants were calculated using the same process parameters (Fig. 5).

In the *Spot Weld Advisor* module, the user first defines the type of material, process parameters, types of electrodes and joint resistance conditions and next, activates calculations. Immediately after calculations are finished, the user receives information about the shape of the weld nugget, the development of the fusion zone, the radius of the fusion zone and the radius of the heat affected zone. The user can also view the diagram of parameters *Weld Process Check* determining the process quality based on liquid metal expulsion (Fig. 6-10).



Spot Weld Mesh

*Working Directory: C:\Users\Tomek\Desktop\SPWA\STD

Sheets

*Number of Sheets: 2

Thickness

Sheet 1: 1.00

Sheet 2: 1.00

Sheet 3: 0.80

Sheet 4: 0.80

☐ Use Spacer

Electrode

*Mesh Type: ● Pre-Defined Geometry ○ Custom Mesh

Parameter	Value
*Electrode Curvature	40
*Electrode Radius	3
*Height H1	5
*Height H2	20
*Internal Radius	5
*External Radius	8

Fig. 3. Module *Spot Weld Mesh*

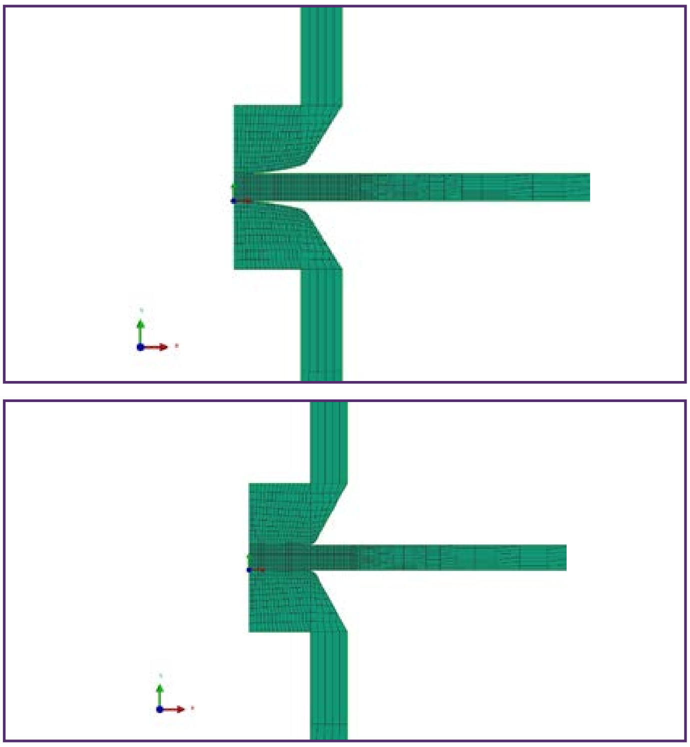


Fig. 4. Computational model of the spot resistance welded joints of two sheets

Spot Welding Process

*Parameters

Intensity Frequency (Hz): 50.00

Squeezing Force (N): 3000.00

Number of Squeezing Periods: 25

*Loads

Number of Loads: 1

Load Number	Period per Load	Intensity
Load_1	20	9.00

Welding current frequency

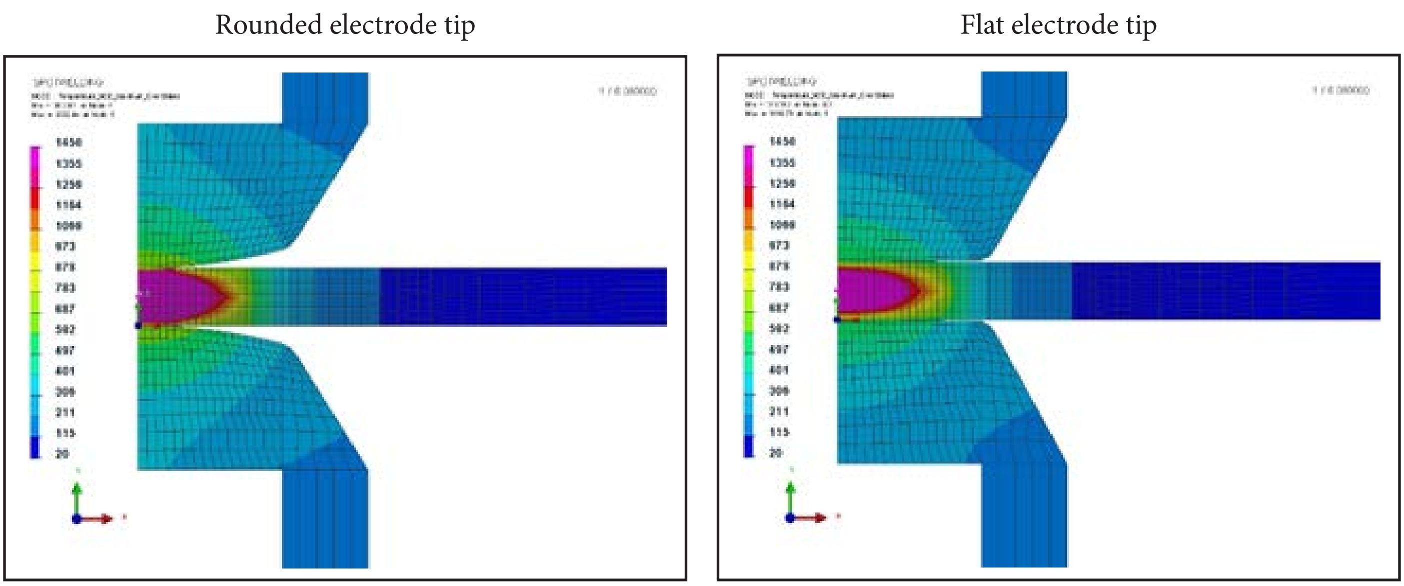
Electrode (squeezing) force

Number of squeezing cycles (squeezing time) 25/50Hz= 0.5 s

Number of current cycles (welding time) 20/50Hz= 400 ms

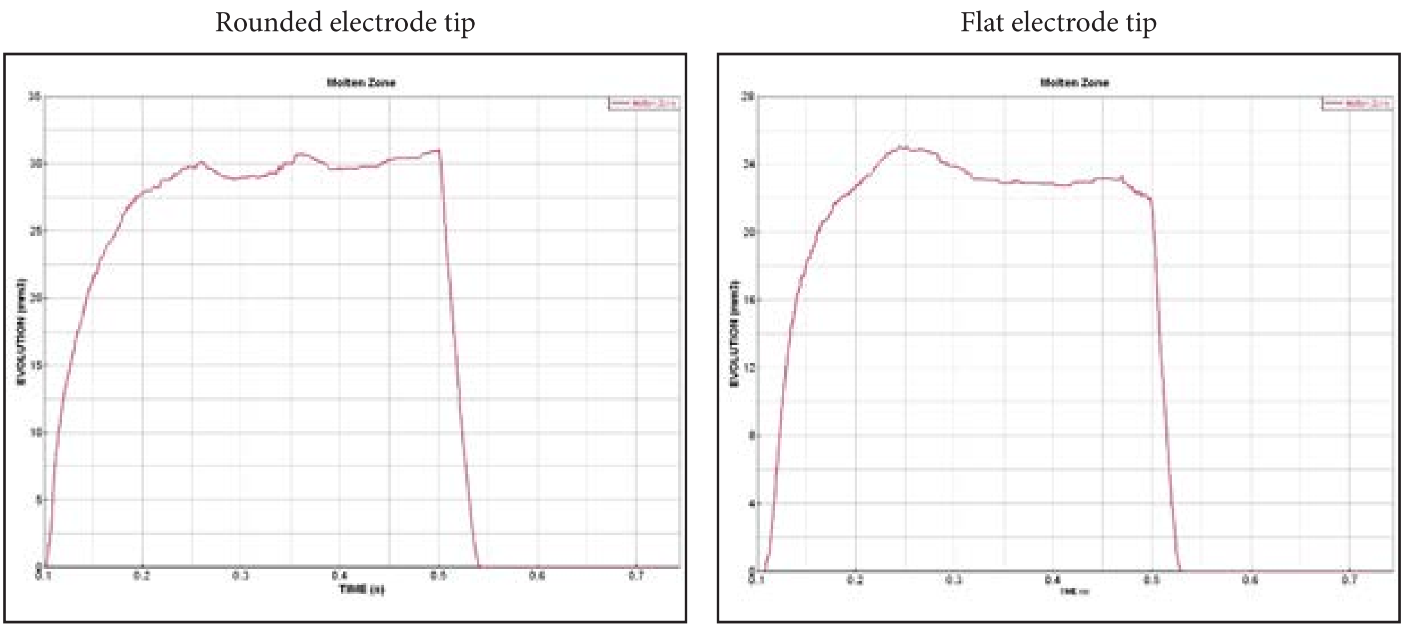
Welding current: 9 kA

Fig. 5. *Spot Weld Advisor* module window: the setting of welding process parameters


Rounded electrode tip

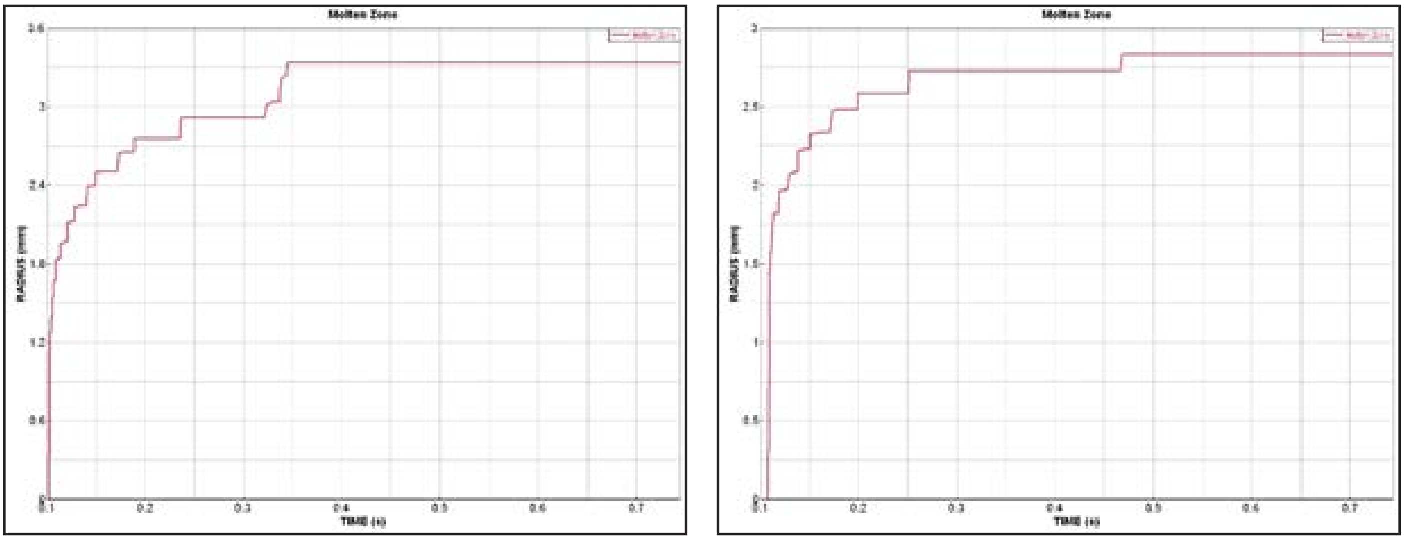
Flat electrode tip

Fig. 6. Weld nugget obtained using electrodes with the round and flat tip


Rounded electrode tip

Flat electrode tip

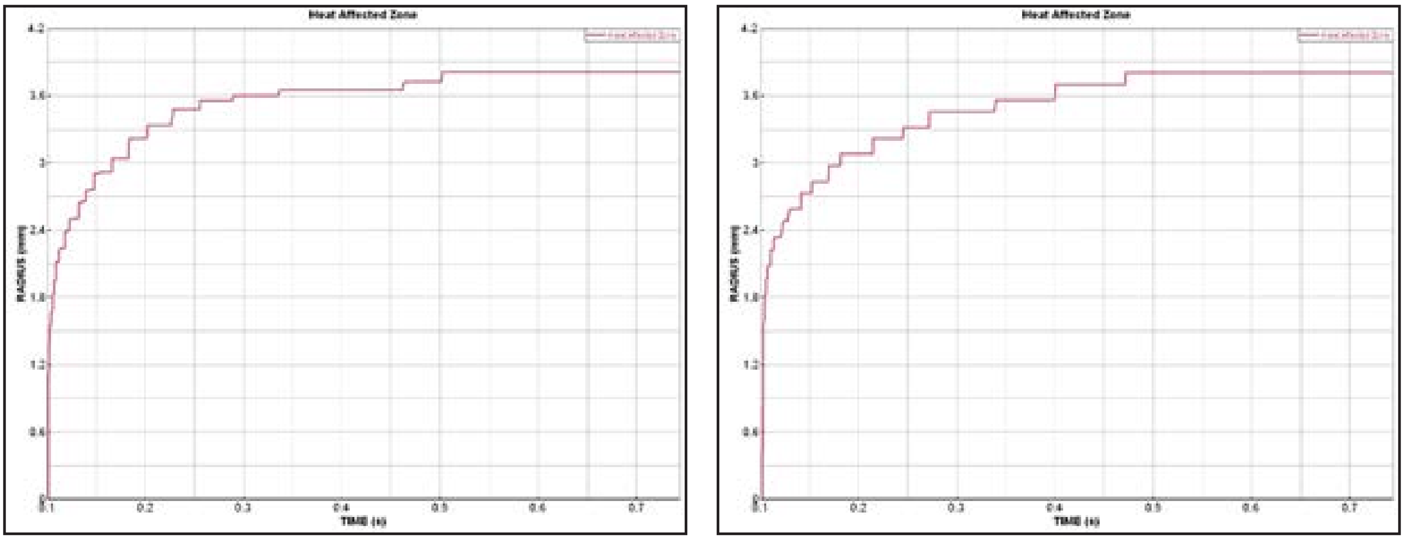
Fig. 7. Changes in the volume of the liquid metal weld nugget during spot resistance welding performed using the rounded tip and flat tip electrode



Rounded electrode tip

Flat electrode tip

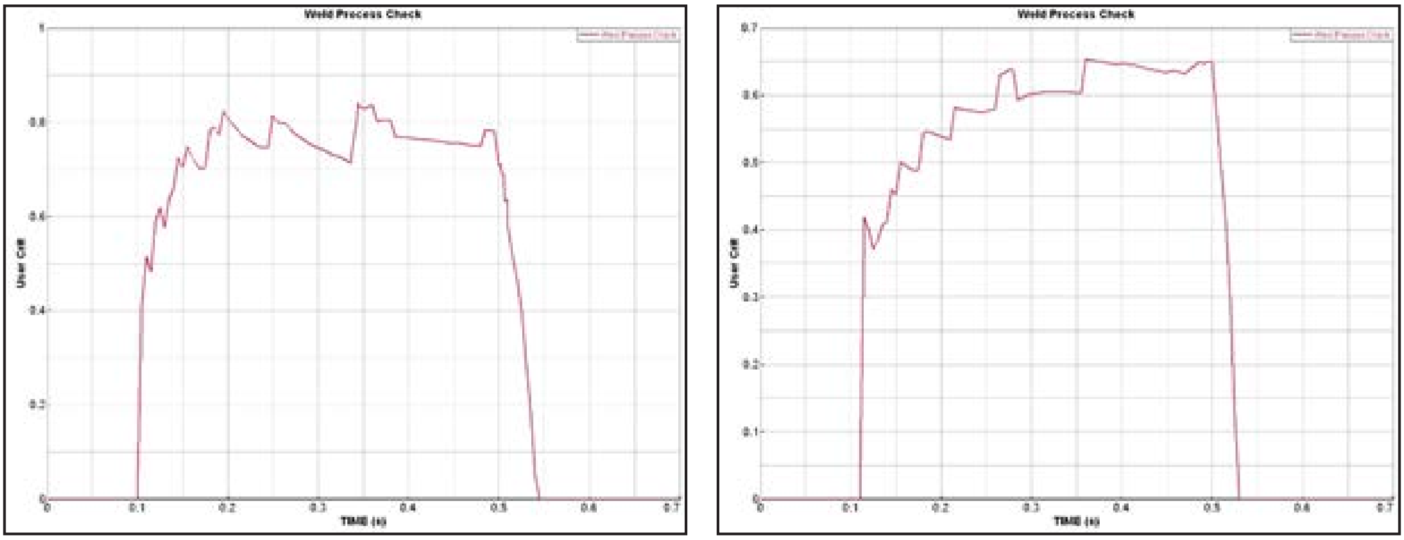
Fig. 8. Changes in the radius of the liquid metal weld nugget during spot resistance welding performed using the rounded tip and flat tip electrode



Rounded electrode tip

Flat electrode tip

Fig. 9. Changes in the HAZ radius during spot resistance welding performed using the rounded tip and flat tip electrode

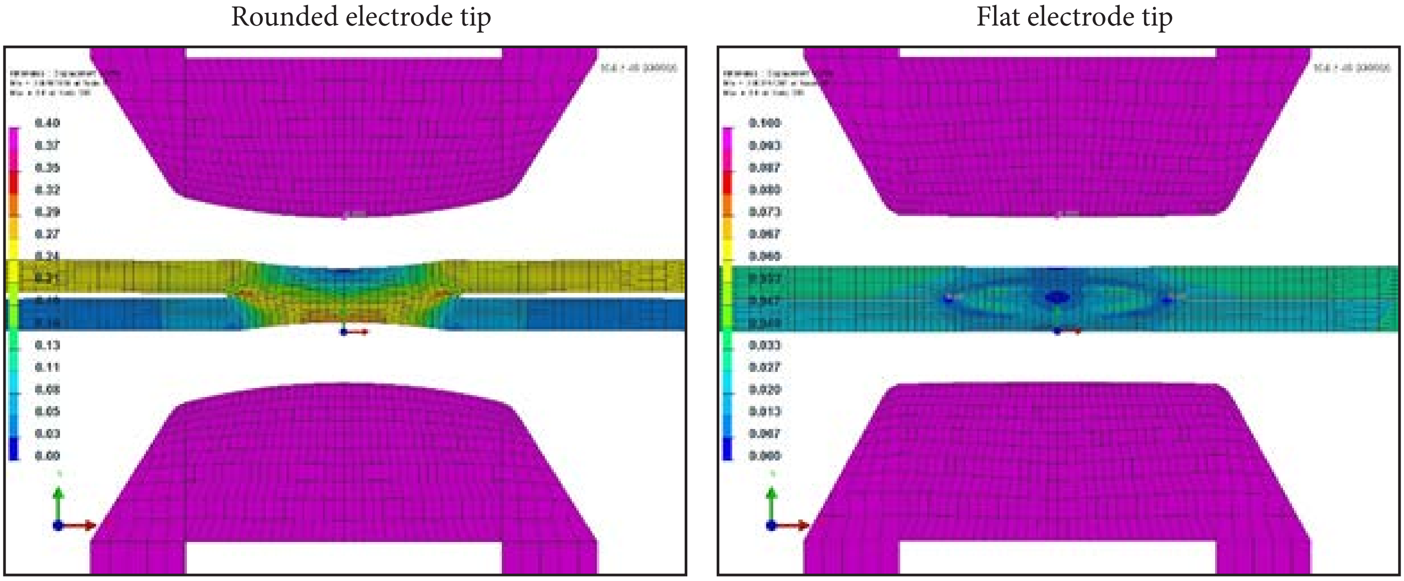


Rounded electrode tip

Flat electrode tip

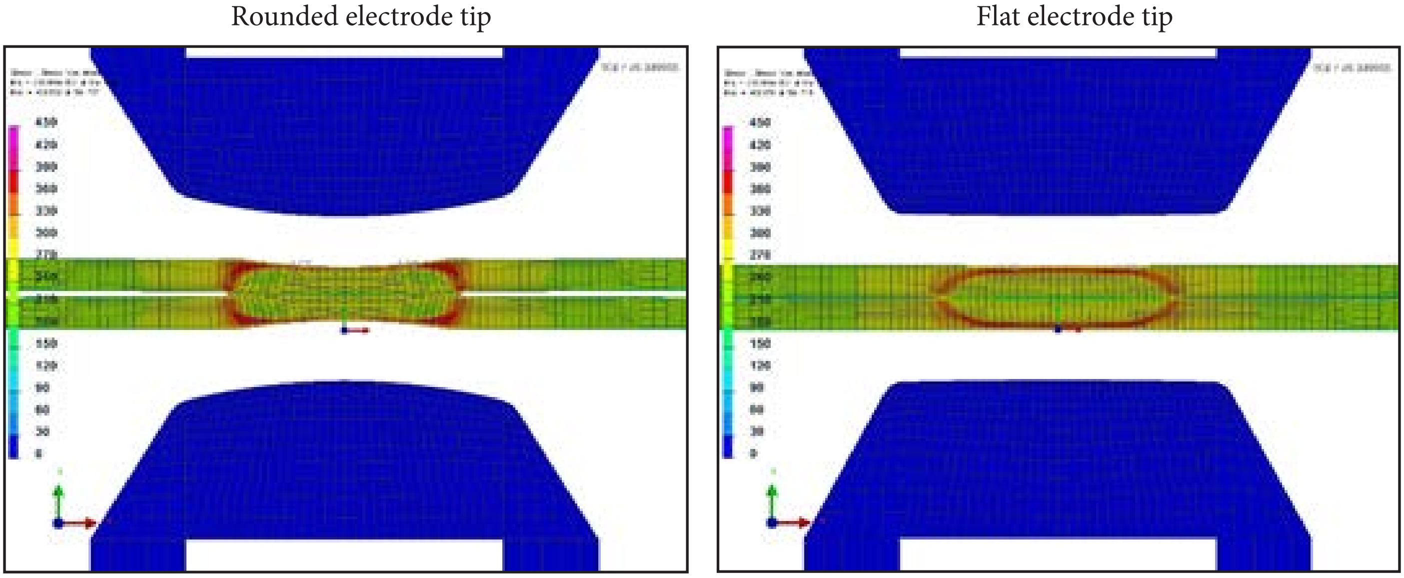
Fig. 10. Changes in the *Weld Process Check* parameter during spot resistance welding performed using the rounded tip and flat tip electrode

The performed numerical analyses enabled the comparison of results in relation to both welding process methods (Fig. 6-12). In addition to data available directly from the *Spot Weld Advisor* module, the user can also access traditional data calculated for the entire welding process. Available data are related to both thermo-metallurgical and mechanical analysis (Fig. 11, 12).


Rounded electrode tip

Flat electrode tip

Fig. 11. Distribution of strains in the spot welded joint made using the rounded tip and the flat tip electrode


Rounded electrode tip

Flat electrode tip

Fig. 12. Distribution of reduced stresses (according to von Misses theorem) in the spot welded joint made using the rounded tip and the flat tip electrode

Summary

The results of the analyses discussed in the article were confirmed by laboratory test results and are consistent with knowledge possessed by welding engineers. The purpose of the analyses was to obtain detailed process-related data making it possible to understand the physics of the process. Such an approach enables the elimination of expensive laboratory tests, which, particularly in cases of tests involving production lines, are often difficult or even impossible to conduct as they entail the retooling and reprograming of production line stations. In addition, the above-presented approach could increase productivity and minimise the number of generated defects and imperfections.

The primary objective of this article was to indicate the potential offered by cutting-edge software programmes enabling the performance of numerical analyses. The issue addressed at this study can be further developed, e.g. by optimising the electrode tip rounding radius in relation to stresses or strains obtained in welded joints (Fig. 13).

Another example can be the use of data obtained in the above-presented analyses in further numerical analyses of elements containing single spot resistance welds and welds made using the MIG method (Fig. 14).

The aforesaid approach to the design of modern and complex structural elements of vehicles and parts of machinery is not only justified but also, in the near future, necessary because of increasingly high quality-related requirements, more complicated and technologically advanced joining techniques as well as high operational properties of new materials. All these require enormous precision when adjusting process parameters. The necessary level of precision can be obtained using advanced computational modules, such as the above-presented SYSWELD. The popularity of advanced numerical analyses and the need for computational support of design processes are particularly visible in the automotive industry and in many other industrial sectors.

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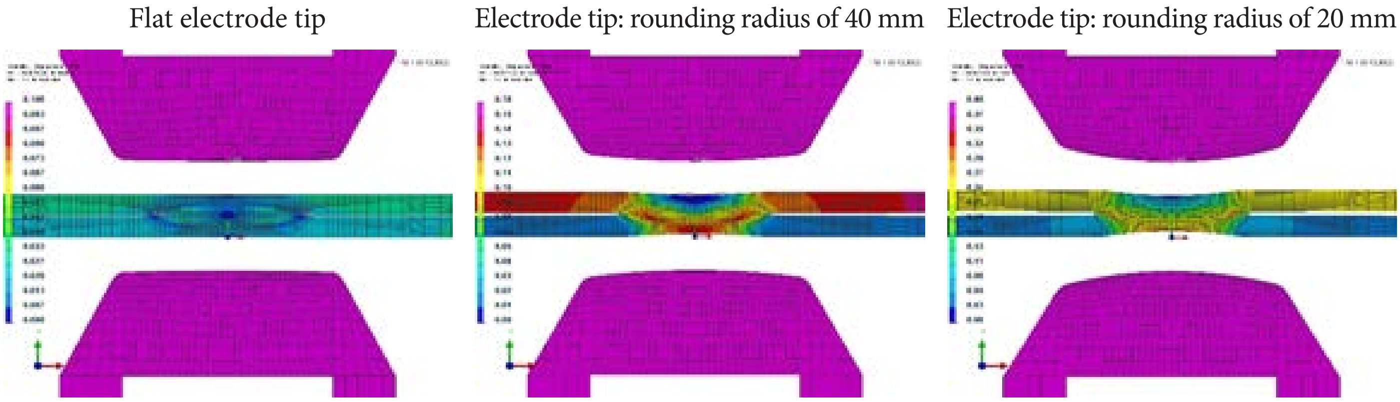
Flat electrode tip

Electrode tip: rounding radius of 40 mm

Electrode tip: rounding radius of 20 mm

Fig. 13. Effect of the electrode tip rounding radius on strains in the spot resistance welded joint

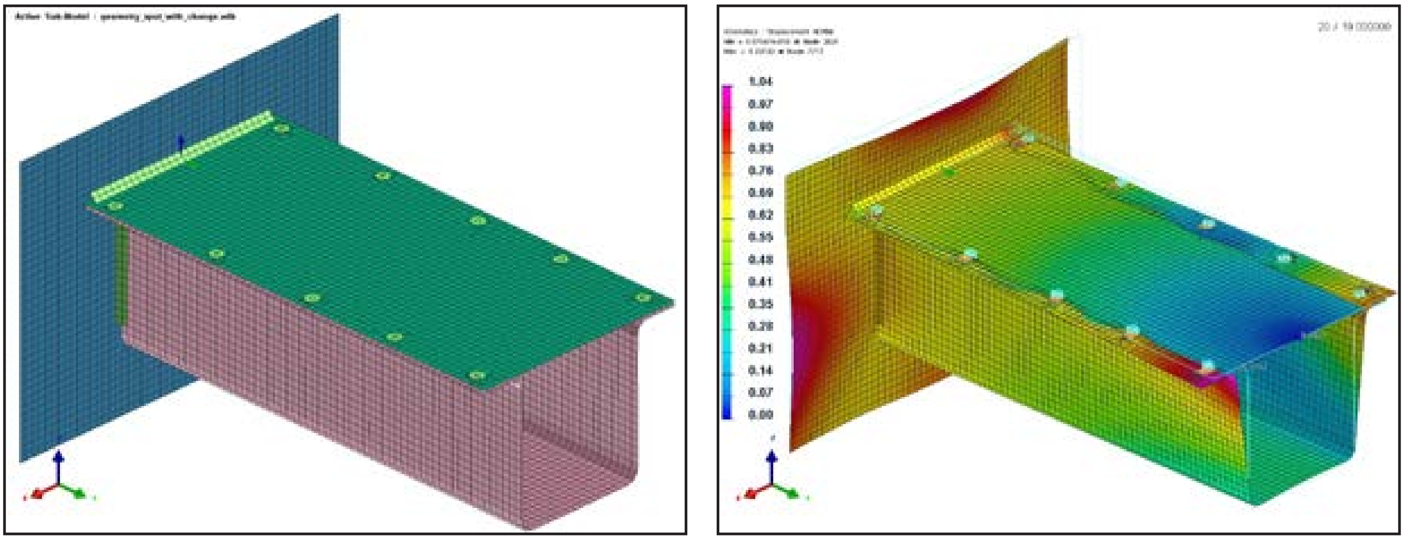

Fig. 14. Discrete model and calculation results concerning the distribution of strains in the element with spot resistance welded joints and MIG welded joints

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