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Numerical Analyses in the Spot Resistance Welding Process

Abstract: The article presents results of numerical analyses of the spot resistance welding process in relation to selected thicknesses of sheets/plates subjected to welding, radiuses of electrode work surface curvature and electrode squeezing force. The two-sided one-spot welding of two sheets made of steel DC04 (discussed in the article) demonstrated the extensive analytical possibilities of the Visual Weld state-of-the-art software application (SYSWELD). The objective of the article was to present possibilities offered to engineers by state-of-the-art computing techniques.

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

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Introduction

Advantages of the resistance welding process need not to be specially enumerated. This process, which is mainly known for the high quality of obtained joints, certainty of their obtainment and remarkable simplicity of automatic control, has been one of the primary processes used in the joining of car body sheets for nearly 90 years (1929/30 Sciaky). The efficiency and repeatability of the process enables very easy robotisation. A specific nature of the spot welded joints allows for a significant increase in the safety margin of the structure. In the event of a failure of one of the welds, related loads can be taken over by adjacent welds [1–4]. However, a correct design of this type of structure, i.e. taking into consideration the degree of complexity of today's welded structures, very often requires complex analyses of the occurrence and distribution of stresses and strains. In such cases, a perfect tool which aids engineer's work and has been used for many years is a software programme for the numerical analysis involving the application of the Finite Element Method. Obviously, in order to conduct analyses of selected manufacturing processes, the above-named programme must specialise in specific tasks. Nowadays, the market of these tools offers such possibilities enabling designers to enjoy much more comfortable working conditions. It should be also emphasised that it is possible to increase the pace of the design process as well as decrease costs resulting from a reduced number of necessary laboratory tests [4–8]. The possibility of checking many variants in a quick and informative way providing much more information about the course of the process results in the fact that a modern engineer will be willing to use the aforesaid tools. In addition, the management personnel will favourably look at the seemingly costly computational packages, which in practice will soon

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save considerable amounts of funds as early as during production preparation, implementation of changes or planning of repairs. An additional advantage is that new variants of designed solutions may be tested in the computer memory, not affecting the flow of the production process [4–9].

Although the process of spot welding is performed in accordance with a simple scheme, i.e. the squeeze of welded elements by welding machine electrodes, the flow of current melting the material of elements in the contact area and the cooling of welded elements subjected to the electrode force combines various physical phenomena (Fig. 1). In view of the foregoing, analysis must include issues of both the thermal metallurgy of the welding process and mechanics.

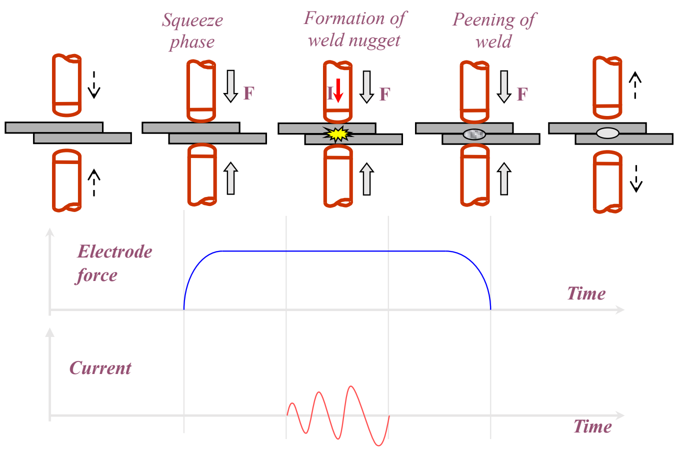

Fig. 1 Course of the spot welding process divided into individual phases [1]

Obviously, there is a whole range of simple-to-control parameters of the welding process out of which optimum parameters should be chosen to ensure the formation of a correct weld. Recommended dimensions of the weld nugget depend on the following [2]:

$$H=(0.8–1.6)\,, \qquad (1)$$

$$d_z=(0.8–1.1)\,d_e, \qquad (2)$$

where H – height of the weld nugget, g – thickness of the thinner of the welded sheets, dz – weld diameter, de – electrode diameter.

The application of software programmes for the numerical analysis of welding processes significantly facilitates the handling of changes in the properties of cutting-edge materials. It also enables the automatic control of primary process parameters as well as ultimate dimensions and geometrical deviations including the distribution and values of generated stresses.

A numerical model of the spot welding process

Similar to the processes of arc welding, thermo-metallurgical phenomena are closely connected with mechanical phenomena occurring in elements subjected to welding. The distribution of stresses and strains in spot welded joints is the effect of temperature distribution and metallurgical transformations in the material being affected by the thermal cycle of the welding process.

In terms of the spot resistance welding process, there are four issues taken into consideration in a numerical solution in computations performed using the Visual Weld package (ESI Group). The above-named issues refer to:

- electrokinetics,
- heat transport,
- metallurgical transformations,
- stresses and strains in joints [1,4].

The diagram showing the abovenamed correlations is presented in Figure 2.

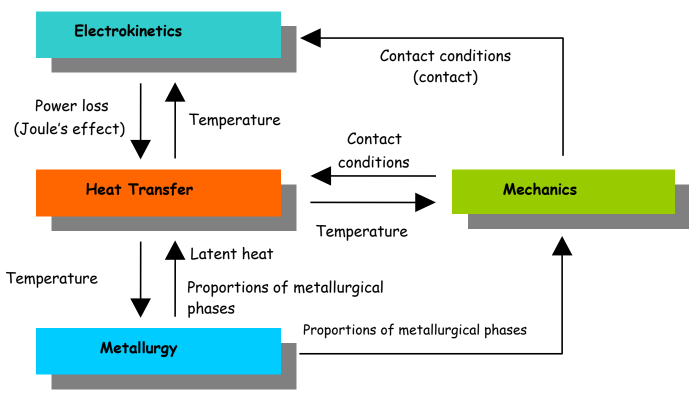

Fig. 2 Correlations between electrokinetic phenomena, heat transport, metallurgical and mechanical phenomena in the spot welding process [1,4,5]

It is necessary to take into consideration the interdependence of thermometallurgical and mechanical issues in order to build a computational model. This is because of the fact that the metallurgical transformations as such generate strains in the material resulting from changes in volume and finally leading, possibly, to plastic strains. The mechanical analysis in such a case is based on standard equations describing static equilibrium. What is interesting is that in terms of the modelling of the welding process involving the use of flat electrodes or electrodes with a large rounding radius, mechanical analysis can be separated from thermometallurgical analyses. The foregoing results from the fact that in thermometallurgical analysis, the contact area between the electrodes and the material being welded does not change in relation to the mechanical contact area in the mechanical analysis. When electrode tips of smaller radiuses are used, a change in the contact area between the electrode and elements being welded plays a significant role in the formation of a weld nugget. Consequently, it is necessary to combine these two types of analyses (an additional option when defining the computational data in the software programme) [1,4].

Numerical analyses of the spot resistance welding process

A computational model was prepared in the Visual Weld (SYSWELD code) software programme, in the modules of "Spot WeldMesh" (the development of a parametric model) and the "Spot Weld Advisor" (a computational model). The "Spot WeldMesh" module includes a very comfortable tool for the development of parametric models of welded joints, which considerably speeds up the creation of a model and the initiation of computations. Based on the geometrical dimensions of a joint provided by the user, the above-named module develops a ready axisymmetric 2D model. Obviously, it is also possible to upload the user's own model (Fig. 3).

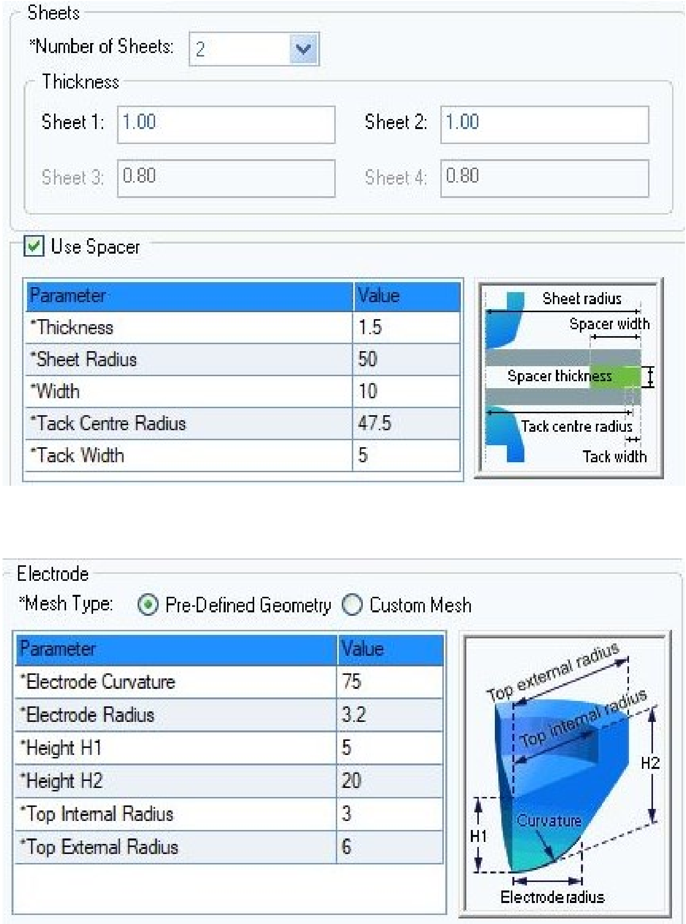

Fig. 3 Dialogue screen of the "Spot WeldMesh" module

The development of necessary discrete models was followed by the performance of a series of numerical analyses related to different variants of the axisymmetric 2D model of the spot welding of two sheets made of low-carbon steel DC04 (EN 10130). During the computations, parameters subjected to changes included the thickness of sheets, the value of current, electrode (squeeze) force and the radius of electrodes rounding. The aforesaid changes aimed to demonstrate differences in obtained results as well as the range of possibilities provided by such analyses.

The results of the numerical simulation, subsequently subjected to discussion, included distributions of temperature fields, metallurgical phases, reduced stresses and mean strains of welded elements. In addition, the assessment also involved diagrams showing changes in the weld nugget radius and the heat affected zone as well as the 'WeldProcessCheck' parameter, defining the quality of the process based on the assessment of liquid metal expulsion probability. The process parameters used in the computations are presented in Table 1.

Table 1 Parameters of the spot welding process of the sheets made of steel DC04 and selected geometrical dimensions of the numerical model

<table>
<tr><th>Joint no.</th><th>Sheet thickness [mm]</th><th>Electrode diameter [mm]</th><th>Current [kA]</th><th>Time of current flow [s]</th><th>Electrode force [kN]</th><th>Time of electrode force exertion [s]</th><th>Radius of electrode work surface curvature [mm]</th></tr>
<tr><td>1</td><td>0.54</td><td>4.8</td><td>6.5</td><td>0.12</td><td>1.5</td><td rowspan="14">0.48</td><td rowspan="3">75</td></tr>
<tr><td>2</td><td>1.0</td><td>6.4</td><td>9.5</td><td>0.20</td><td>2.5</td></tr>
<tr><td>3</td><td>1.5</td><td>8.0</td><td>14</td><td>0.34</td><td>5.5</td></tr>
<tr><td>4</td><td rowspan="11">1.0</td><td rowspan="11">4.8</td><td rowspan="7">6.0</td><td rowspan="11">0.2</td><td rowspan="3">2.5</td><td rowspan="6">30</td></tr>
<tr><td>4a</td></tr>
<tr><td>4b</td></tr>
<tr><td>4c</td><td>1.5</td></tr>
<tr><td>4d</td><td>1.0</td></tr>
<tr><td>4e</td><td>3.5</td></tr>
<tr><td>5</td><td rowspan="5">2.5</td><td rowspan="2">15</td></tr>
<tr><td>5a</td><td>7.0</td></tr>
<tr><td>6</td><td>6.0</td><td rowspan="3">6</td></tr>
<tr><td>6a</td><td>5.0</td></tr>
<tr><td>6b</td><td>4.0</td></tr>
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Note: ▭ – parameters which enabled the obtainment of a correct shape of the weld nugget

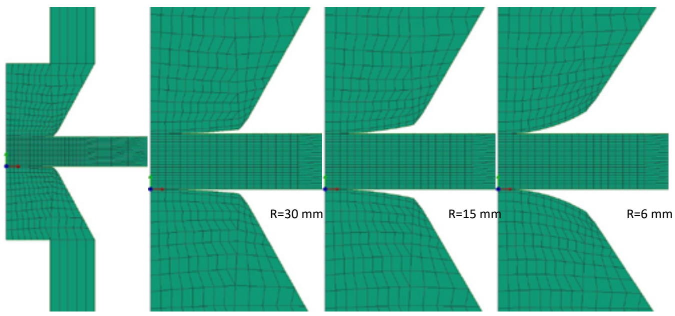

Fig. 4 Axisymmetric computational models of the spot resistance welded joints (from the left – the complete model in relation to 1.0 mm sheet thickness and the radius of electrode work surface curvature amounting to 75 mm; the subsequent models of the radius of electrode work surface curvature being 30 mm, 15 mm and 6 mm)

The "Spot Weld Advisor" module enables the user to enter subsequent data concerning the type of the material of welded sheets, process parameters, such as electrode (squeeze) force, current, the time of current flow as well as the number of current flow cycles and electrode force exertion time as well as, subsequently, types of electrodes and the conditions of contact resistance. The user starts software computations having several fundamental items of information at their disposal directly after the ending of the process. Such information includes the shape of the weld nugget, the diagram of the development of the melted zone (weld nugget volume), the radius of the aforesaid zone, the radius of the HAZ and the diagram of the "WeldProcessCheck" parameter. The latter enables the user to determine the "quality of the process" on the basis of the assessment of liquid metal expulsion probability. Apart from the above-named data accessible, directly from the module "Spot Weld Advisor" module, the user has also access to traditional data computed for the entire welding process in the post-processing module. Available data are concerned with thermometallurgical analysis (distributions of temperature fields, metallurgical phases and thermal cycles) as well as the mechanical analysis (distributions of stresses and strains). The conducted numerical analyses made it possible to compare the results of the analysed variants of the welding process, Fig. 5–14.

In terms of the computation of models varying in the thickness of sheets subjected to welding, the comparison involved the computed values of the radiuses of the welds and HAZ and those obtained in the measurements of actual specimens (Fig. 5, Table 2).

Fig. 5 Distribution of temperature fields (weld nugget) in relation to (from the left) 0.54 mm, 1.0 mm and 1.5 mm thick sheets

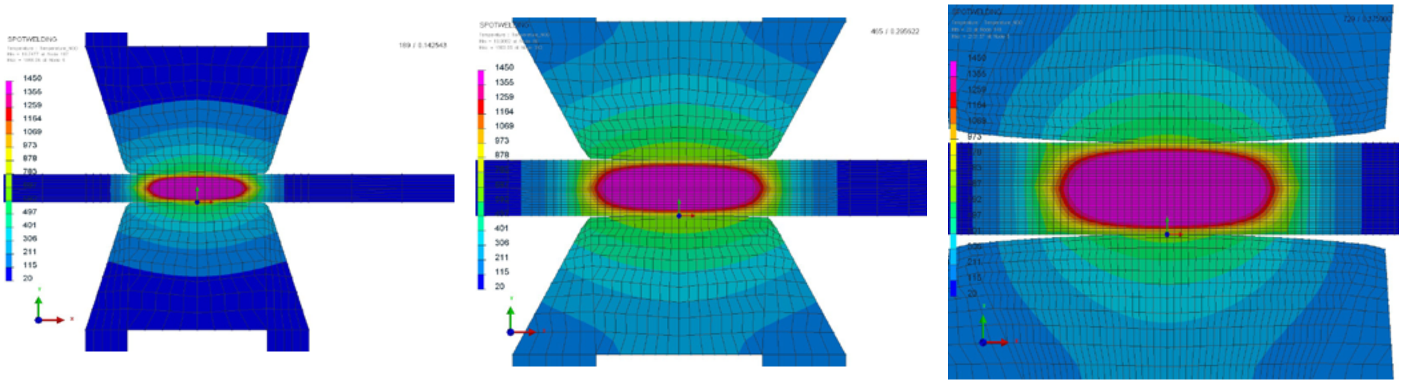

Fig. 5 Distribution of temperature fields (weld nugget) in relation to (from the left) 0.54 mm, 1.0 mm and 1.5 mm thick sheets

Table 2 Geometrical dimensions of the actual and calculated spot welds in the spot resistance welding process involving the 1.0 mm thick sheets made of steel DC04

Joint no.	Weld nugget volume [mm^3]	Weld diameter (computed) [mm]	HAZ diameter (computed) [mm]	Weld diameter (measured) [mm]	HAZ diameter (measured) [mm]
1	6.69	3.68	4.92	3.3	4.8
2	36.55	6.04	7.04	5.6	7.0
3	86.98	7.52	8.90	7.4	8.5

NOTE: Process parameters for selected joint numbers in accordance with Table 1.

For each computed variant it is possible to generate diagrams presenting the correlation between the weld nugget volume and diameter and the HAZ diameter and the time of the process (Fig. 6 and 7).

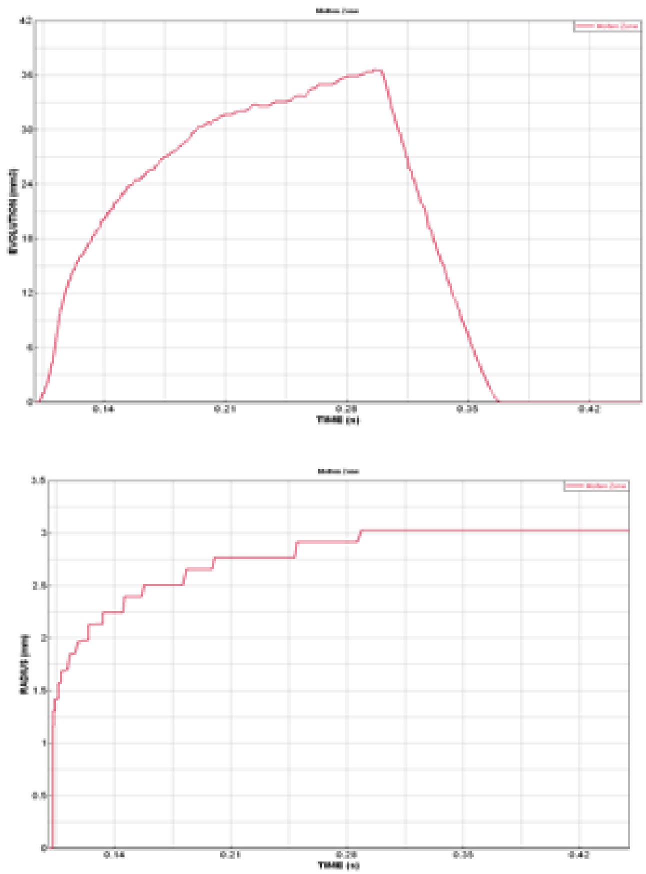

Fig. 6 Exemplary diagrams presenting the formation of weld nugget volume (on the top) and weld radius (on the bottom) in relation to the welding of 1.0 mm thick sheets

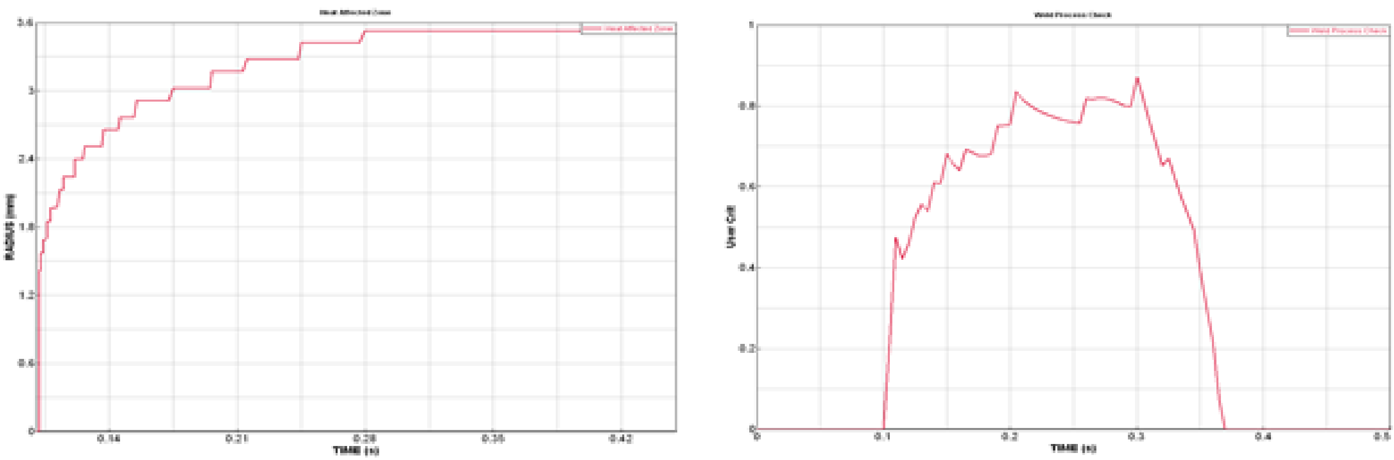

Fig. 7 Exemplary diagrams presenting the formation of the HAZ radius (on the left) and the course of "WeldProcessCheck" parameter (on the right) in relation to the welding of 1.0 mm thick sheets

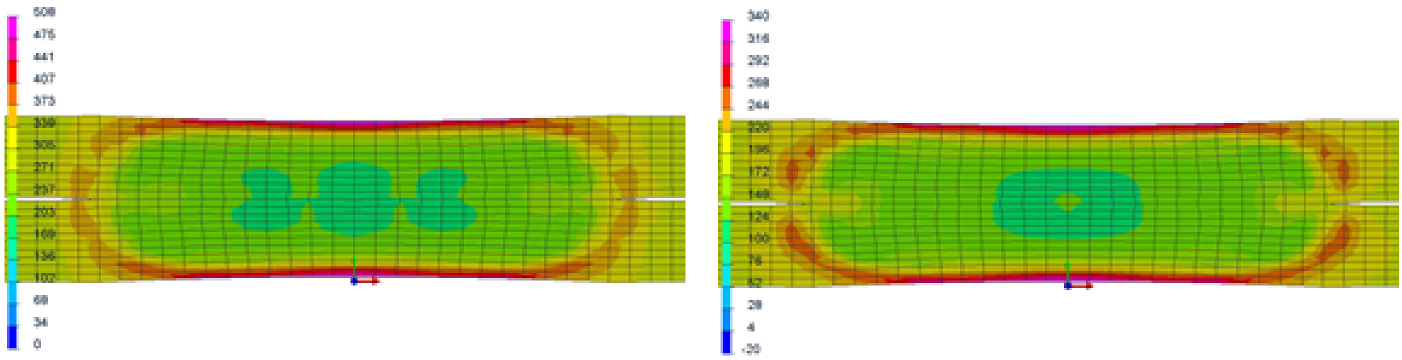

Fig. 8 Distribution of reduced stresses in accordance with the von Mises theory (on the left) and mean stresses (on the right) in the spot resistance welded joint of 1.0 mm thick sheets made of steel DC04; joint no. 2, Table 1

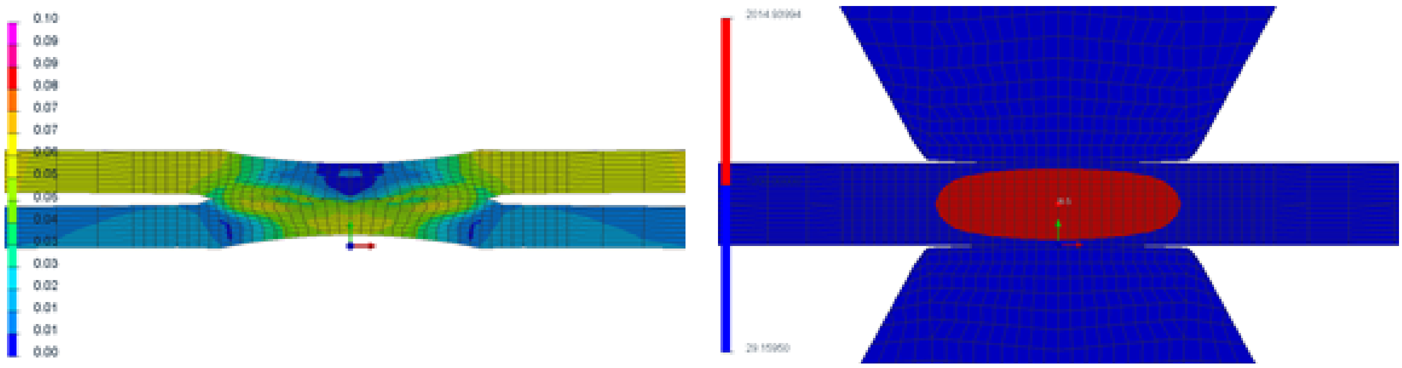

Fig. 9. Distribution of strains in the spot welded joint (on the left) and the shape of the weld nugget (on the right) in the spot resistance welded joint of 1.0 mm thick sheets made of steel DC04; joint no. 2, Table 1

The performed mechanical analysis made it also possible to observe the distribution of stresses and strains in the joints subjected to analysis (Fig. 8 and 9).

Table 3. Geometrical dimensions of the spot welds made for various radiuses of electrode work surface curvature in the spot resistance welding of 1.0 mm thick sheets made of steel DC04

Joint no.	Radius of electrode work surface curvature [mm]	Weld nugget volume [mm^3]	Weld diameter [mm]	HAZ diameter [mm]
2	75	36.55	6.04	7.04
4b	30	13.55	4.28	5.48
5	15	14.72	4.36	5.52
6b	6	4.75	2.76	4.54

NOTE: Process parameters for selected numbers of joints in accordance with Table 1

The use of computational tools aiding welding processes makes it also possible to test different technological variants. It is not always possible to perform such tests in reality, e.g. because of the unavailability of several types of electrodes. In such cases, numerical models do not impose such limitations. It is quickly and precisely possible to determine the effect of changes, e.g. in the diameter or the radius of the electrode work surface curvature on the course of the welding process as well as the obtained shape of the welded joint (Table 3, Fig. 10–12).

The numerical analyses also involved the effect of changes in the electrode squeeze force in relation to a selected variant of the joint in the welding of 1.0 mm thick sheets (Table 4, Fig. 13 and 14).

In addition, the computed values of the diameter and the height of the weld nugget were compared with the values recommended for the three analysed thicknesses of welded sheets (Table 5).

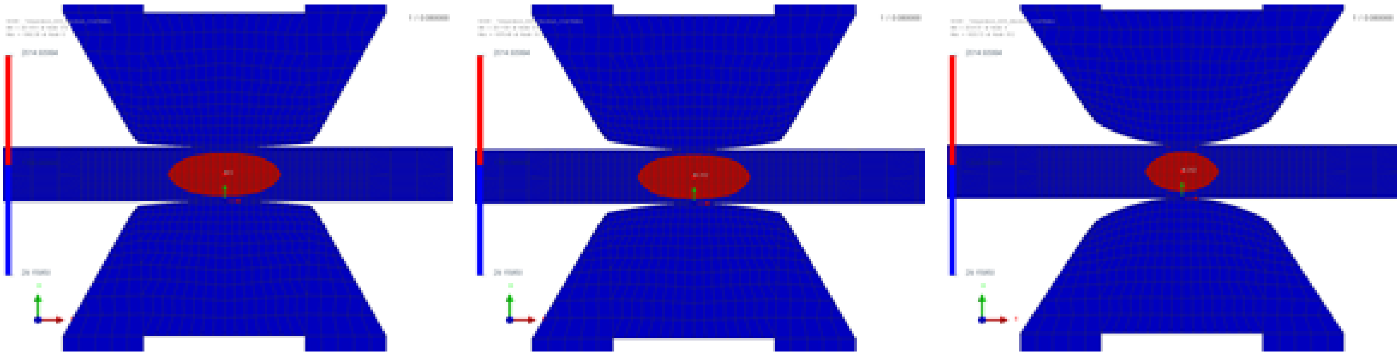

Fig. 10. Weld nugget related to the welding of 1.0 mm thick sheets performed using electrodes of different (from the left: 30 mm, 15 mm and 6 mm) radiuses of work surface curvature

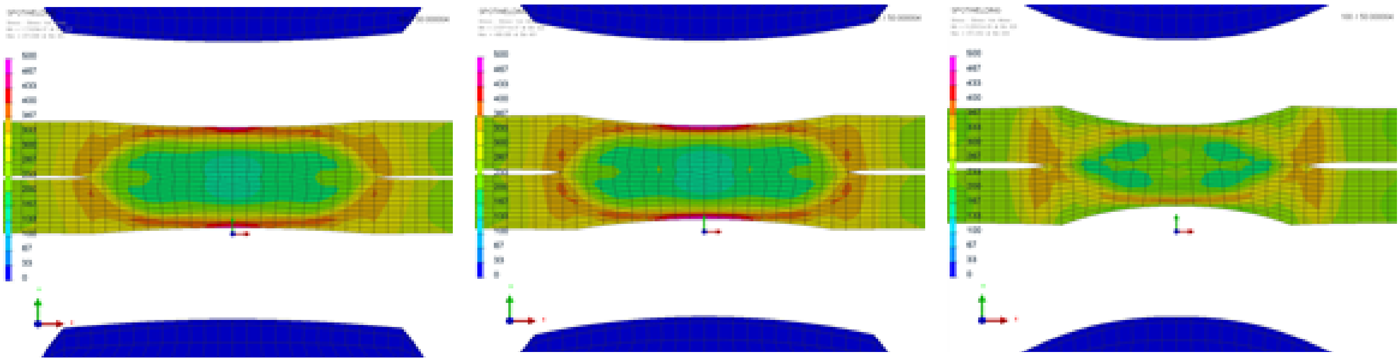

Fig. 11. Distribution of reduced stresses according to the von Mises theory in the welding of 1.0 mm thick sheets performed using electrodes of different (from the left: 30 mm, 15 mm and 6 mm) radiuses of work surface curvature

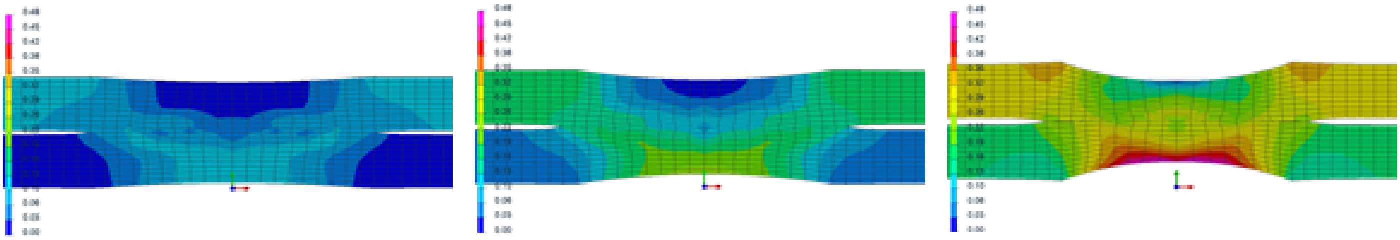

Fig. 12. Distribution of strains in the welding of 1.0 mm thick sheets performed using electrodes of different (from the left: 30 mm, 15 mm and 6 mm) radiuses of work surface curvature

Table 4 Geometrical dimensions of the spot welds made using the constant value of welding current and different values of electrode squeeze force in the spot resistance welding of 1.0 mm thick sheets made of steel DC04

Joint no.	Electrode (squeeze) force [kN]	Weld nugget volume [mm^3]	Weld diameter [mm]	HAZ diameter [mm]
4b	2.5	13.55	4.28	5.48
4c	1.5	18.34	4.48	5.76
4d	1.0	20.54	4.46	5.44
4e	3.5	11.83	4.0	5.8

NOTE: Process parameters for selected numbers of joints in accordance with Table 1

Table 5 Comparison of the computed diameters and heights of the spot weld nuggets in relation to three various thicknesses of sheets made of steel DC04 along with the recommended ranges of values

Joint no.	Weld diameter [mm]	Weld nugget height [mm]	Recommended range of weld diameters	Recommended range of weld nugget thicknesses
1	3.68	0.90	3.84–5.28	0.43–0.86
2	6.04	1.63	5.12–7.04	0.8–1.6
3	7.52	2.6	5.6–7.7	1.2–2.4

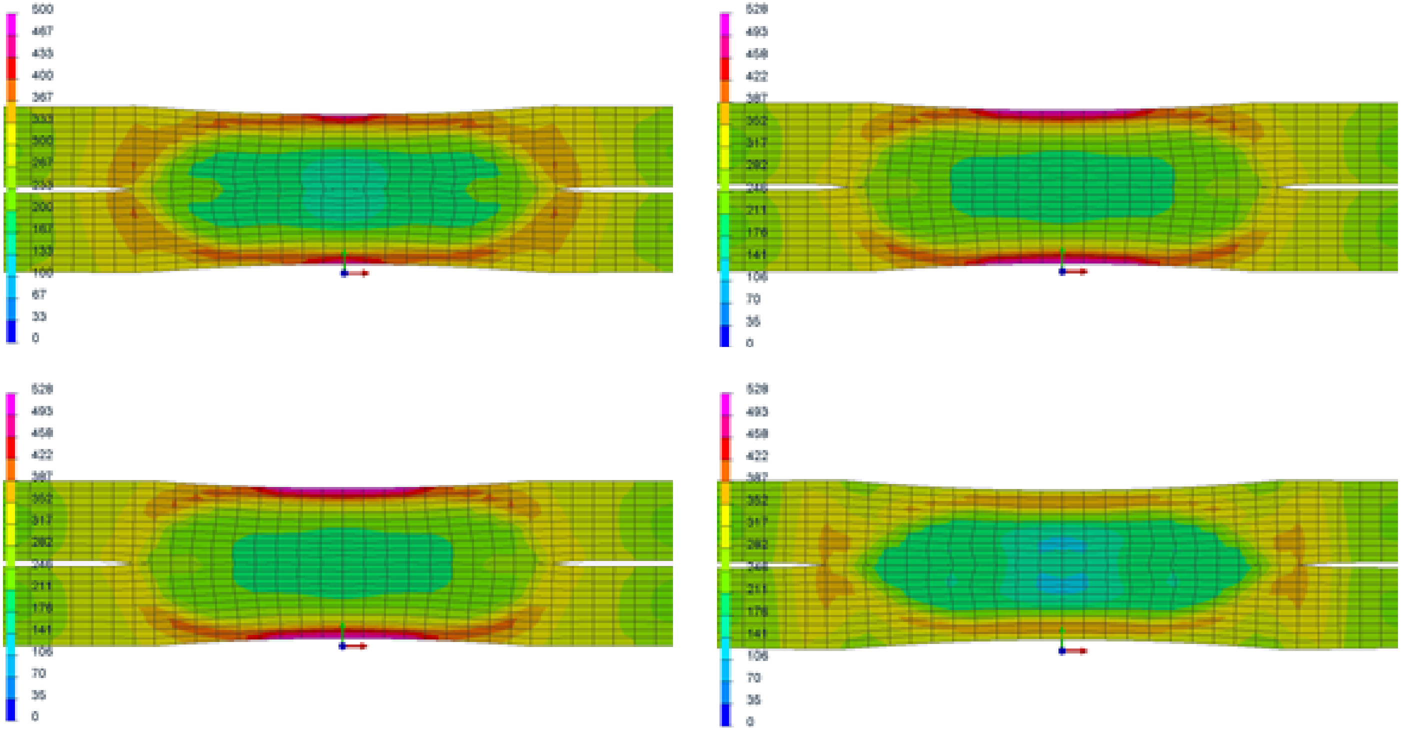

Fig. 13. Distribution of reduced stresses according to the von Mises theory in relation to the welding of 1.0 mm thick sheets and various values of electrode squeeze force

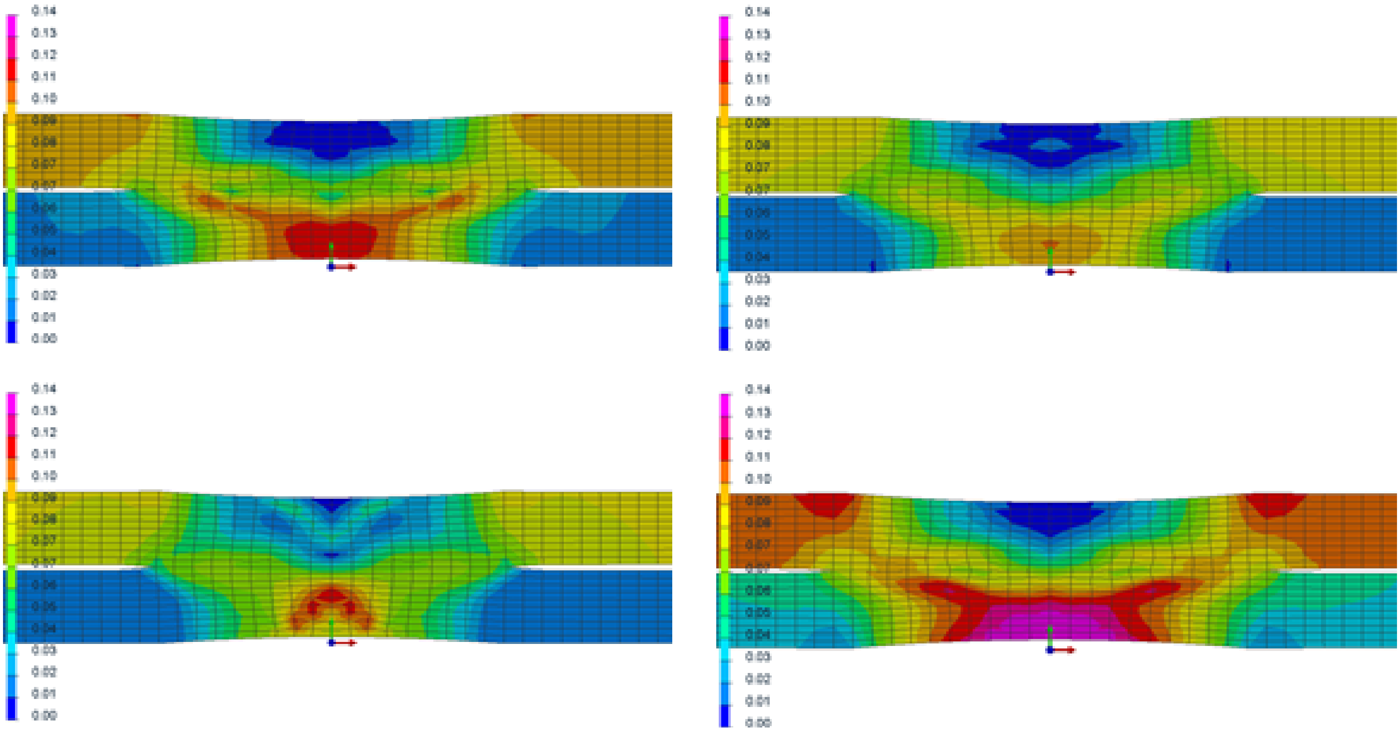

Fig. 14. Distribution of strains relation to the welding of 1.0 mm thick sheets and various values of electrode squeeze force

Summary

The above-presented results of the numerical analyses make it possible not only to confirm their compatibility with the results obtained in the real-life tests conducted in laboratories, but also to obtain much more detailed information concerning the course of the process and the way individual parameters affect the obtained values. As mentioned before, the additional advantage of such tools is the reduction of costs connected with modernisation works or implementation of new production. All this takes place in the computer memory, therefore there is no need to retooling of running production lines or the purchase of different kinds of electrode tips or additional fixtures.

The analyses of the welding of 0.54 mm, 1 mm and 1.5 mm thick sheets revealed high compatibility between the obtained values of geometrical dimensions and the tests conducted in laboratories (Table 2). However, it is impossible to obtain results in the form of diagrams concerning the formation of the weld nugget volume or an increase in the weld nugget diameter and the HAZ diameter without very complex testing methods and high costs (Fig. 6 and 7). A similar situation is related to the observation of the distribution of stresses in the joint (Fig. 8).

Also, the analysis of the application of electrodes having various radiuses of electrode work surface curvature revealed that, despite the results being obvious, the observation of their changes in relation to changes in the radius of electrode curvature makes it possible to choose the most suitable electrode tip for a given application, both in terms of the obtained size of electrodes dent in the welded element and the value of stresses (Fig. 10–12, Table 3). In addition, it is also possible to apply other process parameters in this variant in order to develop a set of parameters in accordance with the designer engineer's assumptions.

The performed analyses of the effect of changes in electrodes squeeze force also revealed that, for instance, the weld nugget volume rapidly increases at a lower value of force, which is connected with greater resistance in the contact between sheets subjected to welding (Fig. 13 and 14, Table 4).

The primary objective of this article was to draw attention to possibilities offered by state-of-the-art software programmes for numerical analyses of welding processes. Such an approach to the design of modern complex structures is justified not only from the economic perspective but is also becoming indispensable because of ever growing market competition and quality requirements. The importance of numerical analyses in industrial applications can be seen, for instance, in the automotive sector, where the manufacturers do not start work on any solutions without the support of advanced numerical analyses.

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