Zygmunt Mikno, Szymon Kowieski, Wengi Zhang

Simulation and Optimisation of Resistance Welding Using the SORPAS® Software Programme

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Abstract: The implementation of new materials such as dual phase (DP) steels, TRIP steels (Transformation Induced Plasticity Steel) and aluminium alloys or joining more complex dissimilar materials (three sheets/plates) having various thicknesses and various chemical compositions pose serious challenges in terms of resistance welding technologies. The article presents the possibilities of the professional Sorpas® software programme used for simulating and optimising resistance welding processes. This software programme assesses the weldability of materials by simulating welding processes and forecasting the final result, including the size of the weld nugget. In addition, the software enables the optimisation of welding processes, the simulation of post-weld joint properties, the assessment of weld quality in terms of microstructural transformations, hardness distribution and strength in specific load conditions as well as makes it possible to determine the field of welding parameters. Available versions of the software are designated as 2D and 3D. The latter version enables the modelling of complex phenomena, e.g. shunting or multi-projection welding.

Keywords: resistance welding, Fem calculations, Sorpas software, 2D and 3D modelling

DOI: *10.17729/ebis.2016.4/2*

Introduction

For over 140 years, resistance welding has been used in the metal industry, particularly in the automotive industry and in the widely defined household appliances industry [1]. Although the technology has been known for many years, it continues to face new challenges, e.g. connected with new materials (advanced high strength steels {AHSS} and aluminium alloys), new solutions in terms of welding machine components (servomechanical actuators) or the (spot) welding of greater numbers of sheets (particularly complicated if sheets have different thicknesses and are made of various material grades, e.g. low-carbon steels, AHSS etc.).

The joining of thin-walled metal elements, commonly performed using resistance welding technologies, often faces problems connected with joint quality, process stability (e.g. liquid metal expulsion) or the longer life of electrodes. Simulations of welding processes offer not only the possibility of better understanding issues

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dr inż. Zygmunt Mikno (PhD (DSc) Eng.), mgr inż. Szymon Kowieski (MSc Eng.)– Instytut Spawalnictwa, Department of Resistance and Friction Welding and Environmental Engineering;
Wengi Zhang (PhD (DSc) Eng.) – Swantec Software and Engineering ApS, Lyngby, Denmark.

concerning various materials and their weldability but also make it possible to optimise welding process parameters. In experimental conditions, obtaining such knowledge requires numerous welding and destructive tests, which are often time-consuming and expensive.

As regards welding processes, the advantages of numerical simulations (FEM calculations) include reduced costs and time of design, technological tests and process optimisation. In addition, FEM calculations make it possible to more adequately use optimisation procedures by determining the allowed field of technological parameters guaranteeing the obtainment of good quality joints.

Since the 1980s, FEM calculations have been used to model and forecast the results of welding processes in relation to specific materials and parameters [2-7]. The usability of FEM calculations has been positively verified by many theoretical and experimental tests. The positive results of the verification have resulted in the growing use of FEM calculations in practical applications, which, in turn, has entailed the growing demand for the optimisation of resistance welding processes in industry, in particular as regards the determination of the most favourable initial welding conditions.

The article presents the possibilities of performing calculations in various configurations of joints. The SWANTEC company, i.e. the developer of the SORPAS® software programme dedicated to resistance welding processes, also runs training courses concerning the operation of the programme. SORPAS® is continuously developed and improved by including new possibilities and options enabling 2D and 3D calculations [8-10]. Licensed users are provided with ready and proven computational models [10].

SORPAS® Software Programme

The Finite Element Method (FEM) in the SORPAS® software programme is used for building numerical models enabling simulations of, in particular, resistance welding processes. More than ten years of tests and industrial use as well as the continuous development of the software programme have resulted in the obtainment of the satisfactory accuracy and reliability of numerical models, data concerning materials as well as the interface and dynamics of welding equipment. The system has also been improved by activities aimed at the automation of preparatory procedures and faster simulation through a more comfortable user graphic interface and a display for the presentation of results. The coincidence of calculation results with those obtained in tests has also been confirmed in publications by welding specialists from Instytut Spawalnictwa [11-13]. The highly accurate representation of actual processes offered by SORPAS® is possible because of combined electric, thermal and mechanical calculations [10].

In the SORPAS® system, the Finite Element Method is used for creating numerical models enabling simulations of resistance welding processes. Simulations of welding processes are performed in order to determine (test) the weldability of new materials by predicting results arising from the use of specific base materials, electrode materials and welding process parameters. Simulations constitute the basis for more advanced tasks involving the optimisation and design of welding processes.

A user-friendly graphic interface presents automatic procedures making it possible to prepare input data, quicken the construction of a model, perform numerical calculations (simulations) as well as to present the results of welding processes. After performing a simulation, the software programme enables presenting the curves of dynamic process parameters in the function of time (e.g. waveforms of voltage, current, power and resistance, courses of electrode force and travel, increase in the weld nugget diameter etc.). During welding processes, the system enables the visualisation of temperature distribution, current, voltage, hardness as well as of strains and stresses in all materials (elements of a given model).

Four databases built in the Sorpas® software programme facilitate its use. The databases contain sets of information related to commonly used materials and their properties, new materials, data related to electrodes and their shapes normalised in the ISO system, data concerning workpieces (enabling preliminary design) as well as characteristics and properties of welding equipment.

Model 2D

Because of the arrangement (geometry) of two-sided spot welding, in most cases it is possible to perform simulations using the axisymmetric (2D) model. In comparison with the 3D model, the use of the simplified 2D model significantly reduces the time of calculations (calculations last on average 30 minutes instead of between ten and twenty hours) as well as significantly reduces memory-related demand for archived data.

Two-Sided Overlap Spot Welding of Two Sheets

Figure 1 presents the exemplary simulation of the two-sided overlap spot welding of two sheets. Part 1a of the figure presents the user graphic interface used for preparing input data, such as materials to be welded, electrodes and welding process parameters. Figure 1b presents a simulation report containing initial conditions and simulation results, including selected curves of process parameters and the final size of the weld nugget [10].

Two-Sided Overlap Spot Welding of Three Sheets

The Sorpas® system is used both by production companies and research centres for numerical calculations (simulations) of complex joints involving more materials than in cases of standard joints (two sheets). Figure 2 presents several examples of the welding of three sheets having various thicknesses and made of dissimilar materials in various combinations of joints and compares the results of simulation with the macrostructure of actual joints. The tests involved the use of four various steel sheets, i.e. DC06 (0.6 mm), HSLA340 (0.8 mm), DP600 (1.5 mm) and TRIP700 (1.2 mm). In all of the tests, the upper sheet was thin and made of low-carbon steel, whereas the other two sheets had various thicknesses and were made of various materials [14-15]. The FEM simulation performed using the Sorpas® software programme was used to determine the most favourable welding conditions before performing the principal technological welding tests. The actual welding conditions presented in Figure 2 (left) were compared with the results of simulation. The results of calculation (the right side of the photographs – Fig. 2) revealed

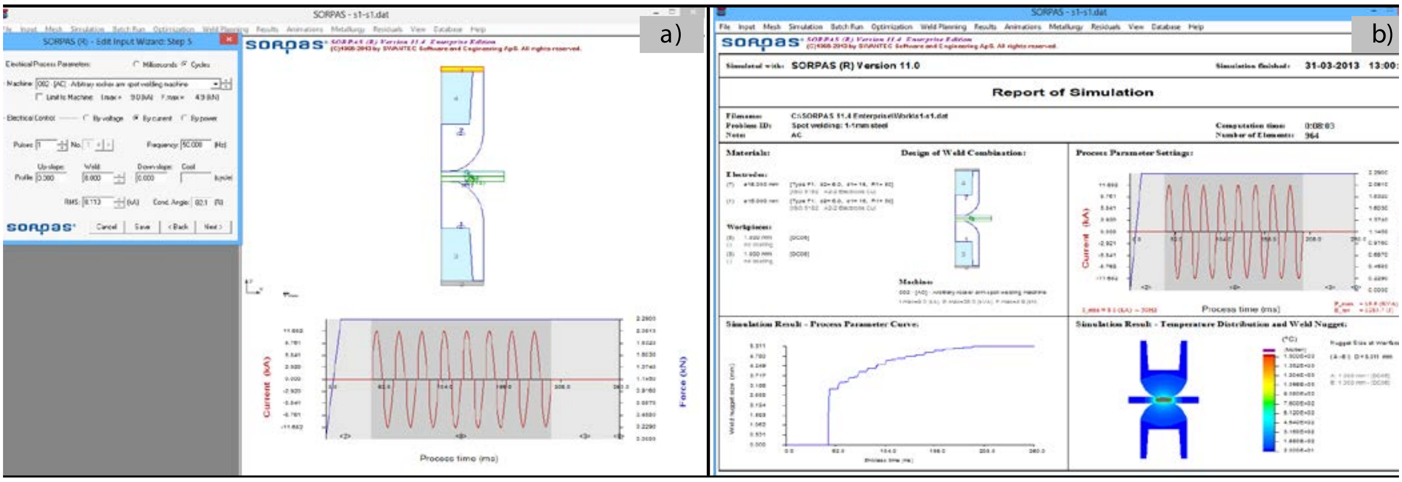

Fig. 1. Simulation of the two-sided overlap spot welding of two sheets, performed using the SORPAS® system: (a) graphic interface for preparing input data concerning materials to be welded, electrodes and welding process parameters; (b) simulation report containing pre-set (input) parameters and anticipated welding process results [10].

significant compatibility of the actual welding test results (the right side of the photographs – Fig. 2 – macrostructures).

Liquid Metal Expulsion

Expulsion during welding processes is simulated by forecasting the initial time of its occurrence and its intensity, i.e. low, medium and high. Figure 3a presents the curve of dynamic resistance with the initial time of expulsion occurrence and its intensity. Figure 3b presents the weld nugget and the area of expulsion occurrence (between the sheets).

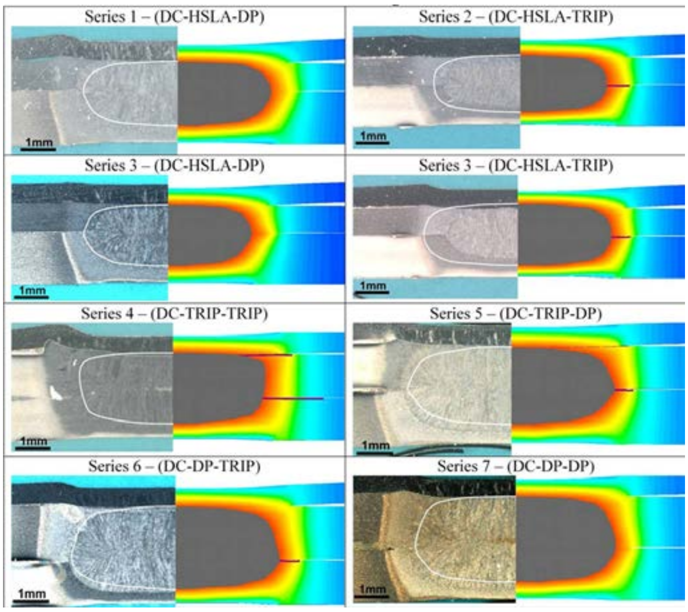

Fig. 2. Comparison of the microstructures obtained during experimental tests and in calculations (SORPAS®) related to the welding of three sheets in three combinations [14].

Examples of Resistance Welding Models

Resistance welding is performed in various configurations, e.g. as spot welding performed using electrodes having specific shapes, as projection welding, where the area of weld formation is determined by projections and as the short-circuit butt welding of rods or sections. SORPAS® enables creating models in relation to the above named methods (Fig. 4a-4c). Spot welding can be performed in the configuration of two-sided welding (Fig. 3b) or single-sided spot welding (Fig. 4a).

Process Optimisation

The results of process simulations were used to develop automated procedures enabling the optimisation of resistance welding process parameters. International standard EN ISO 14327 contains analyses of weldability and information concerning the optimisation of resistance welding along with two diagrams presenting

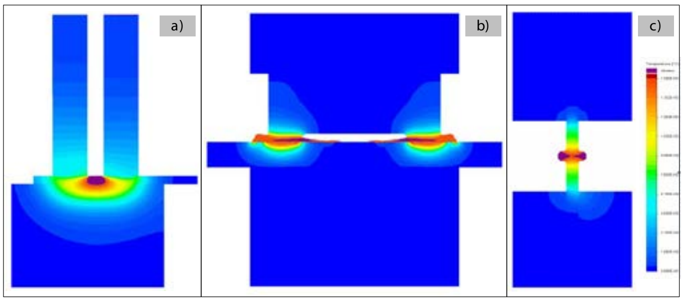

Fig. 4. Examples of resistance welding models: a) spot single-sided welding; b) projection welding of nuts; c) shirt-circuit butt welding of rods.

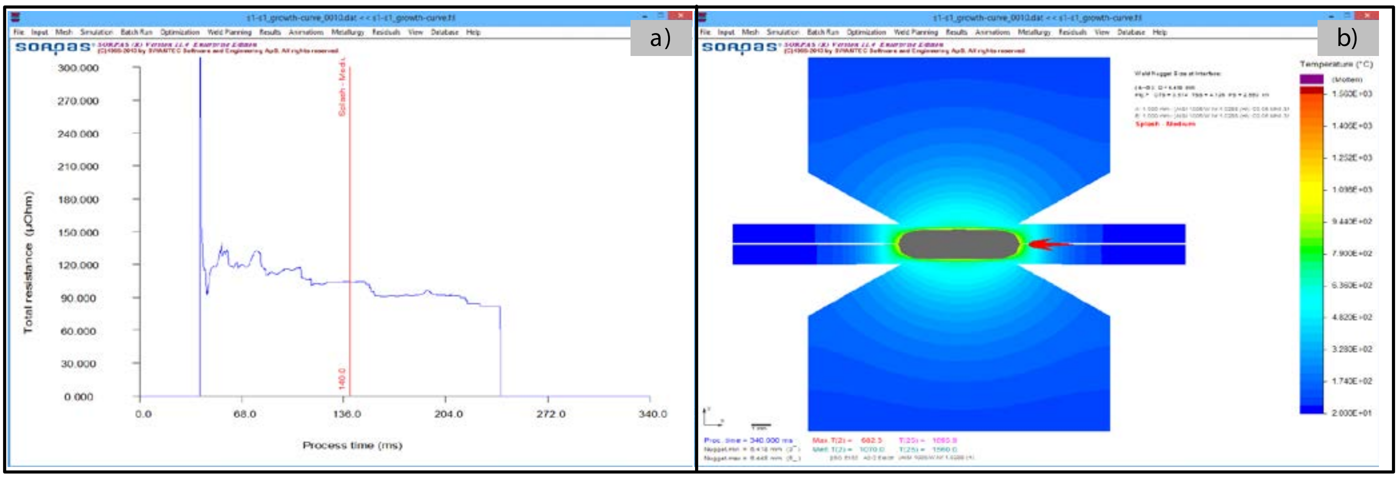

Fig. 3. Simulation of the expulsion of liquid metal from the weld nugget with the anticipated time of expulsion occurrence and intensity; (a) waveform of the selected parameter (static slope resistance) of the process with the time of expulsion initiation and formation intensity; (b) final weld nugget size with the area of expulsion formation.

the curve of weld nugget diameter increase and the determination of weldability (range of proper welding parameters). The Sorpas® system enabled the automatic determination of ranges including the limits of expected expulsion and the window of process parameters.

The curve of weld nugget diameter increase can be created by performing a series of welding tests and increasing welding current while doing so and by measuring the sizes of weld nuggets. In industrial practice, the above-presented tests are time-consuming and expensive. Because of automated procedures, Sorpas® makes it possible to perform simulations of all welds along the curve of weld formation and enables obtaining information about possible expulsion.

In a similar manner it is possible to simulate the range of parameters determining weldability, i.e. by simulating welds within the specific range of welding current and electrode force, making it possible to determine the window of welding process parameters. As regards the first range of parameter changes (window of parameters no. 1), current and welding time change, whereas electrode force stays the same. In the case of the second range of parameter changes (window of parameters no. 2), current and electrode force change, whereas welding time remains unchanged.

Figure 5 presents the optimisation of the spot welding of 1 mm thick sheets made of low-carbon steel. Figure 5a presents the simulated curve of the increase in the weld nugget diameter in the function of welding current. The weld nugget begins to form once a certain value of welding current has been exceeded and grows along increasing current. Black (square) points depict the lack of the weld or its insufficient size. Red (triangular) points represent expulsion. Green (round) points inside represent properly made welds and indicate the window of welding process parameters with the operating range of welding current. Figure 5b presents the range of weldability with current and electrode force as variable parameters and welding time as a constant parameter. Black (square) points represent the lack of the weld or its inadequate size. Red (triangular) points indicate expulsion. Green (round) points represent proper welds and, at the same time, indicate the window of proper welding parameters.

Model 3D

More complex phenomena, beyond the axisymmetric model (2D) such as the axial misalignment or the non-parallelism of electrodes, current shunting or multi-projection welding require the use of the three-dimensional (3D) model.

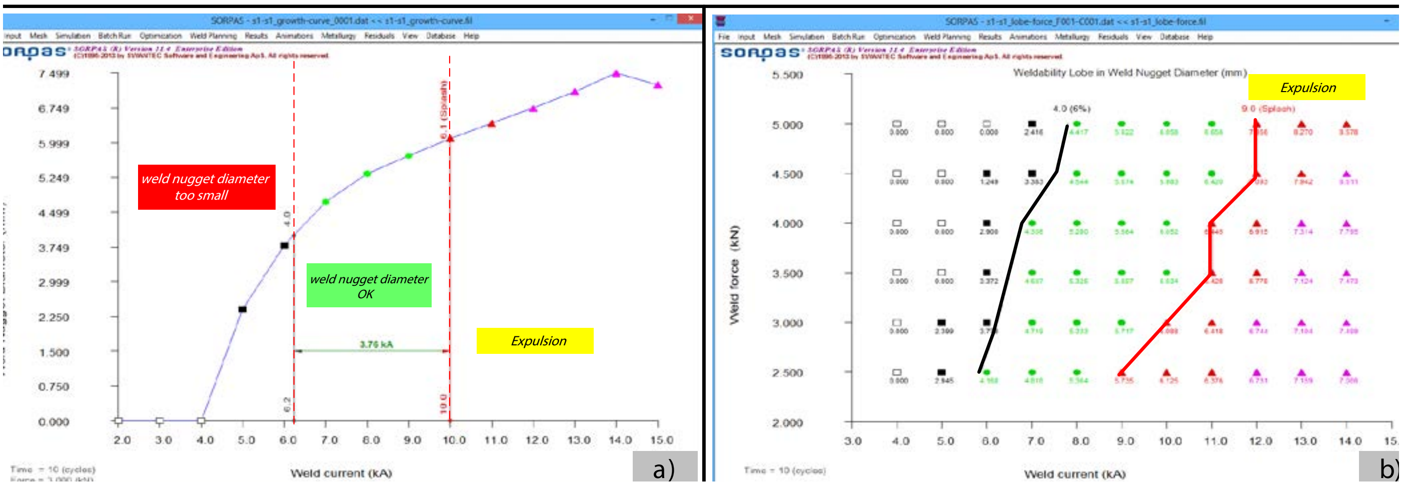

Fig. 5. Process optimisation involving the use of the SORPAS® software programme: (a) curve of the increase in the weld nugget diameter in relation to welding current; (b) range of (proper) weldability along with the window of welding process parameters.

Post-Weld Properties of Welds

The Sorpas® software programme makes it possible to calculate weld properties in relation to microstructural phase transformations or hardness distribution for typical grades of steel used, e.g. in the automotive industry. In addition, Sorpas® 3D enables simulating strength values on the basis of the weld nugget size and the anticipated hardness distribution, which in turn makes it possible to forecast the strength of welded joints (weld).

During heating, austenitisation-related calculations are based on temperature Ac1 and Ac3, regardless of the heating rate. It is assumed that entire austenitisation takes place when the maximum temperature of the process is higher than temperature Ac3. It turn it is assumed that austenitisation does not occur when the maximum temperature of the process is lower than temperature Ac1. The linear interpolation is used between temperatures Ac1 and Ac3. The austenitic transformation triggered by cooling following heating is based on critical cooling rates presented in CTT diagrams. In accordance with the formulas presented by R. Blondeau et al. [16], critical cooling rates leading to the formation of martensite, bainite and ferrite/pearlite are determined on the basis of the chemical composition. P. Maynier et al. [17] present formulas concerning the hardness of each phase in relation to the chemical composition. The value of total hardness is established on the basis of hardness values of individual phases, threated in such case as output hardness values.

Figure 6a presents the example of expected hardness distribution in the spot welded joint made of two sheets, each having a thickness of 1mm. The upper sheet was made of deep-drawing low-carbon steel DC06, whereas the lower sheet was made of dual-phase high strength steel DP600. The figure presents the hardness of the base material around the weld nugget, the hardness following the process of austenitisation as well as the formation of subsequent phases in the weld nugget and in the heat affected zone (HAZ) during cooling. The HAZ revealed the difference between the sheets. Steel DP600 contained the significant amount of martensite, which resulted in increased hardness, whereas the HAZ of steel DC06 contained hardly any martensite, leaving the level of hardness unchanged. The weld nugget, containing phases of mixed chemical composition, contained a certain amount of martensite and was characterised by increased hardness in comparison with the hardness characterising both base materials [15].

Figure 6b presents the exemplary transverse tensile test [18]. The simulation presents the failure outside the weld nugget, which is consistent with observations during the experimental test resulting in a plug failure. Reference publications provide information concerning load curves, i.e. elongation related to tensile-shear strength tests, transverse tensile strength tests and peel strength tests. Further detailed information concerning changes in metallurgical nature as well as the forecasting of hardness and failures is presented in other publications [19].

Figure 7 presents other post-weld strength tests of joints possible to perform using the Sorpas® software programme, i.e. peeling test (Fig. 7b), static tensile strength test (Fig. 7a3) and the above named transverse tensile test

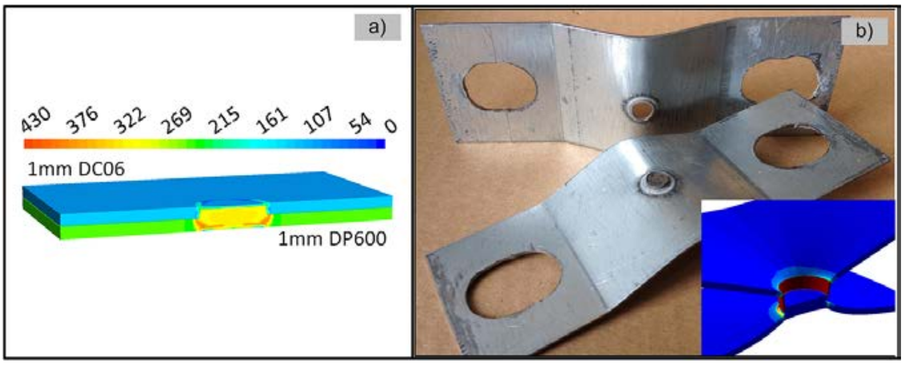

Fig. 6. Simulation (a) of hardness distribution according to the Vickers hardness test in the dissimilar spot welded joint DC06-DP600 and (b) transverse tensile strength tests of two sheets made of steel DP600 [14]. The simulation indicates the area of failure consistent with the experimentally observed plug failure [15].

leading to the plug failure of the joint (Fig. 7C1) and to the interface failure of the joint (Fig. 7C2.)

Shunting of Welding Current

The shunting of welding current is an undesired phenomenon during welding processes. The experimental tests enabled the determination of a distance between successive welds in order to minimise the undesired phenomenon [20-22]. However, the modelling and the analysis of the problem in the 3D model make it possible to deeply analyse the above-named phenomenon [23].

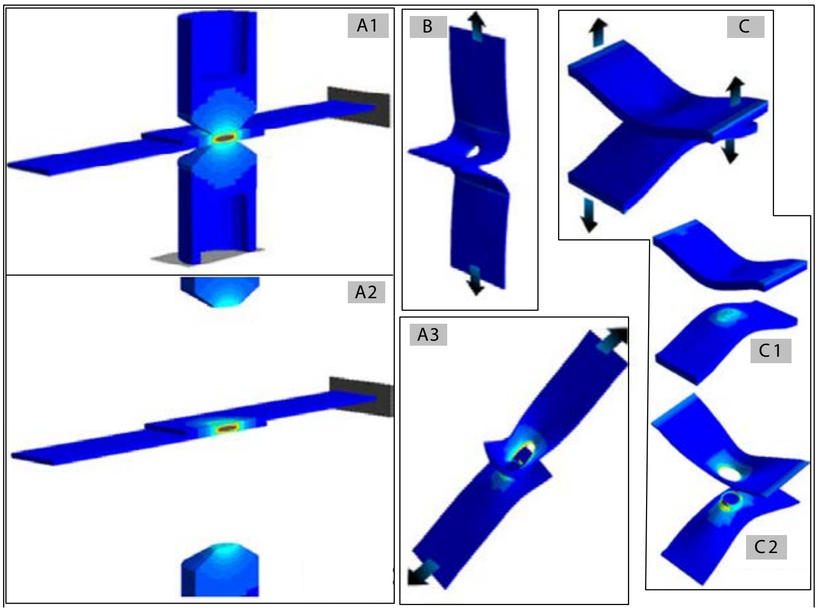

Fig. 7. Welding in the SORPAS® software programme (A1, A2). Computational strength test: A3) static tensile test, B) peeling test, C) transverse tensile test (C1 - plug failure, C2 – interface failure.

Figure 8 presents a welded joint containing three welds (Fig. 8A) made in the following sequence: weld no. 1 (Fig. 8B1), no. 2 (Fig. 8B3) and no. 3 (Fig. 8B2). The software programme enables calculating the principal welding current and shunting current flowing through previously made "points" (welds) as well as makes it possible to analyse the size of the weld nugget taking into account the shunting effect. This enables the adjustment of appropriately higher welding current for successively made welds in order to maintain the constant value of the weld nugget diameter.

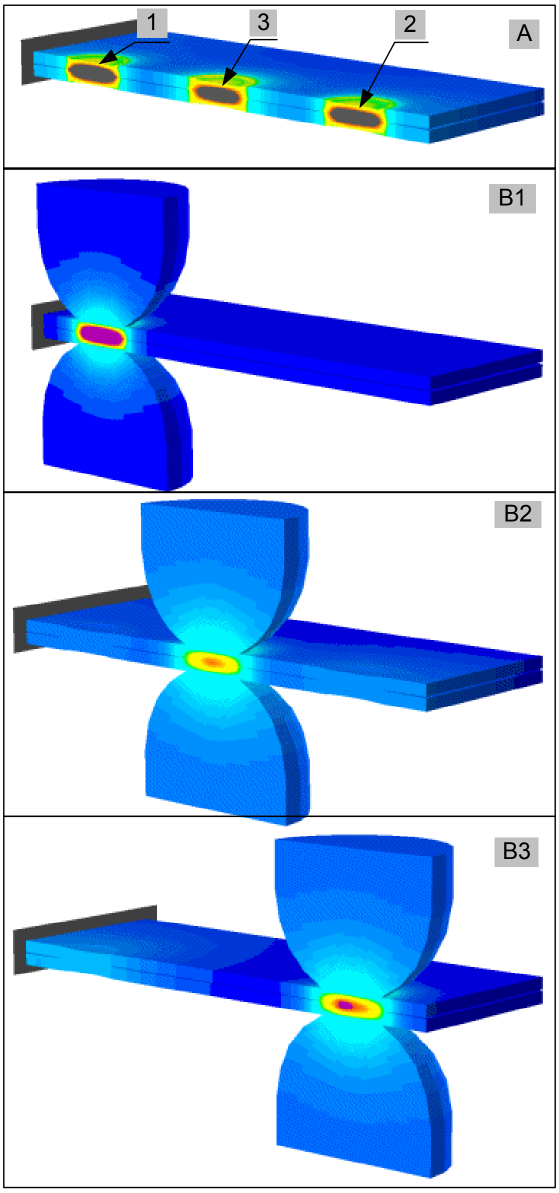

Fig. 8. Shunting of welding current for three welds (welding sequence B1, B3 and B2).

Electrode Force

The software programme featured two built-in programme options enabling the selection of an electrode force system. Electrode force can be performed in two manners, i.e. using a standard, i.e. pneumatic or a servomechanical force system. The first manner, i.e. using pneumatic force, does not require extensive description; the setting of parameters is identical to that using a welding machine. It is necessary to take into consideration appropriate times of initial force, principal force and the separation of electrodes. The software programme automatically takes into consideration the time of delay resulting from the effect of the use of pneumatic elements, i.e. primarily the size of cylinder, on the force of electrode.

The second manner involves the use of the servomechanical system of electrode force, consisting in setting the rate of electrode travel. Such a solution enables the controlled movement of electrodes. However, in such a case, the force of electrodes is the coincidence of the interaction of the electrode travel rate and the welding area heating rate resulting from the flow of current. The advantages of the system are particularly useful in projection welding, requiring the controlled movement of electrodes depending on the projection plasticisation rate. Pneumatic systems can also be used when projection welding, yet the window of parameters is very narrow if compared with that of servomechanical systems.

The exemplary course of the pre-set force in relation to the pneumatic system is presented in Figure 9a. Figure 9c presents the electrode travel rate (as regards the servomechanical system) varying depending on individual technologies. The use of force exerted by pneumatic systems results in the, ultimately uncontrolled, movement of electrodes (Fig. 9b). In turn, the pre-set electrode travel rate enabling the controlled movement of electrodes (Fig. 9d) results in the force of electrodes (Fig. 9e).

Summary

Numerical calculations are very useful when assessing the weldability of new materials and optimising the parameters of welding processes. The Sorpas® software programme for the modelling of resistance welding processes enables performing various calculations, ranging from simple axisymmetric models (2D), e.g. spot overlap welding to advanced models, e.g. multi-projection welding or current shunting, requiring the use of the three-dimensional (3D) model.

Complex graphic options of the software programme enable the visualisation of data in the form of graphic presentations (courses/waveforms of related quantities during welding) and in the form of animated quantities subjected to analysis. The software programme

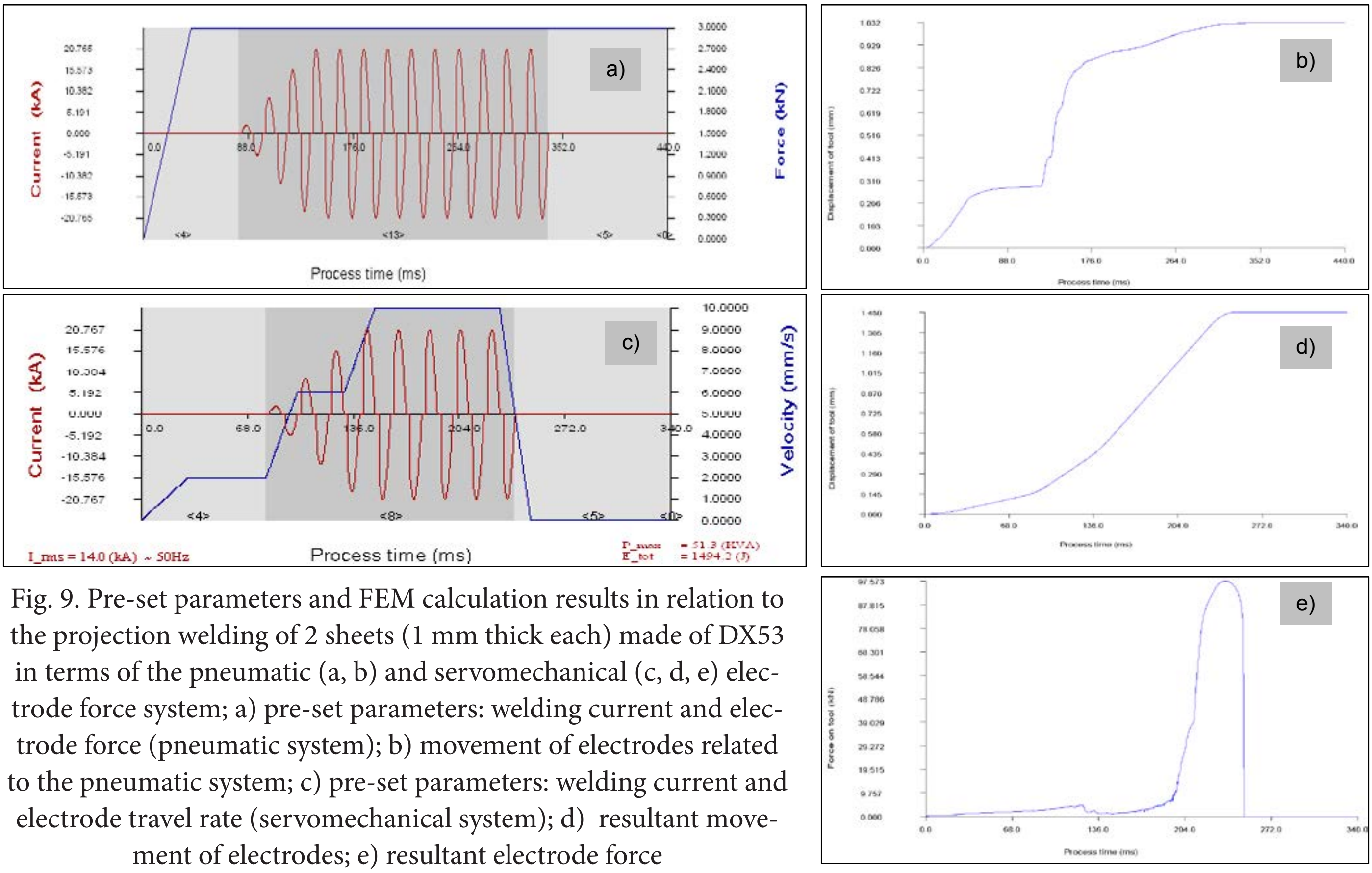

Fig. 9. Pre-set parameters and FEM calculation results in relation to the projection welding of 2 sheets (1 mm thick each) made of DX53 in terms of the pneumatic (a, b) and servomechanical (c, d, e) electrode force system; a) pre-set parameters: welding current and electrode force (pneumatic system); b) movement of electrodes related to the pneumatic system; c) pre-set parameters: welding current and electrode travel rate (servomechanical system); d) resultant movement of electrodes; e) resultant electrode force

makes an excellent tool for determining the initial welding parameters as well as enabling the in-depth analysis of phenomena taking place during resistance welding.

Workers of Instytut Spawalnictwa possess extensive experience in performing numerical calculations of welding processes using the Sorpas® software programme. Instytut collaborates with the Swantec company within the confines of joint national and international projects [24-27]. Instytut offers collaboration in the numerical modelling of resistance welding processes.

Some of the results of numerical calculations (and Sorpas® software programme) have been obtained within research projects PBS3/B4/12/2015 and TANGO1/267374/NCBR/2015 financed by the National Science Centre and the National Centre for Research and Development.

References

[1] Mikno Z., Papkala H., Piątek M.: *Zgrzewanie rezystancyjne – historia, teraźniejszość, przyszłość*. Seminar Proceedings. Paper title: *Kontrola i sterowanie w procesie zgrzewania rezystancyjnego. Jakość, rozwój, konkurencyjność i przyszłość*. March, 2004.

[2] Nied H.A.: *The Finite Element Modeling of the Resistance Spot Welding Process*. Welding Journal Research Supplement, 1984, no. 4, pp. 23-132.

[3] Cho H.S., Cho Y.J.: *A Study of the Thermal Behavior in Resistance Spot Welds*. Welding Journal Research Supplement, 1989, no. 6, pp. 236-244.

[4] Dickinson D., Tsai C., Jammal O.: *Modeling of Resistance Spot Weld Nugget Growth – Applications for the Automotive Industry*. SAE Technical Paper 900738, 1990. http://dx.doi.org/10.4271/900738

[5] Zhang W., Hallberg H., Bay N.: *Finite Element Modeling of Spot Welding Similar and Dissimilar Metals*. 7th Int. Conf. on Computer Technology in Welding, San Francisco, USA, 1997, pp. 364-373.

[6] Zhang W., Kristensen L.: *Finite Element Modeling of Resistance Spot and Projection Welding Processes*. The 9th Int. Conf. on Computer Technology in Welding, Detroit, Michigan, 1999, pp. 15-23.

[7] Zhang W.: *Design and Implementation of Software for Resistance Welding Process Simulations*. SAE Technical Paper 2003-01-0978, 2003 http://dx.doi.org/10.4271/2003-01-0978

[8] Zhang W.: *New Developments and Challenges in Simulation and Optimization of Resistance Welding*. Proceedings of the 4th International Seminar on Advances in Resistance Welding. 15 November 2006, Wels, Austria, pp. 101-114.

[9] Zhang W.: *Recent Developments and Future Outlook for Simulation and Optimization of Resistance Spot Welding Processes*. Proceedings of the 5th International Seminar on Advances in Resistance Welding, 24-26 September 2008, Toronto, Canada, pp. 269-276.

[10] http://www.swantec.com

[11] Mikno Z., Bartnik Z., Derlukiewicz W., Kowieski Sz.: *Zgrzewanie garbowe w obliczeniach metodą elementów skończonych*. Przegląd Spawalnictwa, 2013, no. 11, pp. 64-70.

[12] Mikno Z., Bartnik Z.: *Zgrzewanie rezystancyjne doczołowe zwarciowe w obliczeniach MES materiałów jednoimiennych (part 01)*. Przegląd Spawalnictwa, 2015, no. 3, pp.14-21.

[13] Mikno Z., Bartnik Z.: *Heating of electrodes during spot resistance welding in FEM calculations*. Archives of Civil and Mechanical Engineering, 2016, vol 16, no. 1, pp. 86-100. http://dx.doi.org/10.1016/j.acme.2015.09.005

[14] Nielsen C. V., Friis K. S., Zhang W., Bay N.: *Three-Sheet Spot Welding of Advanced High-Strength Steels*. Welding Journal Research Supplement, 2011, vol. 90 (2), pp. 32-40.

[15] Bennedbaek Rune A.K., Nielsen Chris V., Zhang W.: *Latest Developments in Simulation*

and Optimization of Resistance Welding Processes. Biuletyn Instytutu Spawalnictwa, 2015, nr 6, pp. 31-37
http://dx.doi.org/10.17729/ebis.2016.5/4

[16] Blondeau R., Maynier P., Dollet J., Vieillard-Baron B.: *Prévision de la dureté de la résistance et de la limite d'elasticité des aciers au carbone et faiblement alliés d'après leur composition et leur traitement thermique*. Mémoires Scientifiques, Revue Métallurgie, 1975, pp. 759-769.

[17] Maynier P., Jungmann B., Dollet J.: *Creusot-Loire system for the prediction of the mechanical properties of low alloy steel products*. Hardenability Concepts with Applications to Steels. The Metallurgical Society of Aime Heat Treatment Committee American Society for Metals Activity on Phase Transformations, 1978, pp. 518-545.

[18] Nielsen C.V., Bennedbæk R.A.K., Larsen M.B., Bay N., Chergui A., Zhang W., Martins P.A.F.: *Experimental and Simulated Strength of Spot Welds*. The 8th International Seminar on Advances in Resistance Welding, Baveno, Italy, 2014, pp. 161-172.

[19] Nielsen C.V., Martins P.A.F., Zhang W., Bay N.: *Numerical methods in simulation of resistance welding*. VI International Conference on Computational Methods for Coupled Problems in Science and Engineering, 2015, pp. 322-333.

[20] Papkala H.: *Zgrzewanie oporowe metali*. Wydawnictwo KaBe, Krosno, 2003.

[21] Papkala H.: Wytyczne doboru właściwej technologii zgrzewania punktowego, garbowego i liniowego blach w oparciu o własności fizyczne metali. Instytut Spawalnictwa Gliwice, 1990.

[22] Pilarczyk J. (ed.): Poradnik Inżyniera, Spawalnictwo. vol 1, 2, WNT Warszawa 2005.

[23] Li Y. B., Wang, B., Shen Q., Lou M., Zhang H.: *Shunting effect in resistance spot welding steels. Part 2: theoretical analysis.* Welding Journal, 2013, pp. 231-238.

[24] Mikno Z., Kowieski Sz.: International Project, 6th Framework Programme: *FleXible Production Experts for reconfigurable assembly technology – Xpress* (2007-2011).

[25] Mikno Z., Kowieski Sz.: Invertigation project no. N N501 196940: *Numeryczne i eksperymentalne badania porównawcze zgrzewania garbowego z zastosowaniem pneumatycznego i serwomechanicznego docisku elektrod* (2011-2013).

[26] Mikno Z., Kowieski Sz.: Investigation Project Inweld under the 3rd Contest of Applied Research Programme: *Opracowanie innowacyjnej wysokosprawnej zgrzewarki kompaktowej o podwyższonej częstotliwości*, PBS3/B4/12/2015, 2015-2017.

[27] Mikno Z., Kowieski Sz.: Investigation Project under Tango 1 Competition: *Innowacyjna metoda sterowania serwomechanicznym systemem docisku w technikach łączenia cienkościennych elementów metalowych*, TANGO1/267374/NCBR/2015, 2015-2017.