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Numerical Simulations of Modern Joining Techniques Illustrated with Examples of the FSW and EBW Methods

Abstract: The article aims to present major advantages resulting from the use of tools for numerical analyses of modern welding processes, i.e. friction stir welding (FSW) and electron beam welding (EBW). The article presents basic issues related to the modelling of the FSW process, describes mechanisms to be taken into consideration in relation to numerical analyses of the above-named process and indicates problems which should be taken into account during the modelling of the EBW process. In addition, the article presents exemplary analyses of the FSW and EBW processes.

Keywords: friction stir welding, FSW, electron beam welding, EBW, SYSWELD, modelling, numerical analyses

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Introduction

Numerical analyses of welding processes are cutting-edge developmental methods concerned with the preparation, optimisation and validation of technological processes, enabling the evaluation of boundary states of welded structures, thus increasing safety and efficiency and, in the long term, significantly decreasing production costs. Numerical analyses of industrial production processes are frequently used in cases of casting, press forming and forging processes. Recently, numerical analyses have seen growing popularity also in welding engineering. However, this trend is limited by overly low confidence in calculation results, primarily because of the fact that welding-related numerical analyses belong to the most complicated operations involving the use of computational tools. Numerical analyses concerned with welding processes require utmost precision when preparing primary input data describing technological details, material data describing metallurgical transformations, effect of thermal cycles on material properties, heat input and discharge as well as the fixing of elements in welding processes and during post-weld cooling. All the above-named procedures require immense effort and, more often than not, generate high costs, e.g. connected with the preparation of material databases based on laborious and time-consuming laboratory tests. However, invested time and expenses quickly

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pay off when properly prepared input data enable the obtainment of crucial information about processes and quicken the selection of an optimum technological variant without incurring prototyping-related costs.

The primary advantage of numerical analyses concerning welding processes and heat treatment is the possibility of obtaining important and useful information during processes. In most industrial cases, actual process parameters can be measured only at the beginning and at the end of the welding process and, usually, at several selected areas. As can be seen, complete measurements of welded structures are either extremely difficult or even impossible to perform. For instance, it is nearly impossible to identify the distribution of stresses in the weld and HAZ. In addition, measurements concerning the distribution of temperature fields require expensive specialist equipment and are often encumbered with significant errors. The use of complete results obtained through numerical analyses provides extensive knowledge and understanding of welding process, significantly facilitating and quickening process-related decision-making. In addition, the foregoing makes it possible to reduce, and sometimes even completely eliminate tests and experiments when preparing a new variant of a given technology as well as, consequently, significantly reduce the time and costs of the entire operation, so important in today's extremely competitive market.

The advantage of numerical analyses is the possibility of simulating numerous variants without the necessity of bearing, often considerable, costs. In addition, it is possible to observe the behaviour of the structure in operation and, based on the aforesaid observation, exclude certain variants and adopt new ideas. The use of numerical analysis software programmes provides engineers with great satisfaction resulting from significantly extended practical and theoretical knowledge. Having the foregoing at their disposal, engineers wishing to achieve assumed results can enjoy considerably greater flexibility when performing the optimisation of input parameters, welding sequence, fixing conditions and sequence as well as fixtures rigidity [1, 2].

The use of numerical analysis of welding processes enables the identification of the effect of process parameters on the following quantities (resultant parameters):

- distributions of temperature fields,
- distribution of percentage contents of metallurgical phases (e.g. percentage distributions of ferrite, pearlite, martensite and bainite in steels as well as aluminium or titanium alloys (in relation to their structures),
- HV hardness distributions,
- austenite grain sizes,
- distributions of strains,
- distributions of stresses,
- total plastic strain [1, 2, 3].

Numerical analyses of welding processes can be divided into the following areas where they help make decisions concerning the selection of a proper technological variant:

1. Comparison of several different technological variants, where each variant is subjected to simulation and results of related analyses (metallurgical structure, values and distributions of stresses, strains etc.) are compared. The above-presented approach aims at the selection of a fully (as much as possible) customised technological variant.
2. Assessment of boundary states in structures (resistance to fatigue wear, plasticity loss, creeping, brittle cracking etc.). The assessment is concerned both with the entire welded structure and its selected components (adversely affected by the welding process). Usually, the distribution of stresses and metallurgical phases enables the identification of hazardous areas. Moreover, additional indicators of susceptibility to e.g. hot or fatigue cracking are calculated by advanced software programmes and used in the assessment of hazardous states.

3. Determination of welded structure strains. The issue is primarily concerned with complex welded structures composed of many elements joined by many welds. In cases of such structures, welding sequence is of great importance as it is often very difficult and expensive to optimise welding operations involving prototypes because of the number of tests which would need to be performed. Numerical analyses enable testing various welding sequences and element fixing sequences without the necessity of stopping production lines and incurring high expenses [1, 2].

Numerical analyses of welding processes can be used in relation to all of the conventional techniques as well as, because of recent developmental progression, in relation to cutting-edge techniques including friction stir welding (FSW), electron beam welding (EBW), laser welding or hybrid welding.

The performance of numerical simulations of the FSW process is one of the most complicated tasks because of the necessary inclusion of CFD (Computational Fluid Dynamics) analyses and their combination with mechanical calculations. For this reason, the development of computational technique in relation to friction stir welding can be recognised as ongoing and requiring further research. On the other hand, some computational models and methodology concerning simulations of cutting-edge joining technologies (e.g. EBW or laser beam welding) are already in place [3].

The further part of the article presents examples of the Sysweld software programme in analyses of the FSW and EBW processes.

Numerical Analyses of the FSW Process

Initially, the FSW process was developed to solve problems connected with the joining of aluminium alloys. The heating of the interface of elements being joined results from the change of forces of friction generated by a rotating tool pressed against the elements (on the joint division line) into heat aimed to plasticise the above-named area. The tool is set into rotational motion and, after getting "immersed" in the plasticised material moves along the joint division line. The tools consists of two working elements, i.e. a shoulder "tasked" with the plasticisation of the material (using generated friction) and a probe/pin stirring the material (Fig. 1 and 2). The tool rate of rotation is usually restricted within the range of 100 to 1500 rpm, whereas the rate of welding (tool travel rate) can reach as many as 1500 mm/min (it is even possible to perform the process at a rate of 6000 mm/min). In cases of the welding of thick plates, i.e. thicknesses of which amount to 50 mm and more, the tool downward force can reach tens of kN. The above-named value affects the efficiency of material heating. The maximum temperature at the joint area usually does not exceed 80% of the melting point of materials being joined.

As mentioned above, the FSW was developed to address problems accompanying the joining of aluminium alloys and has been primarily

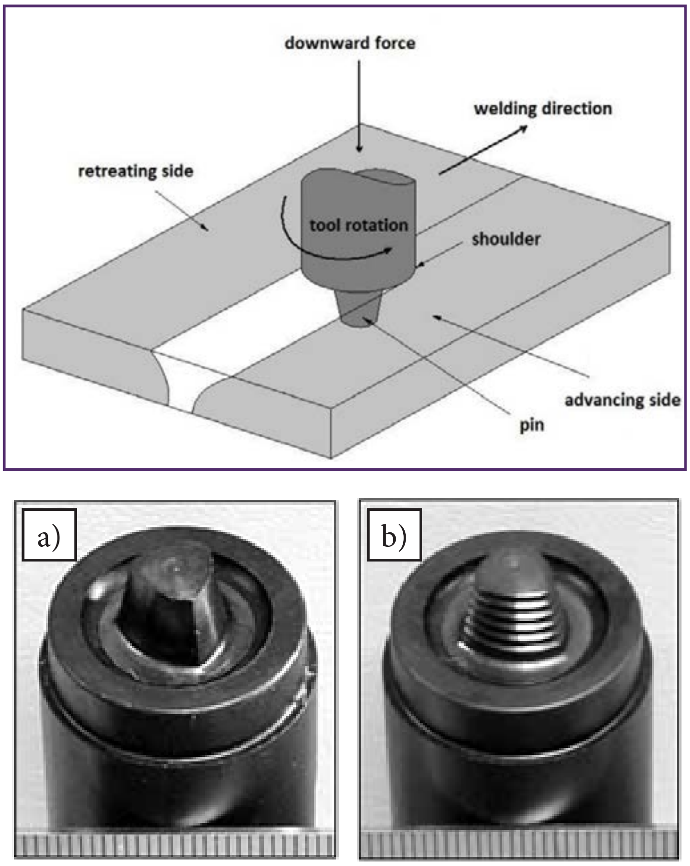

Fig.1. Schematic FSW process and working tool surface [4, 5]

used for this purpose ever since. The previously developed FSW process-related numerical analyses also concern the above-named materials. Similar to the actual FSW process, the numerical analysis of friction stir welding is divided into 3 stages, i.e. the submerging of the tool in elements being welded, the stirring of the plasticised material and the retreating of the tool (Fig. 2).

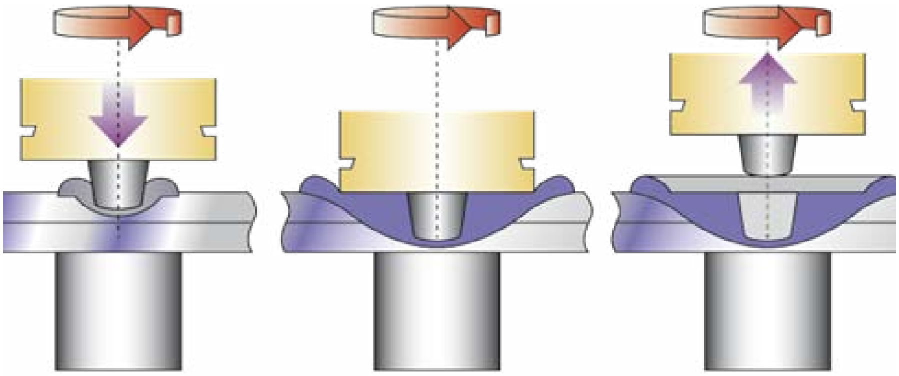

Fig. 2. Phases of the FSW process (division of numerical analysis stages): – a) submerging of the tool in elements being welded, b) stirring of the plasticised material, c) retreating of the tool [6]

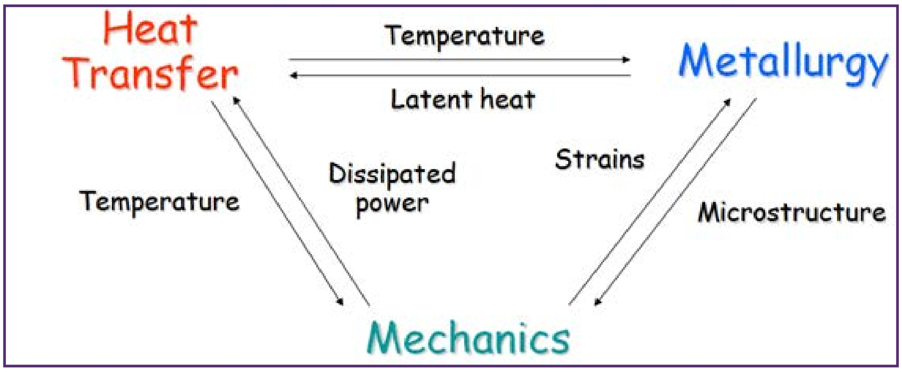

Fig. 3. Numerical analysis of the FSW process as an example of complex numerical analysis [3]

Numerical analyses of the FSW process require the correlation of issues related to heat transport with those concerning the generation of specific metallurgical structures. In doing so, it is necessary to take into consideration the three following types of interactions:

- metallurgical transformations depending on the history of temperature changes triggered by the thermal cycle of the process,
- phenomenon of latent heat accompanying metallurgical transformations, changing the distribution of temperature,
- thermal properties depending on metallurgical phases.

To properly perform the numerical analysis of the FSW process it is necessary to distinguish four primary zones affected by the welding process:

- base material – corresponding to a material not undergoing any metallurgical transformations triggered by the welding process,
- heat affected zone – corresponding to this area of the joint which while adjoining the weld simultaneously bears traces of process heat effect in the form of metallurgical transformations (and a slight level of stresses/strains),
- zone of thermo-metallurgical effect – corresponding to the port of the joint containing thermal cycle-induced metallurgical transformations and high stresses/strains triggered by downward force exerted by the tool,
- weld nugget – joint area with maximum stresses/strains.

As can be seen, the above-presented approach is entirely different from that applied in cases of classical welding processes. When modelling the FSW process, the primary difficulties result from the fact that the tool performs (additional) motion (at a constant rate) along the division line. Numerical simulations of such processes require the use of continuous analysis based on models with the thick mesh, particularly in the weld and HAZ areas. Such an approach significantly increases demand for computational power and hardware resources making, in some cases, analysis highly complicated and time-consuming. Figure 3 presents the complexity of analysis-related correlations.

The above-named analysis is exemplified below in a simulation using a symmetric tool (Fig. 4-6). The analysis involves all of the above-presented assumptions. Calculations were performed for a material base corresponding to an element made of aluminium alloy. The latest version of the SYSWELD software programme provides the possibility of simulating processes using a non-symmetric tool (probe) (see Fig 7). In addition, the figure presents the distribution of temperature fields on the plate and the tool, changes in temperature along the fusion line as well as velocity vectors around the probe.

As can be seen, the development of the above-named analysis requires further research, yet the constant development of computational packages enables the gradual performance of increasingly complicated simulations. This growing potential is of essential importance for the automotive, aviation or aerospace industries, i.e. sectors using the FSW technology more extensively than other industries.

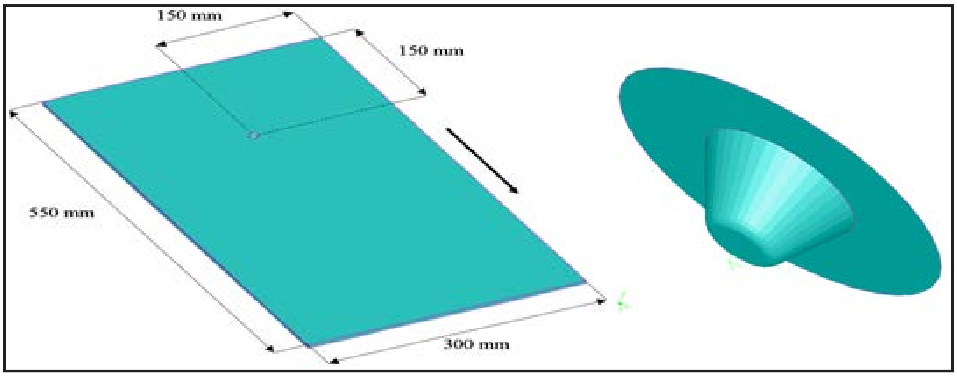

Fig. 4. Computational model with a modelled working tip

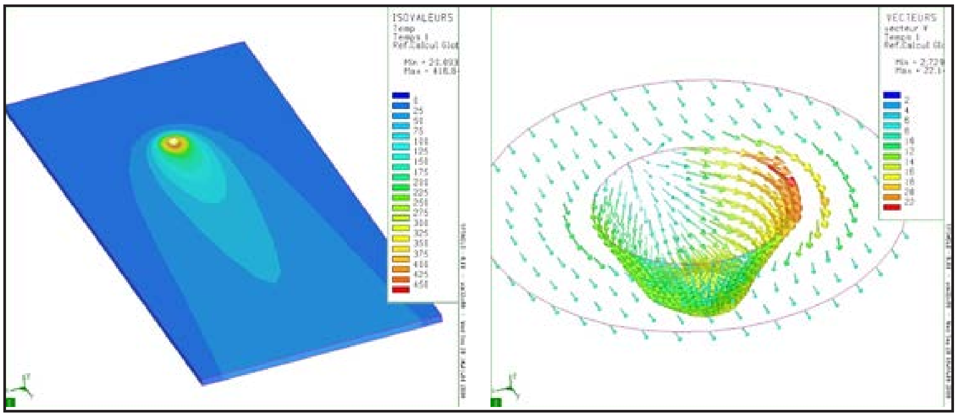

Fig. 5. Distribution of temperature field during the FSW process and the distribution of velocity vectors around the tool

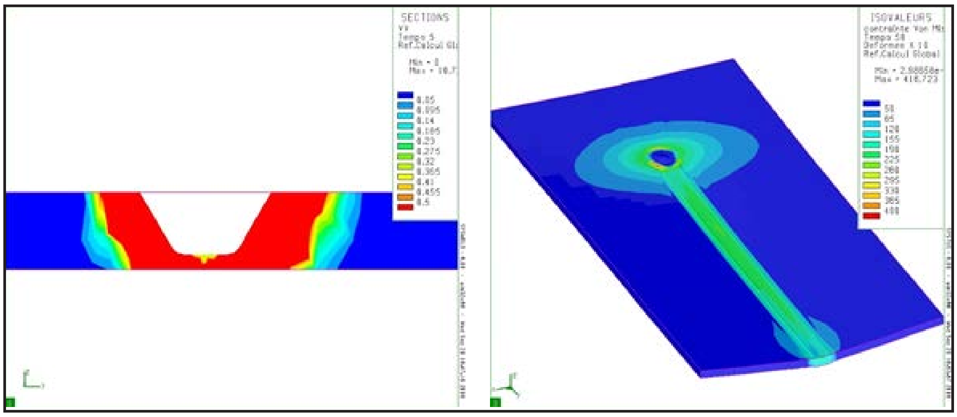

Fig. 6. Cross-section of the welding area and the distribution of reduced stresses

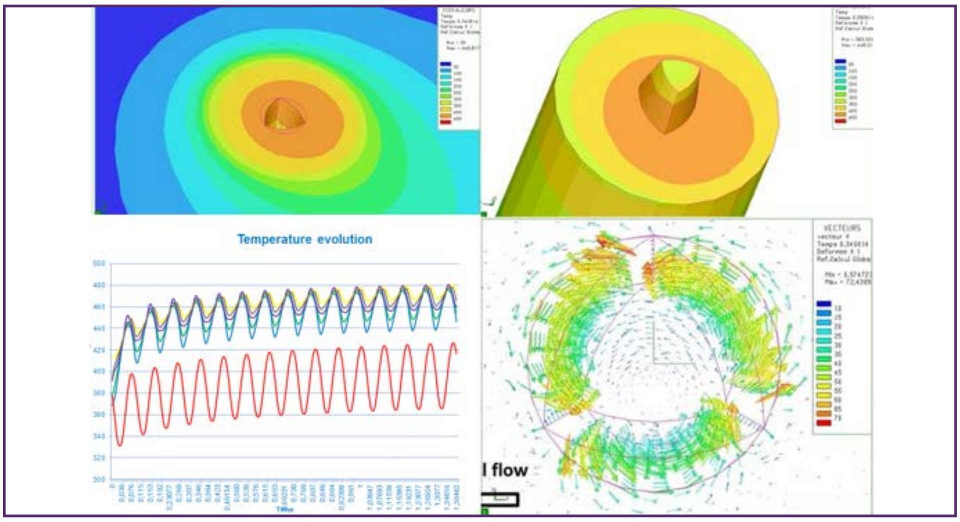

Fig. 7. Distributions of temperature and velocity vectors during the FSW process performed using a non-symmetric tool

Numerical Analyses of the EBW Process

The electron beam welding (EBW) process is a welding technology focused both on high efficiency and quality. The EBW process is characterised by a very narrow heat affected zone (HAZ) and significantly smaller welding strains in comparison

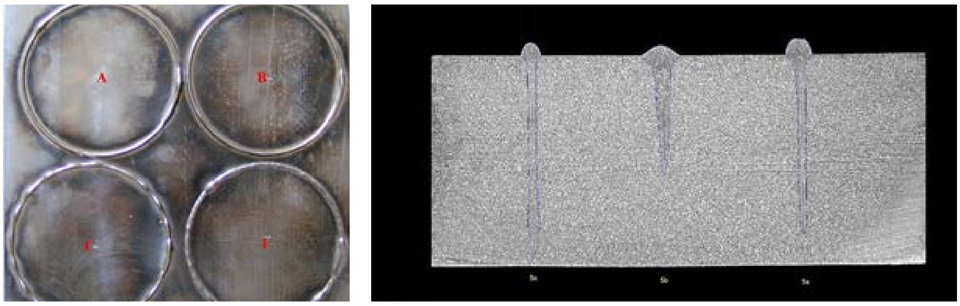

Fig. 8. Girth runs performed using the EBW method and exemplary macrostructures

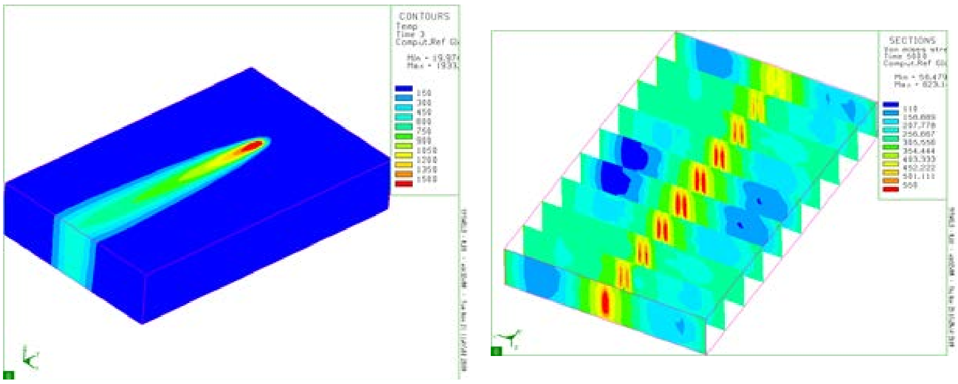

Fig. 9. Distribution of temperature fields during the EBW process and the distribution of stresses following the welding of the test specimens

with those obtained using conventional welding methods. The foregoing is mainly ascribed to the specific shape factor of obtained welds. However, the shape of welds (large elongated area) obtained using the EBW method is responsible for the formation of hot cracks, particularly when welding austenitic steels and nickel superalloys (Inconel). Numerical analyses of the EBW process should be performed using a special heat source model, the energy distribution of which corresponds to a technology being modelled. According to the authors' experience, the heat source model should be verified in relation to each set of parameters by using macrosections of an actual element. Presently, it is not possible to perform precise numerical analysis without process validation. This means that certain process parameters significantly affect the total amount of energy and the shape of the heat source and cannot only be defined by numerical values. Such parameters include:

1. efficiency,
2. shape of the fusion zone and the heat affected zone,
3. focal length.

It is therefore necessary to perform a series of auxiliary calculations so that thermal conditions during simulations could be as close to actual conditions as possible and would represent the specific nature of the EBW process. Depending on the technique, EBW devices operate with or without vacuum. Certain applications enable the feeding of a filler metal in the form of a wire [7, 8, 9]. Each of the above-named technological variants requires changes in the modelling methodology and in the calibration of the heat source.

A computational example of the EBW process contains results in relation to the set of 15 specimens made as regular or girth runs (Fig. 8).

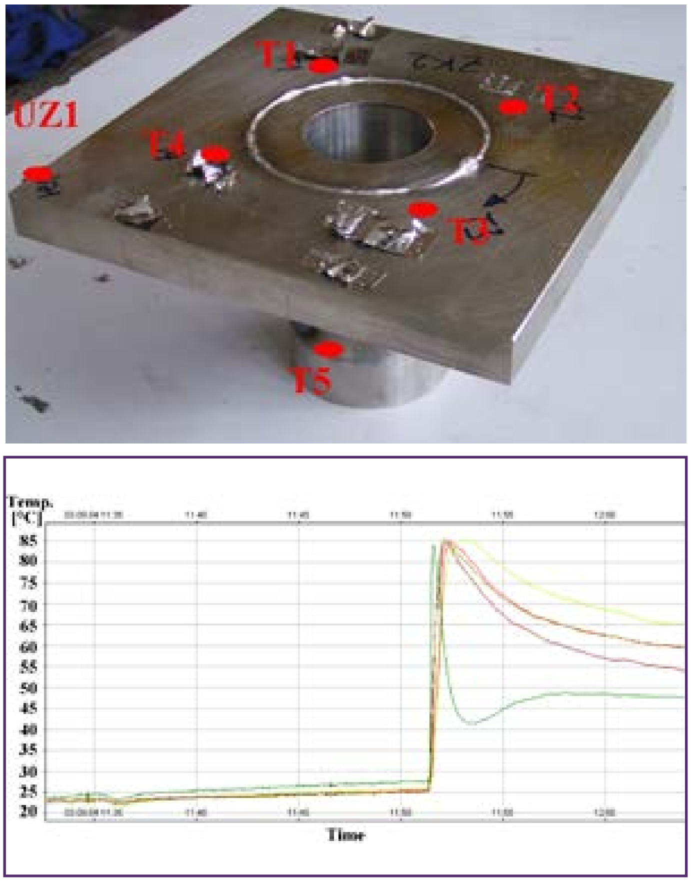

Fig. 10. Element welded using the EBW process and the diagram of thermal cycles recorded during the process

The base material used in the test was austenitic steel grade 316L. The test specimens were also modelled in the Sysweld software programme. The primary purpose of the analyses was to obtain experience concerning the modelling of EBW processes as well as to determine a methodology related to the development of input data used in simulations. Exemplary distributions of temperature fields and post-weld (EBW) stresses, obtained as a result of performed numerical analysis, are presented in Figure 9.

The performance of test analyses and the development of methodology related to the performance of analysis of the EBW process were followed by te sts involving the electron beam welding of an element of a flexible fixing system (Fig. 11). Afterwards, the element was simulated in the Sysweld software programme. Results obtained in the actual tests and thermal cycles recorded using thermocouples were used to validate calculations.

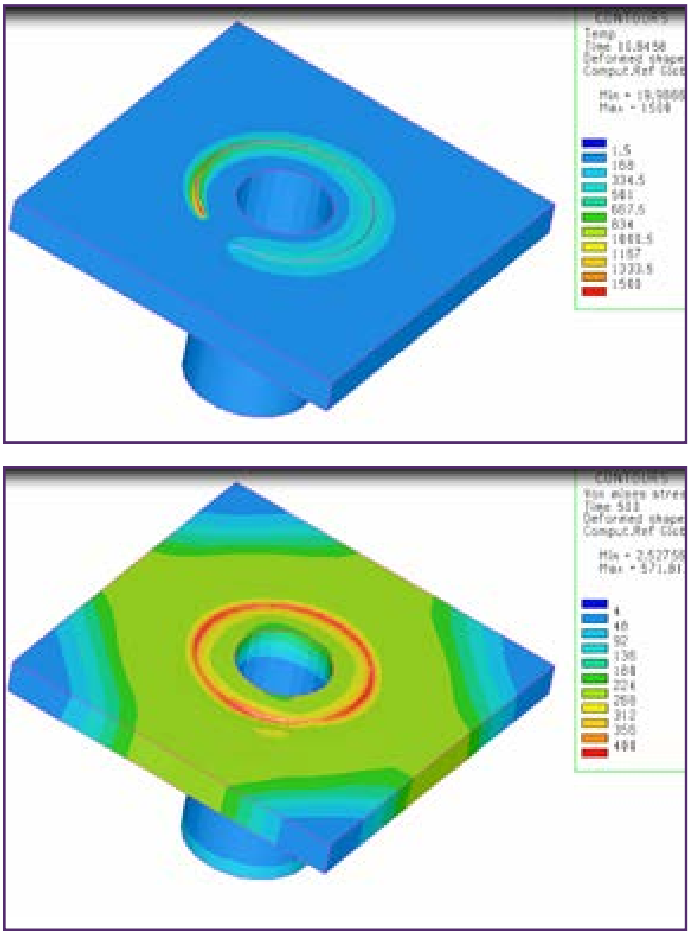

Fig. 11. Distribution of temperature fields during the EBW process and the distribution of stresses following the welding of the element of the flexible fixing system

Summary

In the competitive market economy the primary objective of industrial companies is the constant reduction of production costs without compromising or, possibly, with improving the quality of products. The ability to offer fully customised products requires the possession of detailed knowledge concerning both the product and the process of its manufacturing. The reduction of production costs and that of production preparation time are possible mainly through the minimisation of necessary tests and repairs preceding the start of high-volume production and the delivery of end products. Numerical analyses of welding processes are very advanced and efficient tools enabling design engineers and technologies the obtainment of enormous amount of process-related information. The above-named knowledge leads to the better understating of processes, makes it possible to handle unexpected problems as well as enables the development of new solutions improving production processes.

This article aims to indicate ongoing research works dedicated to the development of tools for numerical analyses of cutting-edge welding technologies, such as e.g., still intensively developing, friction stir welding (FSW).

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