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Use of Welding Process Numerical Analyses as Technical Support in Industry.

Part 1: Introduction to Welding Process Numerical Simulations

Abstract: Welding, as a modern and highly efficient technology, is presently applied in practically all industrial sectors. An increase in the number of welding applications entails higher requirements related to the quality of welded joints. Numerical analyses enable welding process simulations whose results are very close to reality. The results of such analyses include distributions of temperature fields, metallurgical phases, hardness, plastic strains and stresses. The analysis of these quantities makes it possible to relatively optimise welding technologies and to obtain information about the behaviour of welded structures during the entire production process. Numerical simulations constitute very useful tools supporting production preparation processes and enabling the obtainment of high quality products. Presently, the most complex numerical simulation software programmes make up the package offered by the Esi Group including Sysweld, Pam Assembly and Weld Planner. All these programmes utilise Fem-based calculations. This article is the first part of a cycle concerning the possibility of utilising numerical techniques in supporting the design of technologies and structures using computer-aided simulations of welding processes and heat treatment.

Keywords: numerical analysis, welding processes, numerical simulations;

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Introduction

Welding technologies are, at present, probably the most widespread among all other technological processes. However, the use of heat sources and resultant thermal cycles affecting elements being welded lead to the formation of stresses and strains in welded structures. The type and size of welding-induced strains and internal stresses significantly affect many factors such as workpiece fixing methods, physical and mechanical properties of materials, welding methods and parameters, pre-heating temperature, types of welds and joints, ambient temperature and many other factors. Internal stresses negatively affect the service life of structures and their brittle crack resistance. Internal stresses constitute a balanced system of internal forces, which are also present in the case of an entire lack of external loads affecting the structure [1-5].

In turn, strains (deformations) of elements during and after welding constitute a significant

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problem connected with maintaining the appropriate geometrical dimensions of structures. The post-weld formation of unwanted deformations, exceeding acceptance levels, entails additional technological procedures, e.g. straightening. Obviously, this is inseparably connected with increased costs and extended production times [1-5,8,9]. Numerical simulations of welding and heat treatment processes are very modern tools determining the post-weld level of internal stresses and strains of elements, or even of entire structures.

Calculated internal stresses can also be used for lifetime predictions and detecting, as early as at the design stage, areas of potential crack initiation leading to structural failure during operation. The determination and control of strains are also very important due to post-weld treatment and the subsequent fixing of elements. Therefore, it is necessary to find a compromise between the entire rigidity and entire "freedom" of elements to be welded (Fig. 1). Structures of significantly increased rigidity before welding tend to develop considerable internal stresses. In turn, the entire lack of element fixing leads to significant strains. As can be seen, it is impossible to entirely eliminate stresses and strains [1-3,8,9].

Welding process numerical simulations can be used both when preparing a technology for the manufacturing of new elements and structures and at the stage of modifying already

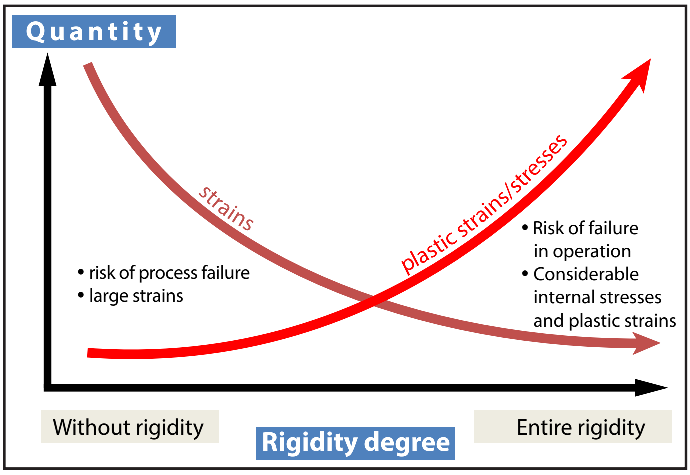

Fig. 1. Contrasting effect of structural rigidity on plastic strains and internal stresses [9]

existing structures in order to assess the fatigue life of elements, taking into consideration the level of internal stresses resulting from welding processes or repairs performed using welding techniques.

The use of numerical simulations makes it possible to reduce the number of tests and prototypes at the technology design stage and provides the significant reduction of time and costs necessary for the preparation of a technology. In addition, numerical simulations enable the analysis of different variants, which leads to the obtainment of initial information related to the behaviour of elements or structures during and after welding without incurring the significant costs accompanying the development and production of prototypes. Often, tests do not reflect the actual conditions accompanying the production of structures, and the creation of prototypes usually entails considerable costs resulting from the high prices of modern structural materials. Numerical simulations offer the possibility of verifying many variants and selecting the most convenient solution. The optimisation of welding technology components such as welding parameters, welding sequence, element fixing conditions and welding direction enable the determination of final output data for an actual production process.

One of numerous advantages offered by the numerical analyses of welding and heat treatment processes is a better "understanding" of a process being modelled. In real welding, knowledge is limited to input parameters and information coming from the observation of post-weld results. Obviously, welded joints can be subjected to NDT, hardness measurements, strain-related tests, macro and microscopic examinations, strength tests etc. On the basis of the results of such tests, it is ultimately possible to assess the welding technology selected. However, in cases of problems, finding their cause is possible only on the basis of input data and post-weld results, without possessing complex knowledge about the course of the welding process itself. Numerical simulations offer the possibility of verifying the entire technological process, step-by-step analysis (e.g. at 1 second intervals) and the obtainment of very detailed data concerning the effect of selected process parameters on strains, distribution of individual metallurgical phases, internal stresses, plastic strains etc. The analysis of the recording of the entire modelled welding process enables the determination of the reason responsible for the formation of occurring problems as well as makes it possible to resolve a problem by modifying the existing technology or developing a new or alternative method [1,2]. According to the experience of the Esi Group engineers, particularly in relation to the power sector and heavy industry, tests performed on small specimens significantly differ from processes taking place during welding large elements of real structures. In some cases, required results (e.g. crack-free elements of specific properties) are obtained using small specimens, whereas problems appear during welding actual structures. This results mainly from design differences (ribs, openings, various dimensions, heterogeneous material etc.) between small specimens used in tests and reals elements of welded structures. Such situations may lead to the formation of cracks and reduced plastic and mechanical properties. This explains the importance of modern computational techniques based on numerical simulations of welding and heat treatment processes, enabling the obtainment of significantly more information about the course of the welding process itself. Presently, numerical simulations of welding and heat treatment processes are commonly used worldwide in heavy, automotive, power, shipbuilding and aviation industries.

In order to present the issue in more detail, the authors of this article intend to prepare a cycle of three articles explaining the possibility of using numerical simulations of welding processes. This article is an introduction to the issue of numerical analysis, whereas the two remaining articles will explain simple tasks along with the validation of results and demonstrate advantages arising from the use of welding process numerical analyses and present examples of complex structures used in the power and transport sectors.

Recently, Esi Group represented in the Polish market by Mecas Esi has signed a strategic agreement with the Silesian University of Technology concerning collaboration in numerical simulations of welding and heart treatment processes. Future plans also assume the opening of a centre of excellence for numerical simulations of welding and heat treatment processes at the Welding Department of the Silesian University of Technology. Due to their considerable experience of welding technologies and materials science, Mecas Esi also cooperates with Instytut Spawalnictwa in Gliwice.

Numerical simulations of welding processes

Presently, numerical simulations of welding processes are widely used in both the development of new and in the optimisation and validation of already existing and applied welding technologies. However, attempts to determine internal stresses and strains date back much earlier. The first works enabling the determination of internal stresses and strains using analytical equations were performed as early as 1938. In 1970, in their first scientific project, Brust, Rybicky, Barber and Masubuchi conducted the first welding process numerical simulation using the Finite Element Method [1]. Twenty years later, industrial implementations of welding process numerical analyses were widespread in, among others, the Usa, Japan, France and Germany [1,6,7].

The recent 20 years have seen significant progress in industry-supporting numerical analyses possible due to enormous development of computers and the possibility of applying new computational methods enabling calculations of very large and complex welded structures.

Since the 1970s, the Esi Group company (previously Framasoft) has been developing software programmes for numerical analyses of welding processes and heat treatment. The present offer includes three different products used for numerical analyses of welding and heat treatment processes:

1. Welding Solution (previously Sysweld). A package enabling the complete transient analysis of welding processes and heat treatment allowing for the entire physics of materials (Fig. 2).

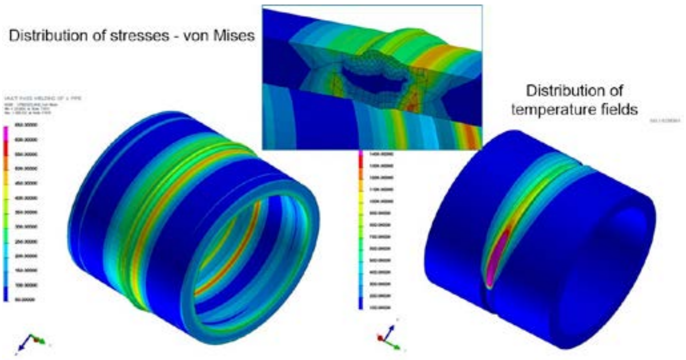

Fig. 2. "Transient" type analysis in module Welding Solution – post-weld stress distribution (left) and distribution of temperature fields at a selected moment [10]

2. Weld Planner. Package primarily dedicated to the transport sector, enabling the determination of the effect of welding processes on strains of complex structures (Fig. 3).

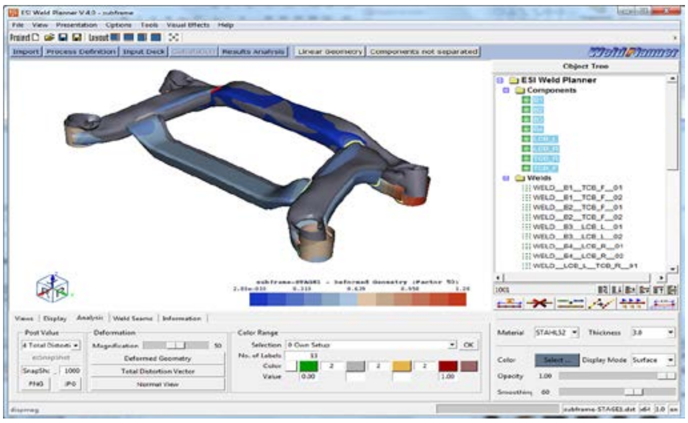

Fig. 3. Main screen of Weld Planner programme with exemplary calculations in the "shrinkage method" technique [10]

3. Pam Assembly. A tool used for determining structural strains resulting from welding processes applied; the tool is based on a modern "local/global" computational technique.

Programme structure and input/output data

Sysweld entirely covers the issues of non-linear analyses, i.e. non-linear heat transfer in any space, non-linear geometry of large strains, isotropic and kinematic material hardening or phase transformations (Fig. 6). Combining the effects of such a large number of phenomena present in welding processes enables the obtainment of the previously mentioned high compatibility of simulation results with the behaviour of an actual element or structure.

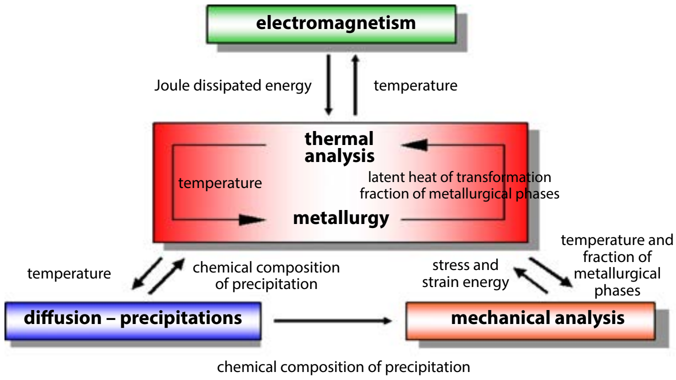

Fig. 4. Sysweld structure [9]

For calculations to be performed, the system requires entering the following data:
- geometry of a joint and/or structure (3D image in any CAD format; in Pro/E, Catia, Ug, I-deas, Patran, Ansys, Iges, Stl, Step formats etc.),
- types and chemical compositions of base materials and filler metals, information concerning welding technologies,
- heat input (current, arc voltage, welding rate),
- welding sequence,
- number of runs and their welding sequence in multi-run welding,
- pre-heating temperature and interpass temperature,
- information about post-weld heat treatment, if applied
- manner and sequence adopted when fixing elements to be welded.

As can be seen, presented above are typical input welding parameters known to an engineer designing a process or a structure.

The diversity of heat source models also enables the simulation of a vast range of welding processes:

- MMA welding,
- gas-shielded MIG/MAG welding,
- gas-shielded non-consumable electrode welding,
- submerged arc welding,
- electroslag welding,
- electron beam welding,
- laser beam welding,
- spot welding,
- friction stir welding (FSW).

SYSWELD enables simulations of welding processes within a very wide range both with and without filler metals, with heat sources remaining (friction welding, spot wielding) and not remaining in physical contact with workpieces (electric arc, laser beam, electron beam). Similarly wide is the range of possible heat treatments including, among other things, tempering, (laser, induction, electron beam, plasma, friction) hardening, surface hardening, carbonising and nitriding.

Results obtained by users of software dedicated to numerical simulations of welding and heat treatment processes are the following:

- temperature fields and gradients,
- distribution of metallurgical phases (phases as ferrite, bainite and martensite in steels but also phases in aluminium alloys and titanium alloys),
- hardness distribution,
- austenite grain size,
- strains (deformations),
- distribution of internal stresses,
- plastic strains,
- intermediate determination of such material properties as yield point and ultimate strength.

Types of welding process analyses

Welding process numerical analyses may be connected with various objectives. Depending on intended solutions and according to the authors' experience, such analyses can be divided as follows:

1. **Analysis of strains**. The analysis is solely focused on strains without providing information related to material structure, internal stresses etc. By ignoring the entire physics of materials and using a simplified computational method ("shrinkage method"), it is possible to determine strains of very large welded structures containing hundreds of welded joints (Fig. 5).

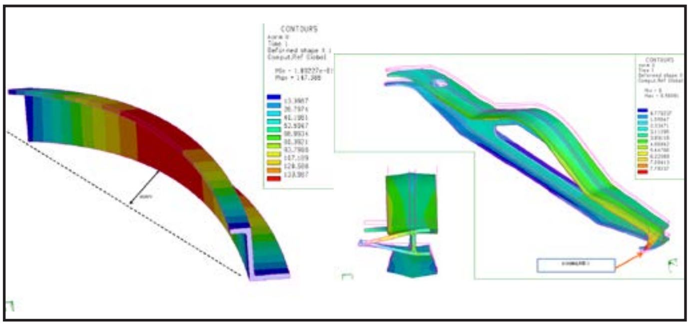

Fig. 5. Strains analysis results – exemplary welded structure

2. Determination of material structure and intermediate determination of yield points and ultimate strength. On the basis of the distribution of hardness and of metallurgical phases, it is possible to determine (using empirical equations) post-weld yield points and ultimate strength of materials (Fig. 6).

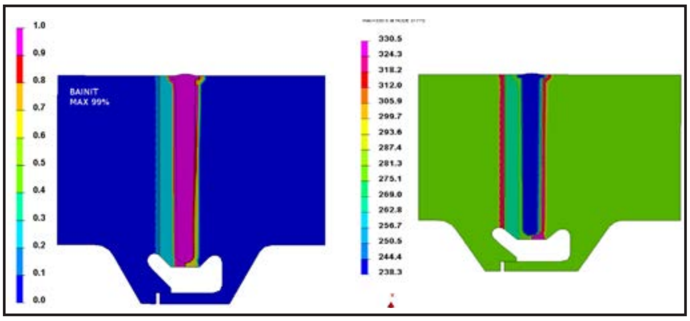

Fig. 6. Bainite distribution simulation results (left) and hardness distribution simulation results (right) on the cross-section of a welded element

3. **Analysis of distribution of internal stresses**. This type of analysis enables the determination of both the value and distribution of internal stresses after welding or after heat treatment processes in welded structures and comparing these results with boundary

values obtained in strength tests performed for individual metallurgical phases.

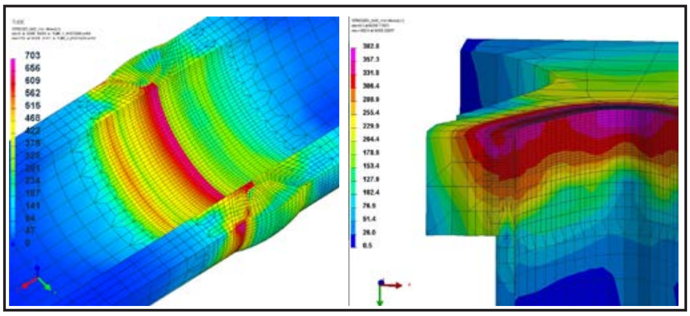

Fig. 7. Results of internal stresses distribution analysis – example of welded structure

4. **Prediction of crack initiation critical areas**. The assessment of susceptibility to cracking is performed using an intermediate method based on calculated indexes and principles governing the formation of individual types of cracks:
a) cold cracks,
b) hot cracks,
c) cracks generated during multi-run welding or heat treatment.
5. **Analysis of welded joint fatigue life**. Presently, after calculating a proper welding process, it is possible to burden the model with external factors such as pressure, forces or temperature. It is important that these loads are exerted in the same computational model containing heterogeneous material (being the result of thermal cycle-induced metallurgical transformations), internal stresses and plastic strains. On the basis of the Van Dang criterion it is possible to perform high-cycle fatigue analyses of welded structures.
6. **Analysis supporting the design of fixtures.** In cases of complicated and large structures, particularly in the transport industry, it is often necessary to design highly complex tooling for fixing elements to be welded. The use of numerical analyses enables designing such fixtures on the basis of results of relative analysis confronted with a reference case. The optimisation of processes obtained as a result of numerical analysis in relation to strains and stresses makes it possible to design optimum sets of fixing elements.
7. **Numerical simulations of repair welding**. Such simulations belong to the most important analyses performed in the power sector. In the event of detecting cracks in elements operated in, e.g., power plants, it is necessary to immediately implement repair actions in order to avoid serious damage or failure. Obviously, in cases of such unscheduled breaks, power unit downtime should be limited to the absolute minimum, due to the enormous losses generated by such idle time. Also, due to high costs of materials used in the production of elements and machinery, such repairs should be performed in a manner allowing the obtainment of the maximum quality level and limitation of errors to the lowest possible minimum. In such cases, numerical analyses allow the entire optimisation of repair technology and its pre-repair verification. Numerical analyses may also enable finding an alternative repair method where the original technology cannot be used due to limitations resulting from conditions present in the power plant.
8. **Relative analysis or optimisation of welding process.** These are the most important analyses performed in industry as they make it possible to consider many variants of welding structure production without the necessity of performing tests on actual specimens. It is possible to conduct a precise analysis often concerned with the effect of individual process parameters on the results of such an analysis.

Summary

Presently, the major objective of manufacturers is the continuous reduction of costs accompanied by the continuous increase in manufacturing quality. In order to satisfy a customer's requirements it is necessary to possess very detailed knowledge about the production process and about the behaviour of the product itself.

The reduction of costs, design time and technology preparation time are primarily possible due to the reduction of the number of experiments and repairs before the final approval of the technology and the manufacturing of a finished product. Presently used numerical simulations of welding processes and heat treatment are very modern and efficient tools. On one hand, this is due to the developmental progression of increasingly complex computational system, whereas on the other hand, it is due to recently observed enormous progress in software programmes intended for such systems. The progress in modelling techniques provided scientists and engineers with a lot of valuable information enabling a better understanding of phenomena connected with the formation of internal stresses and strains in welded structures and hazards related to such phenomena. This article aims to present how very important and interesting information about welding processes and about the behaviour of welded structure can be obtained using modern techniques of manufacturing process simulations. The range of results and analyses is both extensive and detailed. Such results can be used both when developing new elements and structures as well as while modifying and optimising already existing welding and heat treatment technologies and in order to increase the fatigue life and quality of elements and welded structures.

In conclusion, it can be stated that the software package described above is an interesting proposal offering a complex approach to welding and heat treatments of welded elements and structures. In the next article of this cycle, the authors will attempt to present examples of simple tasks along with the validation of results and demonstration of advantages arising from the use of welding process numerical analyses.

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