Monika Restecka, Robert Jachym

IT Systems Used for Welding Process Simulations and Simulators of Thermal-Strain Cycles

Abstract: The first part of the article presents an overview of software programmes assisting welding-related engineering works as well as discusses possibilities and advantages related to the use of such programmes. Software programmes available today enable, among other things, the monitoring of welding processes, calculations of temperature distribution, the determination of mechanical and plastic properties, simulations of distributions of residual stresses as well as simulations of transformations triggered by welding thermal cycles. The second part of the article is dedicated to simulators enabling physical simulations of welding processes as well as describes principles of simulations tests and presents advantages related to the use of this technique.

Keywords: welding-related software, monitoring of welding processes, welding simulations,

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Introduction

The appropriate selection of a welding procedure constitutes a key factor affecting the quality of manufacturing processes used when making any welded structure. In order to properly adjust welding process parameters, it is necessary to perform specific tests and examinations, the results of which can be used in practice. Some of these tests are relatively simple and inexpensive; others can turn out costly and time-consuming. For this reason, tests concerning welding procedures are increasingly based on the modelling of processes. The purpose of modelling is to reduce costs and minimise the risk of an error which may occur during actual welding tests [7].

Undesirable results of welding processes are residual stresses and welding strains which, when significantly exceeded, can lead to the rejection of a given structure as its dimensions and shape fail to satisfy design assumptions. Measuring the values of stresses present in welded structures is a complicated process requiring appropriate skills and equipment. In addition, welding strains are strictly related to an adopted welding procedure. When designing, it is necessary to anticipate and prevent the possible formation of strains. There is demand for complex and accurate tools for simulating welding processes and enabling calculations of temperature distribution as well as the distribution of residual stresses present in elements.

mgr inż. Monika Restecka (MSc Eng.) – Instytut Spawalnictwa, Marketing and Scientific Information Department; dr inż. Robert Jachym (PhD (DSc) Eng.) – Instytut Spawalnictwa, Testing of Materials Weldability and Welded Constructions Department

Tools in demand should also be able to simulate transformations triggered by welding thermal cycles, identify microstructural changes as well as determine plastic and mechanical properties. In some cases, the above named simulations utilise IT systems. Recent years have also seen the growing popularity of physical simulations used in welding tests, heat treatment, hot plastic working and even in relation to the continuous casting of steel. A physical simulation consists in representing a given technological process in a relatively small-sized material specimen. In relation to proper simulation, it is important that all major factors characterising processes (i.e. temperature, strains and stresses with appropriate gradients) should be represented in real time, i.e. at the time of the process. The simulations mentioned above are performed using simulators of thermal-strain cycles [4, 7, 9].

CAE Software

CAE (Computer Aided Engineering) software includes a group of programmes assisting engineering works at the first stages of product development, i.e. during design and structural works. Such programmes can work independently or be supported by CAD software programmes (enabling engineering analyses of designed elements). Without the numerical modelling of geometrical, material and dynamic features, the adjustment of optimum parameters related to a given method could be far more difficult and, in some cases, even impossible. The accuracy of individual analyses directly affects the quality of welds. Sadly, the above named programmes can only be used for making prototypes. When using CAE software, it is very important to properly verify a model created against an actual element, which entails the necessity of updating relevant information and optimising the structure. The CAE-related principle of operation can be described as composed of three stages, i.e. analysis, calculations and the interpretation of obtained results. CAE programmes can be used to perform kinematic and dynamic analysis of mechanisms, thermal and flow analysis involving the Finite Element Method (FEM) and dynamic and static analysis of components (also supported by FEM). Additional advantages of CAE include the possibility of performing simulations as regards the making of structures and simulations of mechanical phenomena [8, 9].

Examples of IT Systems Used for Simulations of Welding Processes

The use of CAE programmes makes it possible to simulate almost any technological process, including welding. Welding is a complex process, in which the quality of obtained joints is not easy to verify. Quite often, quality-related requirements are high. In such cases, the use of simulation in the virtual environment significantly reduces production costs. This fact is one of the main reasons for the growing popularity of numerical methods in recent years. In some cases, simulations may even replace experimental tests, yet simulation results do happen to be encumbered with errors. This is so because actual production conditions often differ from virtual ones and differences related to, e.g., physical phenomena, not always fully predictable during welding, are too large. In order to more precisely take into consideration all factors, it is necessary to perform simulations in several iterations. In this way, it is possible to reduce the occurrence of potential errors and differences between a model created in the programme environment and an actual element. Presented below are examples of CAE systems used when simulating welding processes [9].

Welding Simulation Suite

Welding Simulation Suite (Fig. 1) developed by ESI Group is a package composed of programmes calculating the effect of heat on the structure during and at the end of a simulated welding process. Simulations take into consideration changes in shapes, thermal strains, hardness, phase composition as well as plastic stresses and strains. A factor distinguishing the package is the possibility of simulating multi-run welding and pressure welding. Software programmes making up the package are the following [12]:

– Visual-weld – programme used in the Visual environment, enabling simulations of single and multi-run welding processes involving various types of materials, including steel, aluminium as well as other metals and alloys,
– Weld Planner – programme mainly used for simulating the welding of large-sized elements. The programme enables performing very fast analyses utilising displacement engineering based on simulations of strains. Time required to perform such analyses may amount to a day,
– Pam-assembly – software programme, similar to Weld Planner, dedicated to simulating the welding of large-sized elements using the local-global approach. The programme is based on models calculated using Sysweld and utilises such models to calculate structural strains taking into consideration physical phenomena.

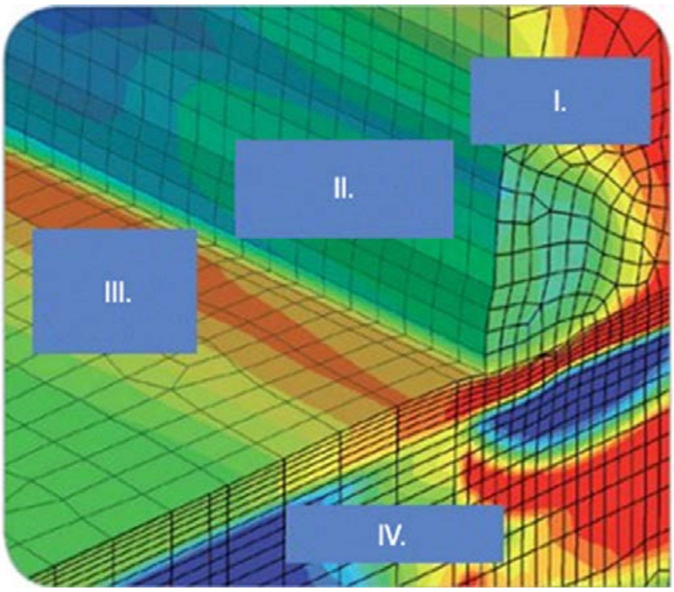

Fig. 1. Exemplary simulations of welding processes using FEM of an element made of various materials (I – element made of nickel alloy Inconel, II – Inconel type filler metal, III – layer of the plated coating made of stainless austenitic steel, IV – structural steel) [12]

SYSWELD

Another element of the Welding Simulation Suite package is Sysweld, an advanced programme for simulating a range of welding processes, including the three-dimensional simulation of welding procedures and of the heat treatment of metals. The software enables the user to perform thermo-metallurgical, electrokinetic-thermo-metallurgical, diffusive and many other analyses. Results of analyses and calculations enable, among others, determining the effect of a selected heat treatment, material, hardening process conditions etc. Calculations performed by the system utilise the Finite Element Method. Sysweld is available in two basic versions:

– heat treatment module (version contains issues related to hardening, tempering and chemical processing, i.e. nitriding and carburising),
– welding module (version contains all principal welding methods).

In order to minimise strains, by selecting an appropriate welding procedure, the software can be used for the optimisation of welding processes. In addition, the programme can import data from cad systems, which quickens analyses. Although a major disadvantage of the software is its high price, Sysweld remains one of the best available tools for forecasting welding stresses and strains [9, 13].

ANSYS

Ansys is one of the most popular systems used in widely defined strength, thermal and electromagnetic analyses as well as in analyses of fluid mechanics. The software enables the modelling and simulations related to structural and fluid mechanics as well as allied simulations. The programme can be used to perform linear and non-linear calculations and optimisation. The Finite Element Method is used when modelling problems concerning statics, dynamics, fields of temperature, mechanics of fluids, electromagnetic fields, diffusion electrostatics and piezoelectricity. Figure 2 presents the exemplary visualisation of test results utilising the Ansys software programme [1, 9].

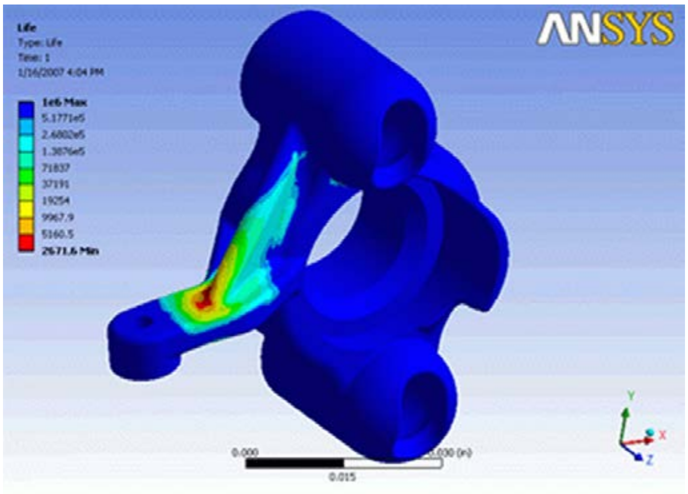

Fig. 2. Exemplary simulation result obtained using Ansys [14]

Although Ansys does not have an environment dedicated to the modelling and simulation of welded joints, the programme enables the development of models taking into consideration thermal and mechanical processes. Because of this functionality, in industry, Ansys is used for simulating welding processes. One of the examples of such an application includes simulations performed when manufacturing the Audi A8 [1, 9].

ABAQUS

The software programme is used for machinery and structural strength-related calculations. Among other things, the programme enables creating models assisting design and manufacturing. It is also possible to simulate the non-linear problems related to the mechanics of solids and fluids. A model to be simulated can be defined from scratch, e.g. using the Femap programme, dedicated to modelling any complicated structure with any number of details and any level of detail, also including boundary and force conditions (if any). A model prepared in the above-presented manner can be imported to the Abaqus software programme. Related analyses are based on thermo-mechanical procedures (Fig. 3). The ability to predict stresses generated in the material during welding enables forecasting the ultimate shape of the product after the completion of the process as well as makes it possible to assess the effect of stresses on the structure [7].

To this end, it is necessary to perform thermal analysis combined with stress analysis. Similar to other applications, it takes considerable time to become familiar with the software programme. In addition, entering data and the simulation process itself are also time-consuming. However, as a result of the increased accuracy of the model and because of the appropriate distribution of the model into finite elements, the accuracy of obtained results is high [7].

MSC MARC

The Msc Marc software programme is used for performing effective simulations of welding processes. The programme requires the use of specialist user procedures. The modelling of a heat source can be performed by using the Uwedflux module. Welding processes can be modelled for flat problems (2D), plates, axial symmetry and 3D problems. The programme enables performing thermal and thermo-mechanical analyses. The possibility of modifying the solver by entering user procedures makes the Msc Marc programme a tool characterised

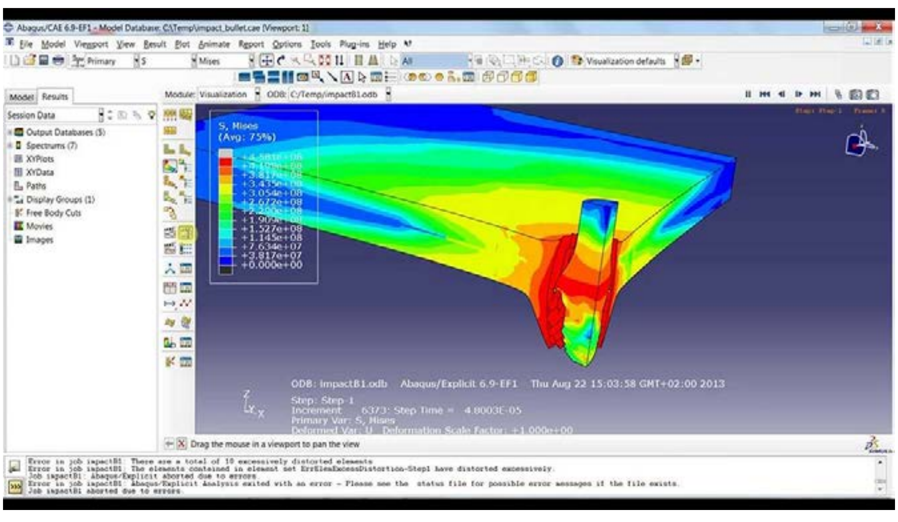

Fig. 3. Window of the Abaqus software programme [7]

by extensive computational possibilities. The software programme also enables performing verification calculations and simulations of complex non-linear problems, e.g. multiple fillet welds. It should be noted that Msc Marc requires considerable computational powers [5].

Simulators of Thermal-Strain Cycles

The use of simulation in tests of technological processes date back to 1949, i.e. the construction of the first simulator of thermal cycles used for current flow-based resistance heating of specimens [6]. The first simulator of thermal-strain cycles was built by the American company Duffers Scientific Inc. (presently Dynamic Systems Inc.). The device was equipped with a pneumatic system of load application. After subsequent modifications the system was provided with a hydraulic servomechanical system making it possible to perform complex thermomechanical tests. Today, Dynamic Systems Inc. produce computer-controlled complex simulators named Gleeble, used in various areas of research including welding engineering, materials engineering, hot plastic working and continuous casting of metals.

Instytut Spawalnictwa also developed (in the 1960s) a simulator of welding thermal cycles based on the resistance heating of a specimen. In the years to come, the simulator was gradually modified and improved (Fig. 4).

Structural changes taking place in the Heat Affected Zone (HAZ) significantly affect the properties of the above named welded joint area, particularly its hardness and related formability, toughness (characterising brittle crack resistance) and susceptibility to hot, cold and annealing crack formation. The manner in which steel responds to a welding thermal cycle constitutes an important factor affecting the steel weldability. In order to test the effect of welding thermal cycles on structural transformations and resultant properties, small specimens are subjected to thermal cycles simulating courses of temperature changes in various HAZ areas (Fig. 5). Such tests are performed using dedicated devices, i.e. simulators of thermal-strain cycles [2].

Worldwide-manufactured simulators of thermal-strain cycles are characterised by various modes of the heating (induction, resistance) and tensioning of specimens (hydraulic, magnetic or mechanical systems) (Table 1).

Simulator of Thermal-Strain Cycles: Gleeble 3500

Instytut Spawalnictwa has multi-annual experience of using the above-presented simulation techniques in terms of weldability testing. Recently, Instytut's laboratories have acquired a Gleeble 3500 (DSI) (Fig. 6) modern simulator

Fig. 4. Main view of the simulator of thermal-strain cycles produced by Instytut Spawalnictwa (version from 1996)

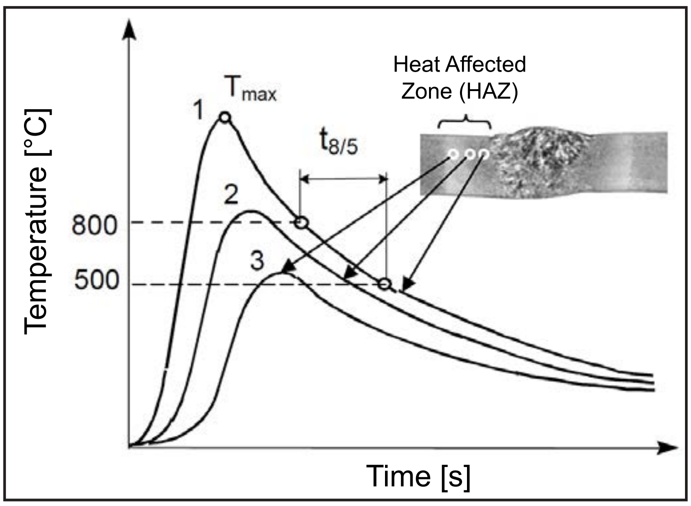

Fig. 5. Welding thermal cycles at various distances from the weld fusion zone [2]

Table 1. Selected specifications of Gleeble, Thermorestor, Smitweld and Instytut Spawalnictwa's simulators of thermal-strain cycles [3, 10]

Name	Specimen heating mode	Specimen cooling mode	Technical possibilities of control
Gleeble	Joule heat	Controlled cooling in jaws cooled by water	$T = f(t)$ $P = f(t)$ $P = f(\varepsilon)$
Thermorestor	induction	Cooling gas (Ar, He) injection	$T = f(t)$ $P = f(t)$ $P = f(\varepsilon)$
Smitweld	Joule heat	Controlled cooling in jaws cooled by water	$T = f(t)$ $P = f(t)$
Simulator IS (version from 1996)	Joule heat	Controlled cooling in jaws cooled by water	$T = f(t)$ $P = f(t)$ $P = f(\varepsilon)$

Designations: P – tensile force, kN; ε – strain, %; t – testing time, s;

for physical simulations of joining processes, replacing the previously used simulator made by Instytut Spawalnictwa. The simulator enables the modelling of thermo-mechanical conditions occurring in the most unfavourable area of a welded joint, i.e. HAZ. The primary specifications of the device are the following:
- hydraulic system for subjecting specimens to stresses and strains,
- maximum load force of 98 kN,
- maximum rate of moving jaw displacement of 1 m/second,
- maximum cycle temperature:
  - 1350°C – Ni-NiCr thermocouple,
  - 1750°C – Pt-PtRh thermocouple.

Among other things, the device makes it possible to simulate welding processes, test mechanical properties of steels at higher temperatures, simulate the effect of welding thermal cycles on the microstructure and properties of steels (HV, KV) and determine the susceptibility of materials to hot, cold and annealing cracking. The device has also been equipped with a specially designed additional working chamber making it possible to perform tests focused on resistance to cold cracking under hydrogen. During tests, specimens can be subjected to any thermo-mechanical conditions and, simultaneously, to saturation with hydrogen.

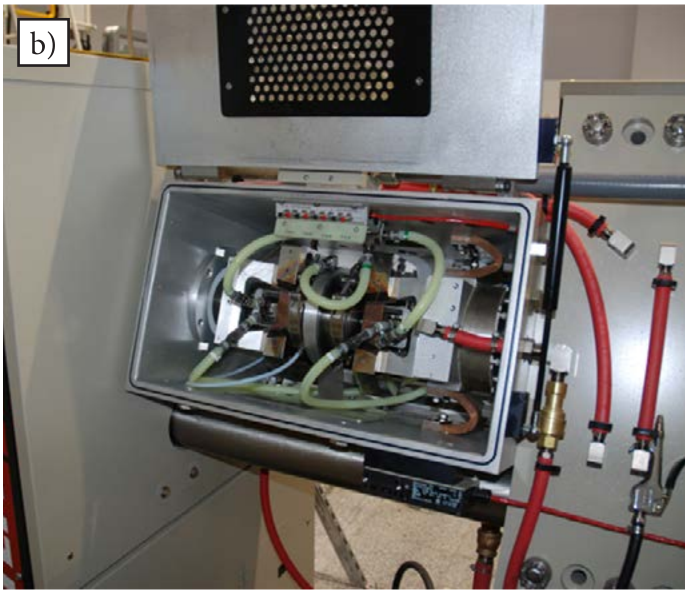

Fig. 6. Gleeble 3500 series simulator for physical simulations of welding processes: a) main view, b) working chamber

Summary

The quality of welding processes is of crucial importance. The key factor affecting the quality of processes used when making welded structures is the appropriate selection of the welding procedure. In order to properly adjust welding process parameters, it is necessary to perform specific tests and examinations, results of which can be put in practice. To this end, it is possible to use a wide range of software programmes enabling the monitoring of welding processes, calculations of temperature distribution, the determination of microstructural transformations, the identification of plastic and mechanical properties, simulations of distributions of residual stresses in elements, and simulations of transformations induced by welding thermal cycles. The adjustment of appropriate parameters is also possible by using physical simulations of welding processes performed by simulators of thermal and strain cycles; the simulators are becoming increasingly popular in tests focused on the weldability of steels. In specimens characterised by relatively small volumes, the above named simulations enable the formation of areas having homogenous microstructures and corresponding to particular areas in the HAZ of welded joints, thus making it possible to perform a variety of tests. Based on obtained results, it is possible to forecast the effect of welding conditions on HAZ properties without performing laborious and expensive tests involving actual welded joints. The possibility of subjecting specimens to stresses and strains at any moment of the thermal cycle makes the simulator a very useful tool when testing steels for their susceptibility to developing various cracks.

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