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Use of Welding Process Numerical Analyses as Technical Support in Industry
Part 2: Methodology and Validation

Abstract: Numerical analyses of production processes have proved useful and capable of obtaining significant savings. However, properly conducted simulations of technological processes require not only the appropriate adjustment of parameters, boundary conditions etc., but also need detailed input data in the form of databases of material properties. The input data mentioned above are decisive for the future conformity of results obtained in numerical simulations with results of actual welding or heat processing. This article, being the continuation of the cycle of information dedicated to numerical analyses of welding and heat treatment processes, presents possible variants of numerical analyses of these processes and exemplary stages of preparation of simulations as well as results of such simulations.

Keywords: numerical analysis, welding processes, numerical simulations

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Numerical Analyses of Welding Processes - Methodology

Presently used numerical analyses of welding processes are very modern and efficient engineering tools. One of the most advanced packages of such analyses is Welding Simulation Solution developed by Esi Group and containing Sysweld, Pam Assembly and Weld Planner modules [1].

Depending on a computational method selected, numerical analyses of welding processes can be divided into three groups differing in the type of a computational package, computational method and the range of results obtained using simulations (Fig. 1).

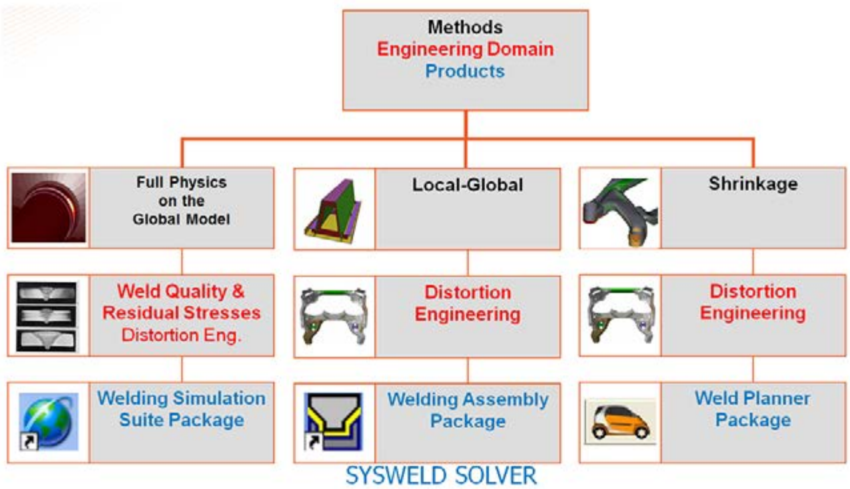

Fig. 1. Computational methods and tools in Welding Simulation Solution package developed by ESI Group`

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In accordance with the diagram presented in Figure 1, numerical analyses based on software developed by ESI Group can be divided into three, primary methods:

1. ***Continuous analysis of a welding process (transient welding – TW)*** also referred to as the "step by step" method using the Sysweld package. In this analysis, the model of a heat source moves along the line defining the trajectory of welding. In this case, parameters describing the model of a heat source are actual parameters of a welding process, i.e. current, arc voltage, welding rate or the heat efficiency of the method, i.e. data which can be found by an engineer in a Welding Procedure Specification (WPS). Calculations are performed for each successive moment increased by a pre-set time step. On the basis of previously gained experience, it can be stated that the maximum time step which can be adjusted without compromising test results is half the length of a liquid metal pool. Therefore, the time step will depend on the technique, rate and other welding parameters. The numerical analysis is divided into two parts, i.e. calculations of thermal phenomena and related metallurgical changes and mechanical phenomena (distributions of stresses and strains). Taking into consideration the necessity of calculating successive moments, the user obtains a large set of thermo-metallurgical and mechanical data concerning the process being simulated. The data-related calculations require time. For this reason, calculations based on the "transient" method are not appropriate when calculating large welded structures containing many welds. However, since the results of such analyses are very extensive (e.g. distributions of temperature fields as well as distributions of hardness, metallurgical phases, stresses and strains), this method is ideal for determining the local effects of a welding process and using them for optimising process parameters, primarily on the basis of results of the distribution of metallurgical phases, hardness and stresses in the weld area and in the partially melted zone.

The Analysis of greater elements or structures requires a certain modification of the "transient" technique, namely the "macro bead deposit" (MBD) method using the Sysweld package. In the MBD method, the heat source is used immediately in one or a few areas (elements) at the same time. Also, the actual trajectory of welding is divided into subareas - in order for welding sequence and directions to be maintained. Heat input to the weld is defined identically as in an actual welding process, i.e. in the form of a thermal cycle. The number of these subareas and the time step are defined on the basis of technological parameters of a welding process as well as on the basis of experience of a person using this method. To some extent, the methodology of MBD calculations is the extension of the "transient welding" method. MBD significantly reduces computational time and increases the possibility of numerical analysis of large and complicated structures while simultaneously maintaining the high conformity of results of such analyses with results obtained during actual welding.

2. ***"Local-global" (LG) method*** using the Sysweld and Pam Assembly packages is particularly important as regards numerical analyses of very large structures in the shipbuilding, automotive and heavy industries. In such cases, the standard computational technique ("transient method"), or even, in some cases, the MBD method may prove incapable due to restricted analysis times and limited computer storage. The primary idea behind the "local-global" technique is an assumption that a welding process leads to locally changed distributions of stresses and plastic strains resulting in a specific state of strains. In such a case, local effects of a welding process are determined using precise computational models of welded joints supported by the "transient welding" or MBD technique. However, it should be noted that the "rigidity" of local models must be very close to reality. This requirement necessitates the very precise determination of

boundary conditions in relation to the fixing of local models – in order to illustrate their location in the actual structure. The results of local analyses are then transferred to the global model (usually presenting the entire structure) – in order to determine total structural strains. The "local-global" method enables analyses of very large structures with many welded joints. However, the method is limited by the fact that results of analyses performed on a global model are only structural strain as well as internal forces and moments in specific fixing conditions. The level of stresses and the distribution of individual metallurgical phases is determined by local models obtained using "transient welding" or MBD analyses. The verification of results obtained using the "local-global" method has been performed and described in publications [2,3].

3. ***"Shrinkage method" (SM)*** utilises the Weld Planner (WP) package used for the fast analysis of strains in structures with a large number of welded joints. Calculations performed by the programme use the numerical analysis of shrinkage. This method consists in the calculation of the shrinkage of elements subjected to the effect of a welding thermal cycle, and next in determining the influence of a local shrinkage on strains of the entire structure. As regards this method, calculations of thermal phenomena and related mechanical changes are not performed; only results of the analysis of mechanical phenomena taking place during welding are used. Weld Planner enables the very fast determination of structural strains caused by a welding process as well as enables the very fast and effective development of a welding plan. The WP package also enables the determination of the manner and sequence of elements fixing and makes it possible to optimise the sequence of welding while maintaining determined dimensional deviations of structures. The Weld Planner user interface is characterised by operational simplicity and intuitiveness.

Numerical Analyses of Welding Processes – the Course and Additional Possibilities

Additionally, performing analyses using the TW and MBD methods can be divided into 3 stages which make it possible to prepare a material database and conduct numerical simulations of welding or heat treatment processes.

At the first stage, a complete CTT diagram for welding conditions is fed via a special Sysdweld module. This results in the obtainment of coefficients describing the kinetics of austenite transformations in relation to welding rates in individual areas of the HAZ. These coefficients depend on the temperature and metallurgical structure of a material and constitute input data to the second stage.

The second stage is a thermo-metallurgical analysis and requires the possession of complete thermo-metallurgical and thermo-physical data of the materials used in simulations. The analysis also uses the classical equation of thermal conduction taking into consideration the latent heat of transformation during the phase transformation and during the melting of metal. Additionally, a connection between phase transformations and thermal conduction is introduced. The results of this simulation stage include a non-stationary field of temperatures, the percentage distribution of individual metallurgical phases, the size of primary austenite grain and the distribution of hardness. The analysis of the distribution of temperature fields is performed at each moment in accordance with a pre-set time step. The proper completion of this stage and the obtainment of entire analysis results require that each time step should be subjected to analysis. For this reason, simulations based on the TW and MBD methods are time-consuming.

The results of the second stage of analyses (primarily the non-stationary temperature field) are used as input data at the third stage of numerical simulation – mechanical analysis. This part of the simulation also requires the possession of entire data related to mechanical properties. These data (thermal expansion coefficient, yield point, hardness, the Young module, etc.) are additionally dependent on temperature and individual metallurgical phases. This stage of the simulation results in the obtainment of information about mechanical properties in individual areas of an element being welded – on the basis of the distribution of individual metallurgical phases and their mechanical properties (e.g. entire strain (containing elastic, thermal, plastic and viscoplastic parts and plasticity triggered by phase transformations), distributions of stresses and strains of a structure being analysed).

After performing thermo-metallurgical and thermo-mechanical analyses, it is possible to pre-set external stresses in the form of forces, moments, pressure and temperature fields, and next, to perform an analysis taking into consideration the results of previous analyses, i.e. heterogeneous material structure, post-weld stresses and plastic strains. It is also possible to assess the fatigue life of a structure using the Van Dang fatigue criterion. An exemplary distribution of post-weld stresses and results of the fatigue life of a welded element, in accordance with the Van Dang criterion, are presented in Figure 2.

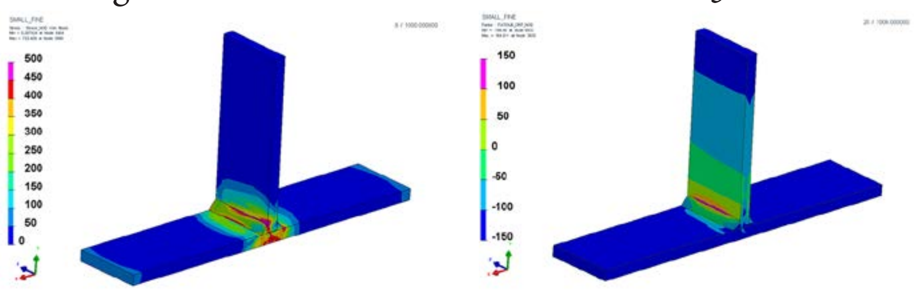

Fig. 2. Distribution of post-weld stresses and the result of high-cycle load analysis according to the Van Dang criterion

One of the most important input parameters of numerical analyses is the model of a heat source [2] representing heat input to a material during a welding process. The previously mentioned results of numerical analyses (related to post-weld stresses and strains) depend significantly on the development of a heat source model ensuring proper heat propagation. This non-stationary temperature field constitutes input data for the analysis of mechanical properties. The SYSWELD package is provided with a special tool named "heat source fitting" allowing easy heat source calibration by changing input parameters in a manner enabling the obtainment of results close to those of an actual process. The user can apply three pre-defined heat source models, i.e. in the form of a double ellipsoid (Goldak heat source), conical and of the Gaussian distribution. Each of these sources can move along a pre-defined straight line, curve and helix. Also, it is possible to define one's own heat source, i.e. the source which the user wishes to use in simulations.

An equally important factor affecting the correctness of results is the quality of input data related to material properties. Heating and cooling of a material is accompanied by phase changes, entailing significant changes of material properties. Therefore, in order to obtain proper results of the numerical analyses of welding and heat treatment processes, it is necessary to know the following data:

1. CTT diagram for welding conditions,
2. thermal conduction coefficient, specific heat, density
3. thermal expansion coefficient, yield point, material hardening (viscoplastic properties).

The obtainment of all data necessary for performing simulations of welding and heat treatment processes on the basis of existing reference publications is often complicated and in many cases impossible. The MECAS ESI company possesses its own internal database concerning approximately 50 various structural material including steels, aluminium and titanium alloys. The company is also intensively testing properties of new materials in order to extend the existing database of materials.

Numerical Analyses of Welding Processes – Validation

Experimental part

In order to obtain results of numerical analyses consistent with actual test results, it is necessary to verify a numerical method and input material data. The validation of such a process was performed within the framework of several projects conducted by Mecas Esi engineers [4-11]. Examples of activities performed in projects aimed to confront numerical models with actual results include, among others, the following:

a) preparation of new material databases,
b) preparation and description of heat sources (description of heat input) for selected welding technologies,
c) development of a methodology for conducting numerical analyses of phase transformations and the effect of a welding process on the hardness of selected materials,
d) development of a methodology for conducting numerical analyses related to strains of welded structures,
e) development of a methodology for conducting numerical analyses related to the formation and distribution of stresses in welded structures.

Each of the analysed cases involved comparisons of results obtained during an actual welding process and tests of welded joints with results obtained in numerical simulations both for small laboratory specimens and large industrial structures. Exemplary parameters subjected to comparisons were the following:

a) recorded and calculated thermal cycles,
b) dimensions of a liquid metal pool and of the Heat Affected Zone,
c) results of hardness measurements,
d) local shrinkage,
e) values of stresses.

The actual welding tests were performed using the following materials – 10GN2MFA, 15Ch2NMFA, X22CrMoV12-1, P92, S235, S355, 306L and 316L. The tests involved recordings of thermal cycles and measurements of joint deformations. The tests were conducted in a manner enabling the determination of the geometry and dimensions of beads and of the fusion line, dimensions and location of the HAZ as well as the hardness of each tested bead. Some specimens were also subjected to post-weld heat treatment.

The determination of material data also involved the use of a Gleeble simulator. The sequence of the tests assumed that the detailed numerical analysis of welding processes in accordance with a selected technology should be conducted first. The next phase involved the selection of critical areas and the recording of thermal cycles corresponding to them. Afterwards, the Gleeble simulator was used to determine material properties in precisely defined areas. The final step included the simulation of results.

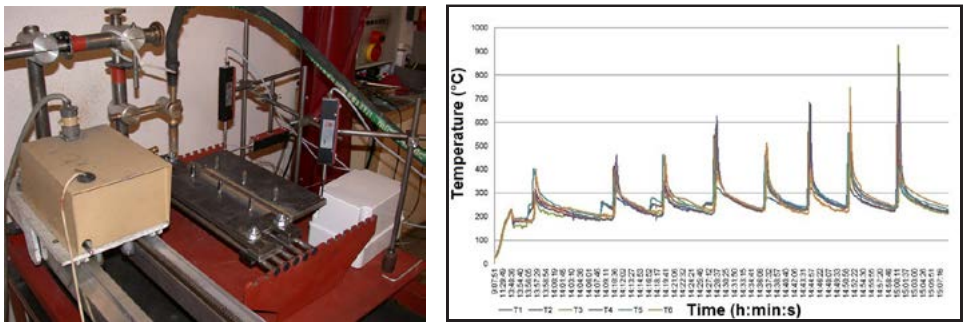

Fig. 3. Welding station used in tests and exemplary thermal cycles recorded when welding joints made of S355 steel

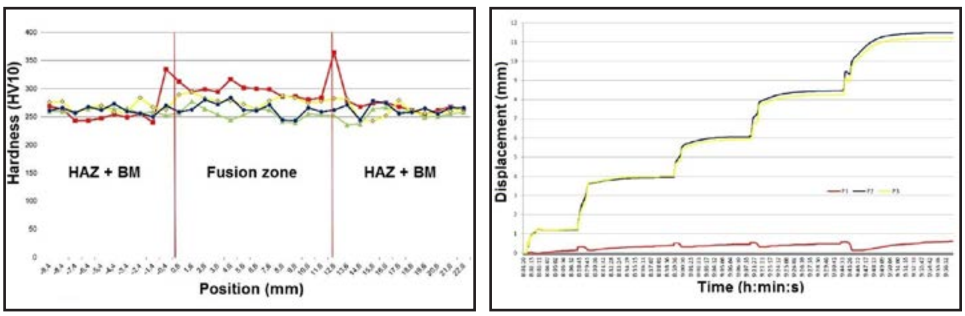

Fig. 4. Results of hardness and strains measurements of a tested joint

Table 1. Comparison of results related to measurement of welded joint strains with numerical simulation results

Bead	Simulation results [mm]		Actual measurements [mm]			
			test no. 1		test no. 2	
	Measurement point no. 1	Measurement point no. 2	Measurement point no. 1	Measurement point no. 2	Measurement point no. 1	Measurement point no. 2
1	0.49	0.40	1.01	1.07	1.19	1.23
2	2.97	2.91	3.62	3.63	3.86	3.90
3	4.21	3.86	5.70	5.45	6.02	5.85
4	6.38	5.92	7.45	6.81	8.38	8.23
5	9.16	8.71	9.12	8.02	11.35	11.10

The welding tests were performed in a manner enabling the determination of the shape of each bead - in order to use this information during the calibration of heat sources. The testing station enabled the recording of thermal cycles and the measuring strains. In addition, the welding process was followed by hardness measurements (Fig. 3 and 4).

Numerical Simulations - Validation

As mentioned before, data obtained during experiments can be compared with simulation results at the stage of calibration of the computational model parameters. Such analyses were performed for all the experiments referred to in the previous sub-section. In each case, the primary purpose of such an activity is the achievement of the high compatibility of analyses results with results obtained in actual welding conditions.

The problem is exemplified by numerical simulation results concerned with the welding of sheets made of S355 steel. Figure 5 presents one of the steps of calibration of a heat source model and the comparison of the actual welding process results with the numerical simulation result in the form of a distribution of temperatures.

The comparison of the distribution of strains of the welded joint with the values of strains obtained during the experiment demonstrates the high compatibility of the simulation and experimentation results (Fig. 4, Table 1). These strains correspond to the specific distribution of stresses, which due to the simulation applied, makes it possible to clarify the mechanism of strain generation and, at the same time, is very difficult to perform in actual experimental conditions, particularly, taking into consideration the fact that the numerical simulation enables tracking the evolution of strains during welding (Fig. 4).

The experimentation also involved the preparation of welded joints which were

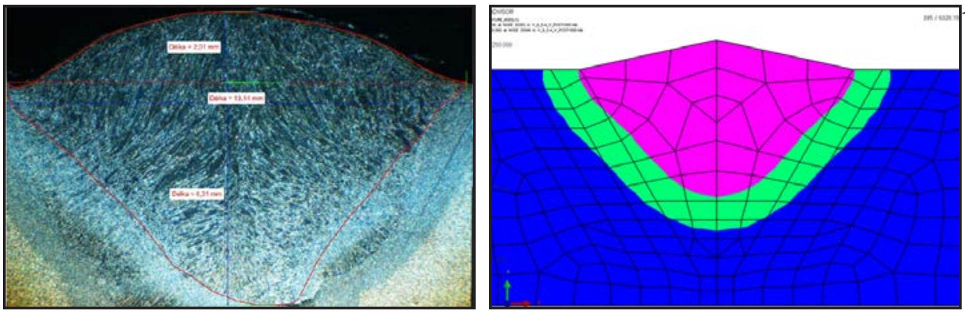

Fig. 5. Macrostructure of the butt joint bead made of S355 steel, the shape of the liquid metal pool corresponding to the macrostructure and the HAZ area during a numerical simulation

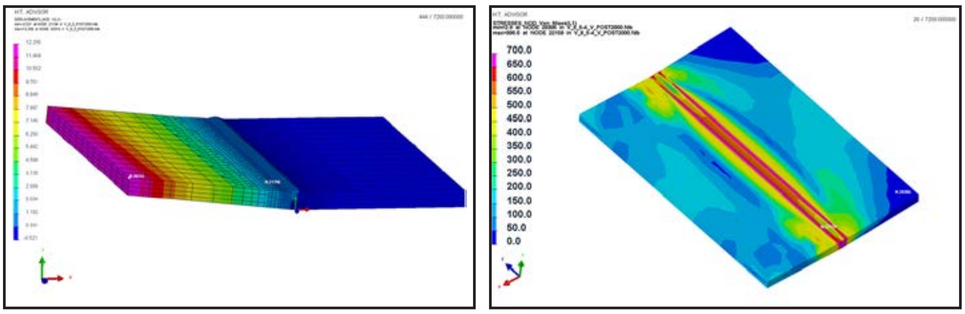

Fig. 6. Distribution of post-weld joint strains (left) and stresses (right)

Table 2. Comparison of stress values measured in a welded joint with numerical simulation results

Material: steel 10GN2MNFA	Actual measurement		Simulation result	
Type of heat treatment	σ_x[MPa]	σ_y[MPa]	σ_x[MPa]	σ_y[MPa]
hardening (water)	-695	-773	-630	-736
hardening (oil)	-150	-140	-98	-114
outdoor cooling	25	94	42	53
hardening (water) + PWHT 500°C/1 hour	-241	-198	-196	-183
hardening (water) + PWHT 500°C/2 hours	-180	13	-131	-21
hardening (water) + PWHT 500°C/4 hours	25	18	43	-3
hardening (water) + PWHT 500°C/8 hours	96	87	77	65
hardening (water) + PWHT 640°C/4 hours	8	15	18	-5
hardening (water) + PWHT 680°C/4 hours	15	-5	12	15
Material: steel SA-336F22V	Actual measurement		Simulation result	
Type of heat treatment	σ_x[MPa]	σ_y[MPa]	σ_x[MPa]	σ_y[MPa]
hardening (oil)	-259	-250	-273	-232
hardening (oil) + PWHT 610°C/2 hours	-92	-59	-71	-43
hardening (oil) + PWHT 410°C/3 hours	-101	-97	-160	-134

Note: σ_x, σ_y – longitudinal and transverse stresses
PWHT – post welding heat treatment

next subjected to various post-weld, heat treatment procedures. The level of post-weld stresses was determined in the central part of the sheet, using the magnetoelastic method of the Barkhausen effect [12]. The cases tested were also simulated in the SYSWELD software programme. Table 2 presents the comparison of results obtained in stress measurements with results obtained during numerical simulations.

Summary

Numerical simulations of welding processes are modern and efficient tools, particularly at the design stage, for controlling and optimising production processes in today's industry. Numerical calculations allow flexible changes in technological processes and make it possible to reduce the number of tests, significantly decreasing costs, increasing the quality and prolonging the fatigue life of welded products and structures, making them more competitive on the market. However, it should be noted that in order to obtain the high quality of numerical analyses, it is necessary to possess a large number of input data (material properties, description of boundary conditions, etc.), which are not always easy to obtain and verify. The primary purpose of this article was to present a methodology for verifying experiments and results of numerical analyses as well as input data used in simulations.

This objective required the presentation of an experimental process of obtaining input data in the form of thermal cycles, distribution of strains in selected areas, determination of sizes and shapes of liquid metal pools, and of the HAZ, based on macrostructural tests, hardness measurements etc. Such data are subjected to calibration in numerical analyses in order to remove interference introduced by some input data. The primary purpose of such an activity is to obtain data close to the results of tests performed on testing stations. This creates the possibility of obtaining high quality input data for numerical analyses (model of material properties, description of heat transfer method, description of heat input during welding, etc.). With such a set of input data, verified numerical simulations are entirely useful tools for obtaining highly valuable results concerning both a single welding process and complex welding works when making large structures.

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