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The evolutionary optimization of selected welded structures

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Analysis and modelling

ABSTRACT

Purpose: of this paper is to present the recent possibility of evolutionary optimization method application to predicting the proper welding parameters in the weld process. The objective of the welding simulation is to study the temperature generated during the welding process and to investigate residual stresses in the component after the welding. Such results give the possibility to determine stress and strain state of welded parts and properties of materials in welding zones. From other side it gives the possibility to perform optimization process looking for welding parameters (welding speed, welding power source etc.) or initial shape of welded sheets according to displacement state (welding of thin metal sheets with stiffeners – T joints). Those results are the base for fatigue analysis too.

Design/methodology/approach: In the paper the foundations of FEM simulation of welding process are presented. Also a grid based evolutionary optimization of welding parameters influences on strength parameters in the heat affected zone (HAZ) is shown. Numerical simulation of a welding process using the finite element method is applied.

Findings: Results for coupled thermo-mechanical problem are prescribed. Two examples, the grid based evolutionary optimization of HAZ parameters and grid based evolutionary optimization of T-joint component deformation, illustrate the possibility of computational simulation and optimization of welding are presented.

Practical implications: Computational simulation and evolutionary optimization give a lot of information very important for engineers. An undesirable side-effect of welding is the generation of residual stresses and deformations in the component and the quality of the weld has a substantial impact on the fatigue life of the structure. These resultant deformations may render the component unsuitable for further use.

Originality/value: The presented the grid based evolutionary optimization procedure is a new tool for better understanding and predicting the welding behaviour from the thermo-mechanical process point of view. It gives the possibilities to optimize main welding parameters in order to achieve better structures, taking into account nearly full set of welding parameters, temperature dependent material parameters and simulating the coupled thermo-mechanical problem.

Keywords: Computational welding; Evolutionary optimization; Finite element calculationl; Coupled thermo-mechanical problem

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1. Introduction

Welding is one of the most commonly used join process but till now it is still difficult to simulate it in standard CAE systems based on finite element method. In most of them this requires the writing of specialized, additional user subroutines for specific boundary conditions (a heat source, a weld path, a filler element treatment, a material behaviour etc.) what makes it difficult and inconvenient in use. It causes that the simulation of welding is extremely difficult.

From other side such a simulation gives a lot of information very important for engineers. An undesirable side-effect of welding is the generation of residual stresses and deformations in the component and the quality of the weld has a substantial impact on the fatigue life of the structure [1,2,3]. These resultant deformations may render the component unsuitable for further use. Also, the residual stresses form the input for subsequent manufacturing or structural processes.

The objective of the welding simulation is to study the temperature generated during the welding process and investigate residual stresses in the component after welding. Such results give the possibility to determine properties of materials in welding zones and stress and strain state of welded parts [4,5].

The welding process simulation allows foreseeing effects of thermal cycle on a microstructure of HAZ, what is crucial for strength parameters of this zone. One of the most important parameter is cooldown rate t8\5 (the cooling period from 800°C to 500°C). On the base of a t8\5 graph it is possible to determine a basic strength and plastic properties of the a heat-affected zone (HAZ) in welding joint. Finding the optimal value of t8/5 can be one of goals of simulation and optimization of the welding process [6,7].

Obtained results can be also the base for optimization process of welding parameters for e.g. thin metal sheets with T stiffeners, where the folding often exist (cars body, airplane panels, shipbuilding, frame construction), for welding the tubes in the cooling structure of boiler accessories and for a fatigue analysis of welded structures [8].

Welding simulations are the base for optimization process of welding parameters for obtaining the required strength parameters in welded parts. Simulations are time consuming and an optimization using the standard procedures is very difficult but the parallel or distributed calculations give expected results in acceptable time. As the evolutionary algorithms cooperate very good with this techniques and allow to freely define the fitness function based on the complicated parameters they are often chosen as the optimization method.

In the paper the application of grid based evolutionary optimization technology [9,10] is presented. The welding parameters (velocity, source power, cooling temperature and time, shape of the source, heat input, weld flux etc.) are coded by chromosomes genes. The fitness function can depends on a cooling time in selected point of HAZ or stresses and displacements for process parameters described by chromosome.

The connection of welding process simulation and evolutionary optimization gives the new possibility in simulation of welding processes.

2. FEM simulation of welding process

Welding is a thermal process with specialized boundary conditions connected with high temperatures, fast heat input to the body, moving heat source and a desire course of cooling down.

It is the complicated multiphysics process from the computational point of view.

The computational welding method have been strongly developed during past 10-15 years. They introduce to computer simulation more and more descriptions of processes occurring during welding connected with heat transfer and mechanical behaviour. Most of them are based on finite element method [11]. They cover the topics of computational modeling of welding processes in general [4,5], modeling of specific welding processes, influence of geometrical parameters, heat transfer and fluid flow during welding [12,13], residual stresses and deformation in welds [1,2], fracture mechanics, fatigue of welded structures [3], welds in plates and other structures and components.

In the FEM modelling all parameters should be taking into account in order to obtain the exact solution and needed information. It is now possible to precisely simulate the welding process in some of CAE systems based on finite element method. It should be mentioned that full set of welding parameters and material temperature dependent data can be now considered during simulation and optimization. Those parameters are: moving heating source, velocity, source power, cooling temperature and time, shape of the source, heat input, weld flux and Young's modulus, coefficient of thermal extension, specific heat, conductivity etc [6].

The main parameters of welding process (shape of the source, velocity, power, etc). are modelled by weld flux and weld filler and the problem is solved as the coupled thermo-mechanical problem.

Welding heat input can be specified through:

- modelling the heat input as a spatially varying distributed flux applied to the base metal and filler elements or
- modelling the heat input as a spatially varying temperature boundary condition applied to the nodes of filler elements.

Weld flux is modelled as a disc shaped surface heating source or a double ellipsoidal shaped volume heating source according to the Pavelic's model or Goldak's model [14]. The more useful is Goldak's double ellipsoidal shaped weld heat source model, which can be used to specify volume fluxes in 2-D and 3D (Fig. 1).

$$q_f(x,y,z) = \frac{6\sqrt{3} f_f Q}{abc_f \pi\sqrt{\pi}} \exp\left(\frac{-3x^2}{a^2}\right) \exp\left(\frac{-3y^2}{b^2}\right) \exp\left(\frac{-3z^2}{c^2}\right) \quad (1)$$

$$q_r(x,y,z) = \frac{6\sqrt{3} f_r Q}{abc_r \pi\sqrt{\pi}} \exp\left(\frac{-3x^2}{a^2}\right) \exp\left(\frac{-3y^2}{b^2}\right) \exp\left(\frac{-3z^2}{c^2}\right) \quad (2)$$

where q_f and q_r are the weld flux rates per unit volume in the front and rear weld pools respectively; $Q=\eta VI$ is the applied power; a is the weld width along the tangent direction x; b is the weld penetration depth along the arc direction y; c_f and c_r are the forward and rear weld pool lengths in the weld path direction z; f_f and f_r are some dimensionless factors [1].

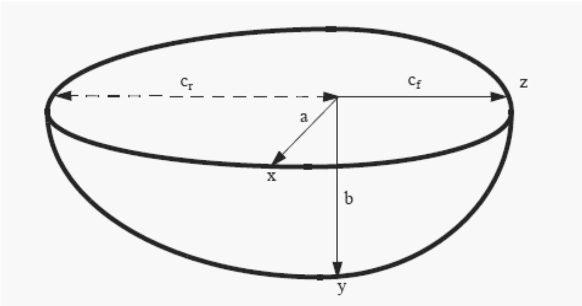

Fig. 1. Double ellipsoidal weld flux Goldak's model

The characteristics of temperature dependent material parameters (Young's modulus, thermal extension coefficient, specific heat, conductivity, etc).) are taken into account during the simulation.

It gives a possibility to increase significantly the thermal conductivity for high temperatures to model stirring effect in molten metal. Also, latent heat of solidification and solid-solid phase transformation capability can be considered here.

2.1. The arc welding simulation

As the simulation object the welding of two plates with MAG technology is considered. The dimensions are 300x150x5 mm. The plates and filler are discretized using 8-noded brick, the discrete model is presented in Fig. 2. The average global element length is about 1 mm. The filler is modelled as "dynamic" elements, which arise in the model with moving heat source. The filler and plates are modelled as the contact body.

Plates are fixed in the Y direction on the bottom faces and in XZ direction on free edges as shown in Fig. 2. All nodes have initial temperature 30°C. A face film boundary condition is applied to all the exposed faces of plates (sink temperature is 30°C, the film coefficient is taken as 0.02 N/mm^2/sec/°C).

As the welding boundary condition the volume weld flux and weld path are applied. Volume weld flux with a proper dimension of heat source is described in the vicinity of a filler material. Weld path is modeled as an adequate curve. In this model the heat input is modeled as a spatially varying temperature boundary condition applied to the nodes of filler elements. The melting point temperature is set to 1500°C and the welding speed is 1.33 mm/s.

The material properties (Young's modulus, thermal extension coefficient, specific heat, conductivity) are temperature dependent (Fig. 3).

Basic results obtained from simulation are: stresses, displacements and temperature distributions in welded parts. The temperature distribution obtained during the simulation after time t=38 s and t=76 s is presented in Fig. 4 and von Mises stresses are presented in Fig. 5. Using the special postprocesing tools it is possible to determine the temperature in each node in any time of the simulation.

The welding process simulation allows foreseeing effects of thermal cycle on a microstructure of HAZ, what is crucial for strength parameters of this zone. One of the most important parameter is cooldown rate t8\5. On the base of a t8\5 graph it is possible to determine a basic strength and plastic properties of the welding joint (Fig. 6).

Simulating the welding process the cooldown rate t8\5 can be determined for every point in the structure. Below in the Fig. 7 the cooldown rate for selected node in the HAZ is presented.

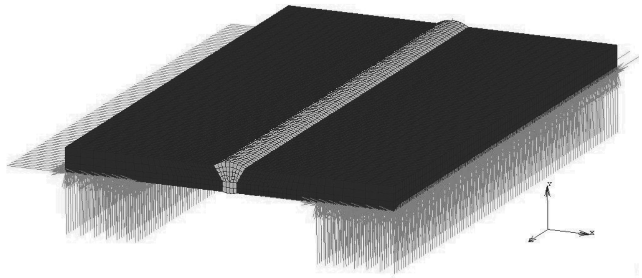

Fig. 2. FEM model and boundary conditions

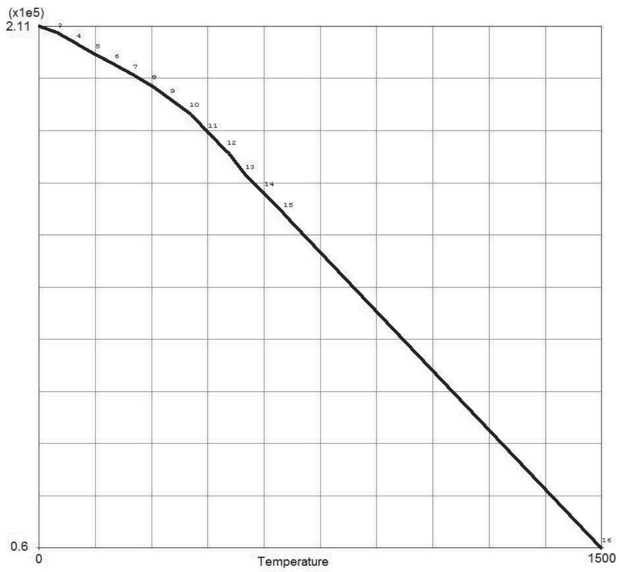

Fig. 3. Temperature dependent material parameters - Young modulus

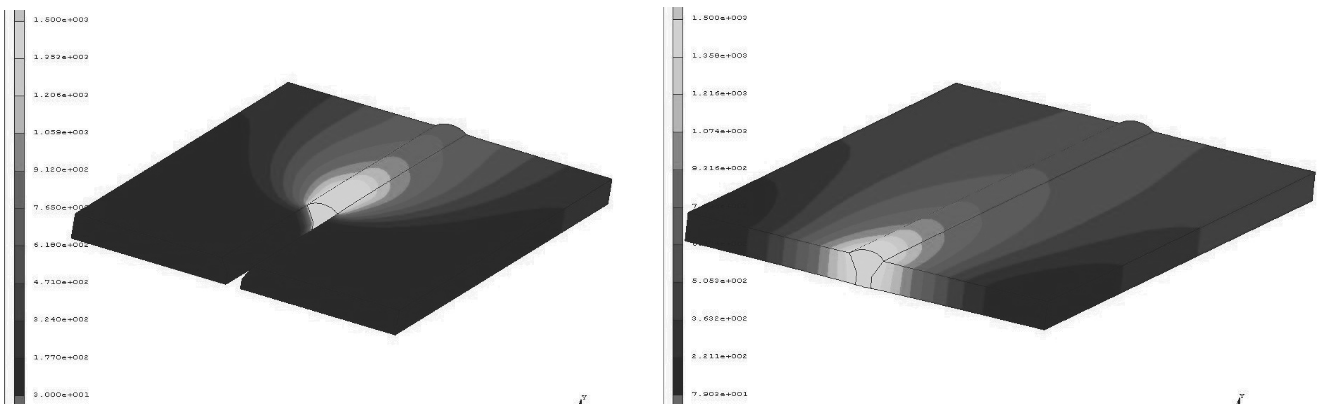

Fig. 4. Temperature distribution after t=38 s and t=76 s

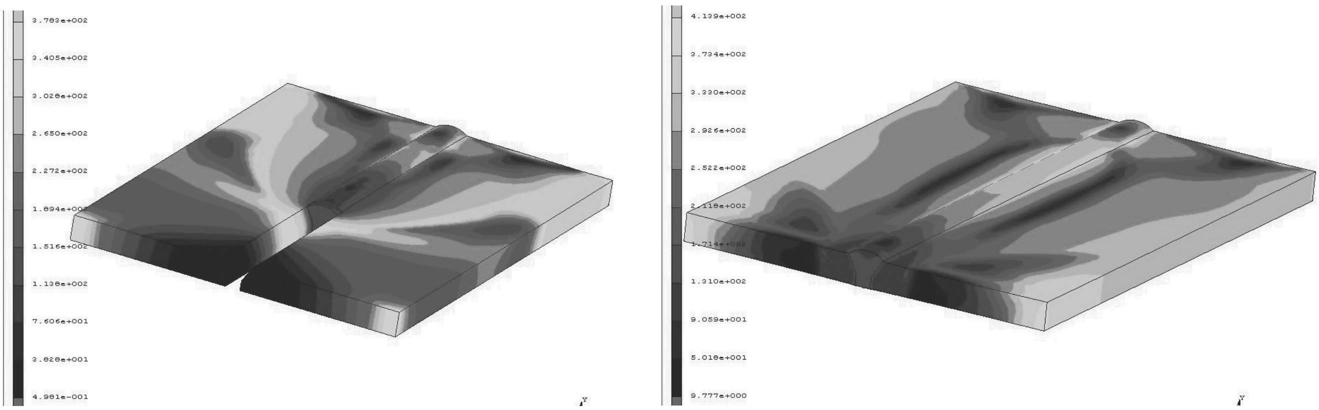

Fig. 5. Von Misses stress distribution after t=38 s and t=76 s

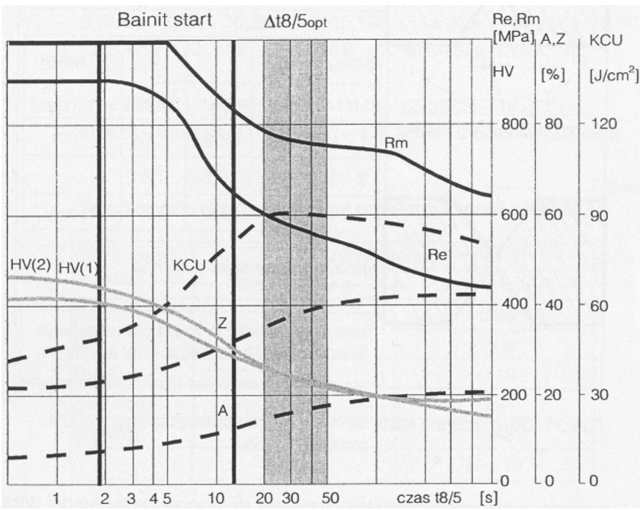

Fig. 6. Strength parameters via t8\5

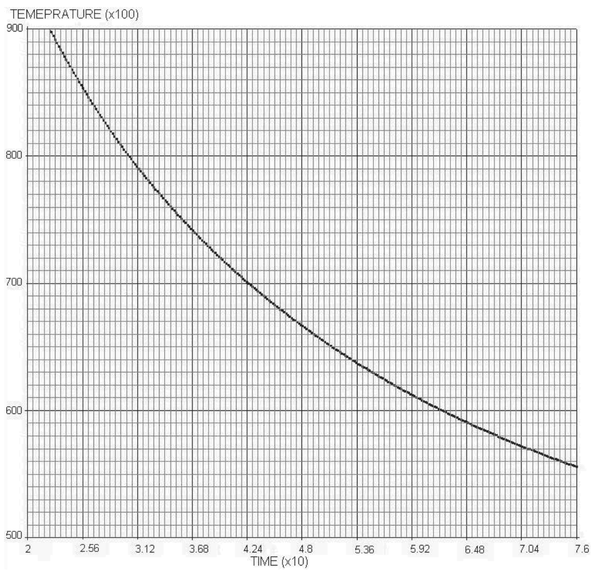

Fig. 7. Cooldown rate t8\5 diagram for selected node

3. The evolutionary algorithm and grid based calculations

The genetic and evolutionary algorithms (EA) [15] are based on mechanisms taken from biological evolution of species. The selection based on the individual fitness, mutations in chromosomes and individuals crossover are adopted. The genetic algorithms operate on binary coded chromosomes. The term evolutionary algorithm is more widely used for different modifications of genetic algorithms (also for algorithms operating on genes containing floating point numbers). The evolutionary algorithms operate on a population of individuals. The individuals contain one chromosome in most cases. The following description concerns the evolutionary algorithm used in numerical examples. The staring population is created randomly. Next the fitness function values are computed for each chromosome. The selection chooses chromosomes for a new parent subpopulation taking into account fitness function values. Evolutionary operators change chromosomes' genes and create chromosomes for the offspring population. The uniform and Gaussian mutations and the simple crossover are randomly chosen to perform chromosome changes.

The new chromosome are evaluated. The algorithm works iteratively till the end optimization condition is fulfilled. The flowchart of evolutionary algorithm is presented in Fig. 8.

Particularly evolutionary algorithms as the genetic algorithms (GA), evolutionary programming and strategies are often used in solving optimization problems. Those methods are widely applied in many fields for solving search and optimization problems, but using them in solving practical mechanics problems is still rare. As the results of the research on applications of the evolutionary methods in optimization of mechanical structures, new approaches of the evolutionary optimization is proposed. It allows solving a large class of optimization problems of continuous mechanical structures concerned with welded structures. The aim of the paper is to present an evolutionary approach to optimization of welded structures.

The main difficult step especially for mechanical problems is evaluation of the fitness function value. For the optimization of the welded structure the fully coupled thermo-mechanical simulation have to be performed many times.

The fully coupled thermo-mechanical simulation on standard workstation takes long time. It can be acceptable for single simulation but in optimization problems the hundreds or sometimes thousands of analyses should be performed.

The grid calculation are applied in order to speed up the calculations. The grids are build from distributed computer resources connected using fast networks [16]. The grids are created on the base of computational resources distributed in departments, universities and also companies. The high security standards and ability to identification and creating policy for users are implemented in grids. The grid based on Alchemi framework is used in the paper [17]. The modified evolutionary algorithm [9,10] is presented in Fig. 9. The fitness function evaluation is performed in parallel way. The grid allows us to use remote computers during optimization process. The maximum speedup of computations is equal to number of chromosomes in population. The communication between fitness function evaluators is not needed and this allows to use remote computers even only slow connection between them exists. The Alchemi is build form coordinating node Alchemi manager and working nodes Alchemi executors. The Alchemi manager can access Alchemi executors but also other, remote Alchemi managers. The manager manages queue of jobs and in our case decides on which computer the fitness function should be evaluated.

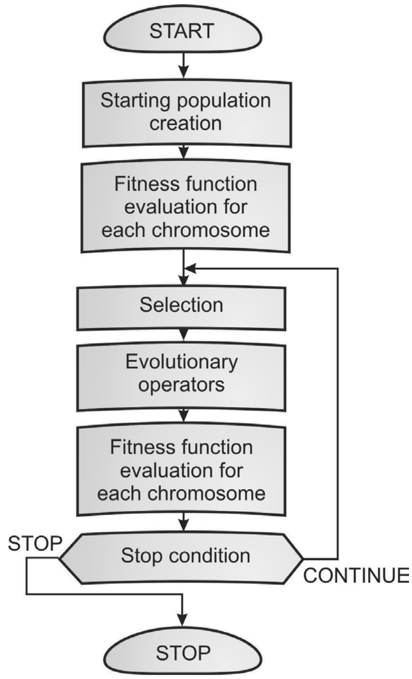

Fig. 8. The evolutionary algorithm flowchart

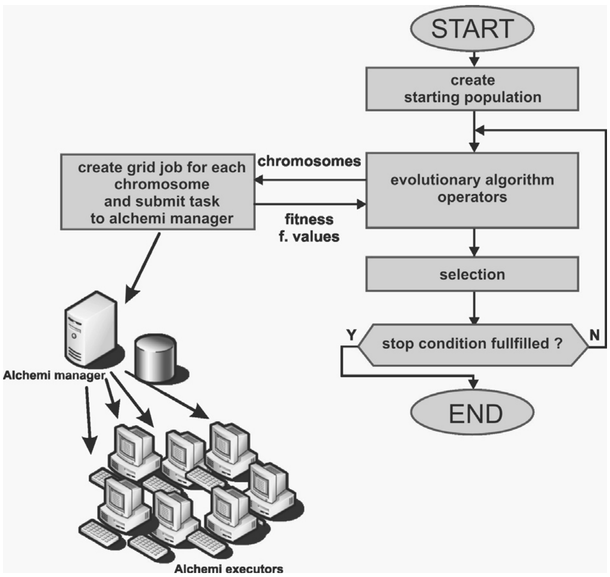

Fig. 9. The grid based calculations

4. Evolutionary optimization of selected problems - examples

4.1. The evolutionary optimization of HAZ parameters

In welding, the so-called cool down rate t8\5 (Fig. 6) is one of the most important parameter and the possibility to determine them in the simulation is very helpful from practical point of view. On the base of this graph it is easy to determine and construct strength and plastic properties of the welding joints. Searching the proper welding parameters will be the goal of the optimization process.

The optimization goal is to find the proper welding parameters as welding speed, face film value, preheating temperature in order to obtain the best strength parameters in HAZ.

The optimization goal is to find the proper cooldown time providing the best strength parameters in HAZ for the welding of two plates. As the example object the welding of two plates with MAG technology is considered as in paragraph 2.1 (Fig. 10).

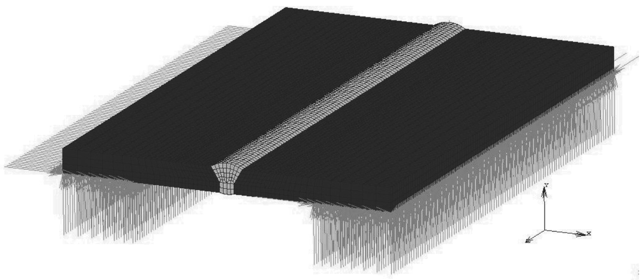

Fig. 10. FEM model and boundary conditions of two welded plates

The optimization goal is to find the welding parameters giving the optimal t8/5 time between 20-50 s, with respect to stresses in the components:

t8/5 = <20s,50s> σ <250 MPa

The chromosom consists of:

(ch)=[weld speed, face film value, welding power]

and the fitness function is defined as:

$$F(ch) = p + \frac{1}{n_{t8/5}} \sum_{1}^{n} t_t \tag{3}$$

$$t_t = \begin{cases} t_{8/5} - 20 & if \quad t_{8/5} > 20 \\ 50 - t_{8/5} & if \quad t_{8/5} < 50 \end{cases}$$

$$p = t_s \cdot n_b \tag{4}$$

where: t_t - transition time;
p – penalty;
t_s - analysis time;
n_b – number of nodes without $t_{8\backslash 5}$.

Using the evolutionary optimization procedure combined with the grid computation the results presented on the Fig. 11 were obtained.

4.2. The evolutionary optimization of T-joint component deformation

The second example is connected with so-called T joint of the metal panels (Fig. 12). This structure is often used as cars body, airplane panels, in shipbuilding, frame construction etc. Welding of a thin plates is often connected with a folding of them. Numerical optimization, can be helpful in avoiding this problem.

The optimization goal is to find optimal welding parameter such that the displacement of a free edge is below 0.2 mm:

displacement < 0.2 mm

The chromosome consists of:

(ch)=[weld speed, face film value, welding power]

and the fitness function is defined as:

$$F(ch) = \min \frac{1}{n} \sum^{n} y_n \tag{5}$$

where: y_n - node displacement
n - number of nodes on the free plate boundary

Results of optimization are presented on Fig. 13. Founded optimal welding parameters secure during welding that the folding will be reduced to the acceptable state.

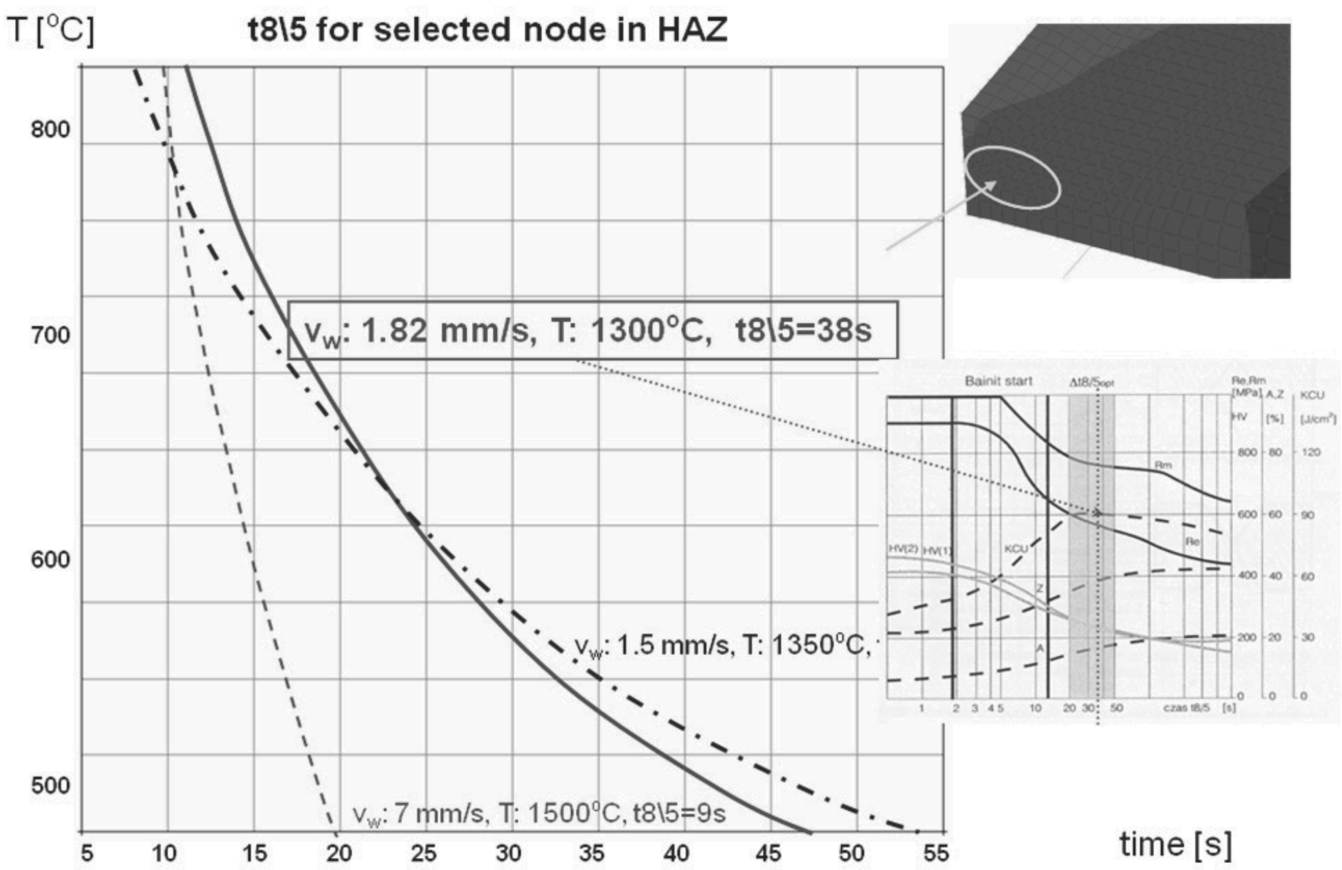

Fig. 11. The results of evolutionary optimization of HAZ parameters

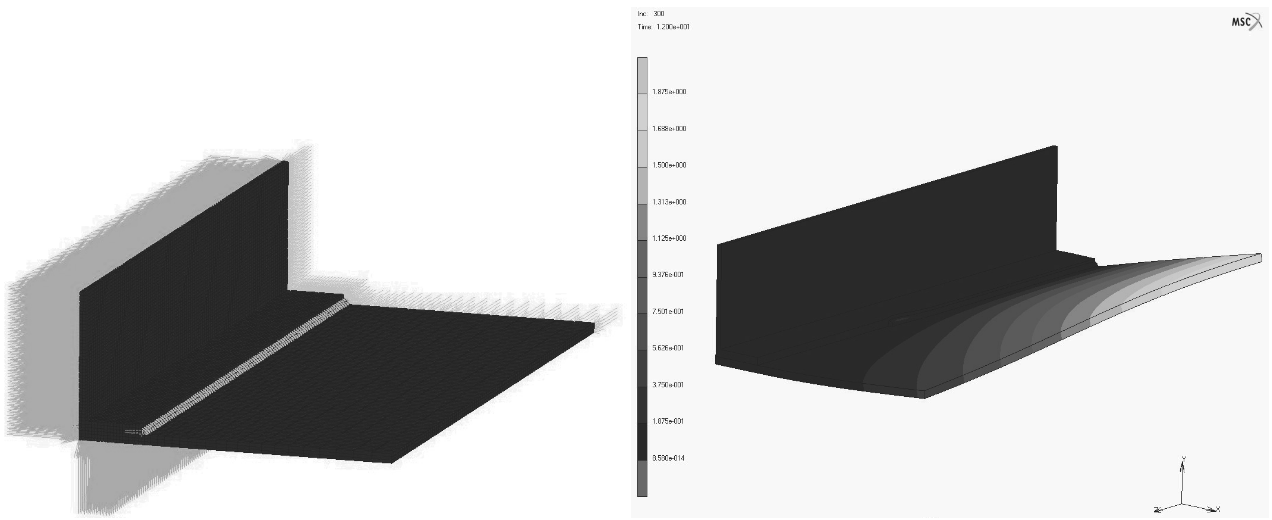

Fig. 12. T joint of panels and folded state after welding

a) b)

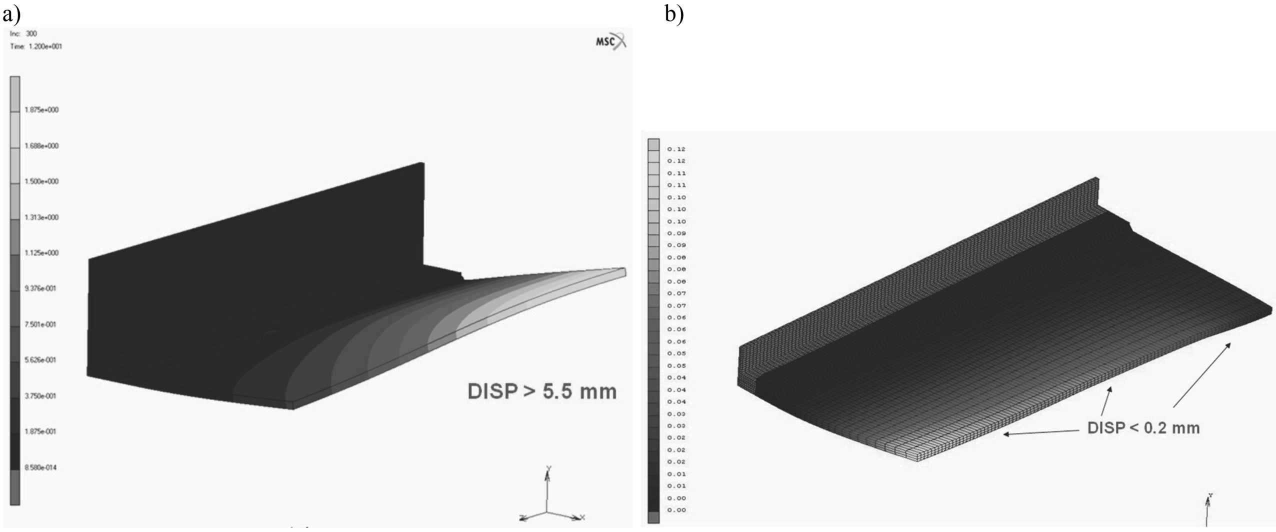

Fig. 13. Results of optimization of the T-joint of the panels: a) folding state before optimization and b) after optimization

5. Conclusions

The large progress in development of computational welding is observed during last 10-15 years, but using the evolutionary optimization in this topics is still rather rare. Most of optimisation procedures are based of classical optimization methods [18,19,20], but applying them to solve the complicated multiphysics optimization problem has many disadvantages. In this paper the evolutionary approach connected with the parallel computing is proposed.

Using advanced CAE systems connected with parallel and grid based evolutionary computing it is possible to perform an advanced complex simulation of welding process and analysis of welded parts. It is possible to perform: a static linear analysis of welded components, a coupled thermo-mechanical simulation of welding process, an optimization process of welding parameters.

In this area there is no so advanced evolutionary optimisation technology applied yet.

This paper presents the test of a grid based evolutionary optimization of welding parameters influences on strength parameters with adequate numerical results.

The connection of the welding simulation and the optimization process gives the new possibility in simulation of welding processes.

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