# Experimental solution heat tasks welding of non-ferrous metals and verified numerical simulation

**Helena Kravarikova**

Slovak University of Technology, Faculty of Materials Science and Technology,
Institute of Production systems and Applied Mechanics, Department of Mechanics
helena.kravarikova@stuba.sk

Corresponding Address: Helena Kravarikova, MTF STU in Trnava Paulinska 16, 917 24 Trnava, Slovak Republic

**ABSTRACT**

Examination of temperature fields in fusion welding process is a fundamental solution to the problem in developing weld ferrous metals. Produced welds must meet the required mechanical properties such as strength, toughness and stiffness. For this reason, most study area is the area in the immediate vicinity of the welded joint, the heat effected zone (HAZ). In the HAZ due to the melting of material to be welded and the filler material admixture occurs if the structure is changed. Changing the structure of the material can cause changes in physical and mechanical properties, which may result in a change of strength and may be the destruction of the weld joint. For this reason, it is important to study formation of thermal field and their maximum temperatures that characterize the shape and size of the HAZ.

Solution tasks heat in welding non-ferrous metals was carried out in two different ways. The first way to solve temperatures generated during welding was the realization of a classic experiment. In real experiment, the temperature measured by thermocouples at selected type of the experimental sample to be of aluminium. The process of aluminium welding method was GTAW, which correspond to the major welding parameters. Subject to the conditions of the welding process in a protective gas atmosphere has been addressed and the role of thermal numerical simulation. Solving problems by FEM was as non-stationary and non-linear. Results obtained in the course of the investigation of temperature in the weld and close during the course of the welding process is divided into two parts. The first part provides a graphical view results in real experiment. The second part contains the results of numerical simulations obtained using ANSYS.

**Keywords:** FEM, HAZ, thermo-physical properties, thermal field, welding parameters, numerical simulation

## 1. INTRODUCTION

Wide range of used non-ferrous metals is processed for a selected group of materials used in engineering production processes. In terms of world consumption is currently the most widely used non-ferrous material is aluminium, which is included in the group of light non-ferrous metals. In our case, we opted for the solution of aluminium experiment. Aluminium has a very strong position in the automotive industry. Since aluminium has a very wide application in the automotive industry , which uses methods of fusion welding method, therefore, we conducted an experiment examining the thermal cycle and changes in the shape of experimental samples in the process of hot-melt welding method. To implement the weld joint we choose fillet weld. Of producing weld technology we chose shielded welding. Experimental solutions heat tasks weld ferrous metals was to solve real experiments and numerical simulation using FEM.

## 2. CONDITIONS DURING THE EXPERIMENT

The experimental sample was prepared from technical sheet aluminium of a thickness of 1,5 mm, a width of 100 mm and a length of 200 mm. Geometrical shape is show of Figure 1. Dimensions of the experimental samples were sufficient for stable welding process and width of HAZ.

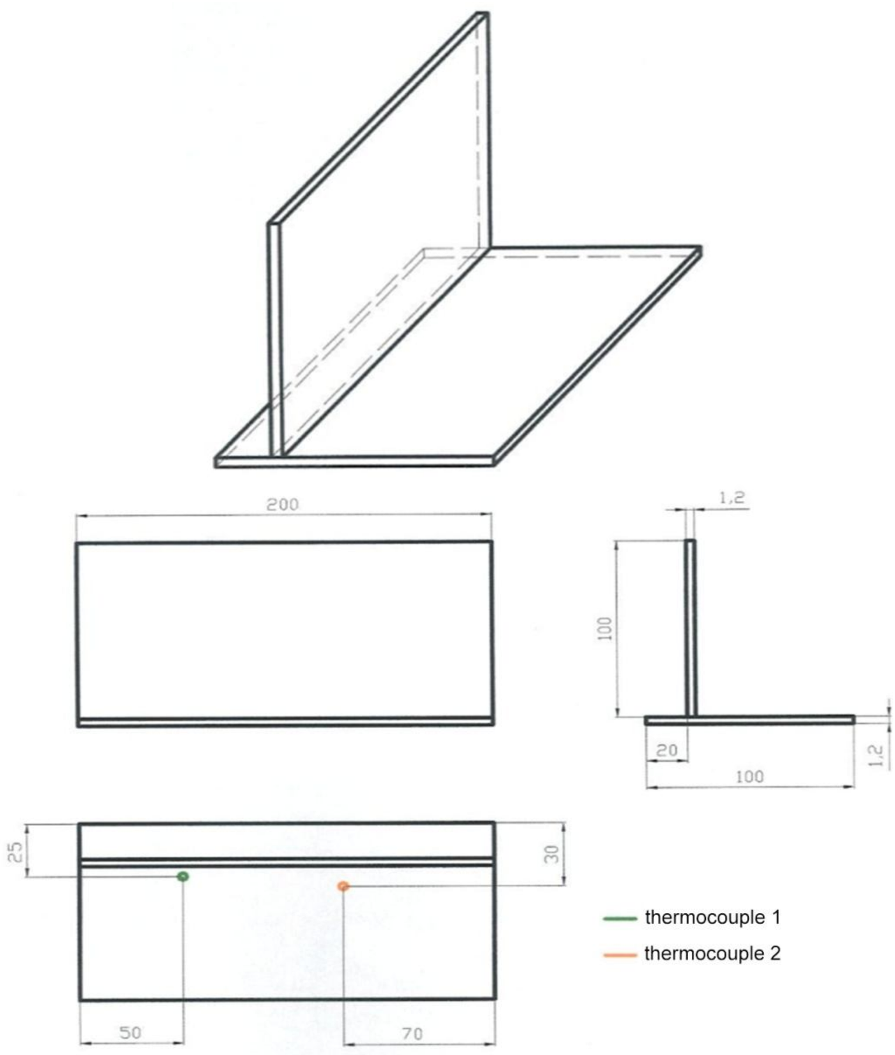


Fig. 1 Geometric shape and dimensions of the experimental samples

To obtain heat during welding were run two thermocouples type K. Thermocouples were connected to the measuring device that writes the measured values directly into the computer at a set time step.

Aluminium is a metal that is a very good electrical and thermal conductor. Density of aluminium is 2790 kg.m$^{-3}$ and its melting temperature is 660$^{o}$C. Crystallizes in a face cubic lattice, which predetermines its good formability. Of the air is relatively stable and relatively quickly covered with an oxide layer having a protective effect against further oxidation. The chemical composition of technical aluminium is given in Table 1, [5].

Table 1: The chemical composition of technical aluminium

| The chemical composition | Si | Fe | Cu | Mn | Mg | Zn | Ti | others |
|---|---|---|---|---|---|---|---|---|
| [weight %] | 0,06 | 0,17-0,25 | 0,1 | 0,005 | 0,02 | 0,02 | 0,002 | 0,01 |

Mechanical properties of the weld, especially strength must be the same as the welded material was therefore used additional material type AlSi12. The chemical composition of the additive material is given in Table 2, [5].

Table 2: The chemical composition of the additive material

| The chemical composition | Si | Fe | Cu | Mn | Mg | Zn | Ti | others |
|---|---|---|---|---|---|---|---|---|
| [weight %] | 10,5 – 13,5 | 0,3 | 0,03 | 0,001 – 0,4 | 0,05 | 0,15 | 0,15 | 0,01 |

For welding aluminium sheet 1,5 mm thick GTAW method of alternating current were selected as welding parameters:

- continuous welding current $I$ = 54 A,
- the mean voltage during welding $U$ = 8.1 V,
- protective atmosphere gas flow rate $Q$ = 12 l min$^{-1}$,
- average speed welding was $w$ = 1 mm.s$^{-1}$.

As a protective atmosphere of Argon gas was used. The experiment was implemented at ambient temperature 20°C.

## 3. NUMERICAL SIMULATION OF THERMAL TASKS THE WELDING PROCESS

Numerical simulation solution temperature fields by FEM, is more frequently used as a real experiment. In our case, we used modeling to verify the results of our experimental solution. Because the numerical simulation for verification of the results, because the modeling must be maintained all the conditions under which the experiment was conducted.

### 3.1 The basic differential equation of heat conduction

Heat flow introduced into the base material during the welding process is a moving heat source at a constant rate and produces a temperature field. Temperature field is the geometric instantaneous temperature in the examined material, which is represented by isothermal surfaces or lines (1). For the investigated problem can generally express temperature field equations of the form [1, 2, 4]:

$$T = f\,(x,y,z,t) \qquad [\mathrm{K}] \qquad (1)$$

Differential equation of heat conduction Fourier-Kirchhoff is formulated on the basis of the law of conservation of energy, in rectangular Cartesian coordinates has the form [1, 2, 4]:

$$\rho . c_p \frac{DT}{Dt} = \frac{\partial}{\partial x}\left[\lambda_x \frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda_y \frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[\lambda_z \frac{\partial T}{\partial z}\right] + \dot{q}_v(x,y,z,t) \qquad [\mathrm{W.m^{-3}}]$$

(2)

Where:

$\lambda$ [Wm$^{-1}$K$^{-1}$] – the coefficient of thermal conductivity of the coordinate axes $x$, $y$, $z$,
$\rho$ [kgm$^{-3}$] – density,
$c_p$ [Jkg$^{-1}$K$^{-1}$] – specific heat capacity,

$T$ [K] – temperature,
$DT/Dt$ – substantial derivative temperatures,
$q_v(x, y, z, t)$ – internal volumetric heat source.

For solid body material homogeneity can be differential equation of heat conduction Fourier-Kirchhoff written in the form [1, 4]:

$$\frac{\partial T}{\partial t} = a\left(\nabla^2 T + \frac{\dot{q}_v}{\lambda}\right) \qquad [\mathrm{K.s^{-1}}]$$

(3)

Where:
$\nabla^2$ is Laplace operator,
$a$ [$\mathrm{m^2.s^{-1}}$] thermal diffusivity.

A necessary and sufficient condition for the solution of the differential equation of heat conduction is to determine boundary conditions. Boundary conditions III. type shape (4), expresses the connection Fourier law for heat conduction and Newton's law of convection to the total heat transfer coefficient. Is the coefficient of heat transfer of heat by convection and radiation, [1, 4]:

$$\lambda\left(\frac{\partial T}{\partial n}\right)_s = h_k(T_s - T_r) + \varepsilon\,\sigma_0(T_s^4 - T_r^4) = h_c(T_s - T_r) \qquad [\mathrm{W.m^{-3}}]$$

(4)

Where:
$T_s$ [K] – surface temperature,
$T_r$ [K] – ambient temperature,
$h_c = h_k + h_r$ [$\mathrm{W.m^{-2}.K^{-1}}$] – combined heat transfer coefficient,
$h_k$ [$\mathrm{W.m^{-2}.K^{-1}}$] – heat transfer coefficient,
$\varepsilon$ – emissivity,
$\sigma_0$ – Stefan – Boltzmann constant.

### 3.2 Heat balance in the welding process

Welding will transform the electrical energy from the arc welding of heat energy. Thermal energy is consumed for melting base and filler material, the heat conduction in the solid material and the losses to the surroundings. Determining the actual heat input arising per unit of time, is transferred to the base material, is one of the important parameters of the numerical simulation. When calculating the heat input start from Goldak equation, which is of the form, [2, 3]:

$$Q_{(x,y,z,t)} = \frac{6\sqrt{3}\, f\, Q_b}{a\, b\, c_{1,2}\, \eta\sqrt{\eta}}\, e^{-\frac{3x^2}{a^2}}\, e^{-\frac{3y^2}{b^2}}\, e^{\frac{-3(z-w(\tau-t))^2}{c_{1,2}^2}} \qquad [\mathrm{W}] \qquad (5)$$

Where:
$Q_b$ - heat delivered by during welding
$\eta$ - coefficient of thermal efficiency,
$w$ – welding speed,

$x, y, z$ – coordinates indicating the position of the heat source at time $t$,
$a, b, c_{1,2}$ – position of the geometry of the molten drops.

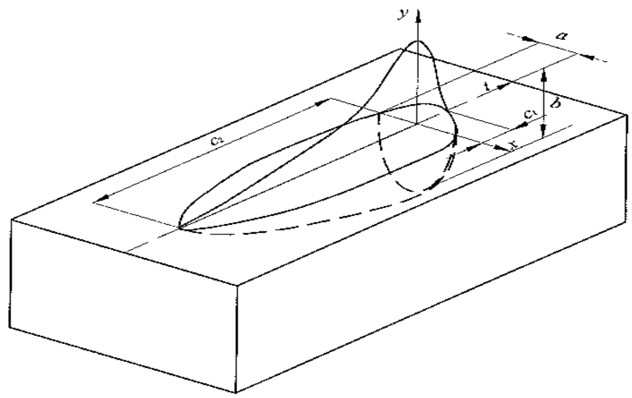

Fig. 2 Model Goldak's double ellipse and calculated heat flux

### 3.3 Conditions during the numerical simulation

For thermal analysis is necessary to define not only the thermo-physical properties of the base material, but also additional material. Whereas the use in welding additive material with similar chemical composition as the basic material, then we can consider by numerical simulation with the same thermo-physical as the basic material, which is aluminium having a purity level 99.5%.

Material model for solving the thermal problem consists of the following thermo-physical properties according to temperature change:

- coefficient of thermal conductivity,
- specific heat capacity,
- density.

Modeling fillet weld geometric model was created so that the shape and size identical to the real experimental sample. To solve using FEM is necessary to network. Figure 3 is the geometrical model and generated network.

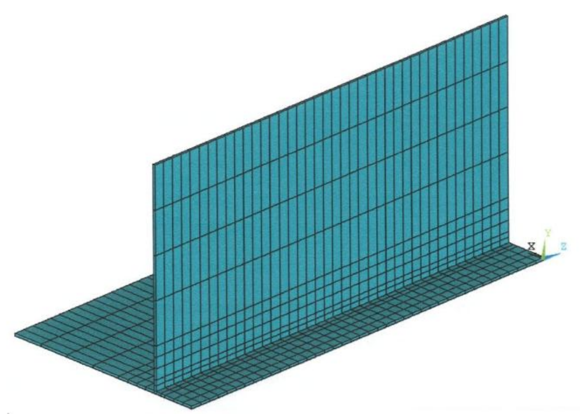

Fig. 3 The geometrical model and generated network

Initial conditions for the numerical analysis of the technological process GTAW welding method were based on the baseline for the experimental sample used in the real experiment. At the initial time *t* = 0 s, the initial temperature of the sample at the level of the experimental the surrounding environment. The ambient temperature was 20°C.

During the welding operation, the total heat flow introduced into the base material is the sum of supplied heat flow by conduction, convection and radiation. Cooling the welded material after welding expresses boundary condition III. type in the form (4). Overall heat transfer coefficient is dependent on the temperature change of 0.2 emissivity of aluminium.

On the basis of the welding parameters for the experiment, the calculated heat input by equation (5) and applied as a moving heat source. Feed speed of the heat source is identical to the speed of the welding experiment.

Numerical experiment temperature fields were solved using FEM numerical modeling using ANSYS, as non-stationary and nonlinear problems.

## 4. RESULTS OF EXPEIMENT AND NUMERICAL SIMULATION

Results of the examination of the matter during the temperature in the weld zone during welding are divided into two parts. The first section provides a graphically displays the results of the real experiment. The second part consists of the results of numerical simulation results obtained using the FEM program ANSYS.

### 4.1 Results of the experimental measurements

Results experimentally measured temperatures with thermocouples placed in HAZ according to Fig. 1 are written in Table 3 and graphically shown in Figure 4.

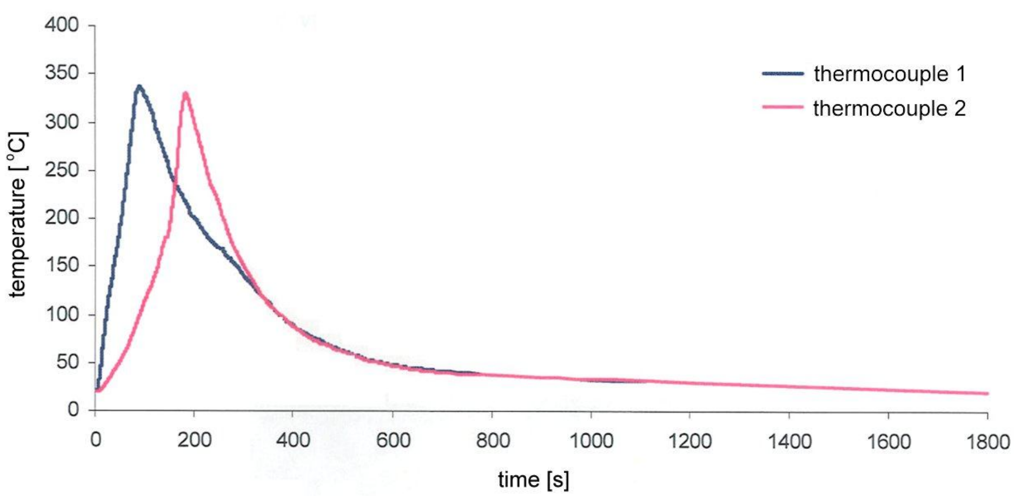


Fig. 4 Graphic representation measured temperatures depending on the time change

The graphic views shows that the thermocouple 1 positioned closer to the weld recorded quicker increase in temperature, and higher temperatures than the thermocouple 2. The maximum temperature measured thermocouple 1 was 327,697 °C at the time of 100 seconds from the start of welding. The maximum temperature measured thermocouple no. 2 was 300,013 °C at the time of 200 seconds from the start of welding. The whole process of welding and cooling to room temperature was carried out for 1800 s. At the time of 1800 seconds to the beginning of the welding temperature field is uniform and the experimental sample cooled down to ambient temperature. Experimental samples were cooling by natural convection in air.

Experimentally measured temperature with thermocouples 1 and thermocouples 2 are written in Table 3. Temperature values were measured according to the change in the time interval of 0,5 seconds.

Table 3: Results experimentally measured temperatures

| Time [s] | Thermocouple 1 [$^oC$] | Thermocouple 2 [$^oC$] |
|---|---|---|
| 0 | 20 | 20 |
| 50 | 189.671 | 50.635 |
| 100 | 327.697 | 114.307 |
| 150 | 249.963 | 189.873 |
| 200 | 200.411 | 300.013 |
| 250 | 169.324 | 214.623 |
| 300 | 140.621 | 151.041 |
| 350 | 112.114 | 110.56 |
| 400 | 89.297 | 88.011 |
| 450 | 74.202 | 71.991 |
| 500 | 62.581 | 61.736 |
| 550 | 58.094 | 52.362 |
| 600 | 48.276 | 47.042 |
| 650 | 44.330 | 42.526 |
| 700 | 40.573 | 39.730 |
| 1800 | 20 | 20 |

## 4.2 Results of numerical simulation

The result of thermal analysis of numerical simulation of weld joint is made out of aluminium thermal field. Solution with FEM in ANSYS we have gained heating pattern changes depending on the time during the entire length of the weld.

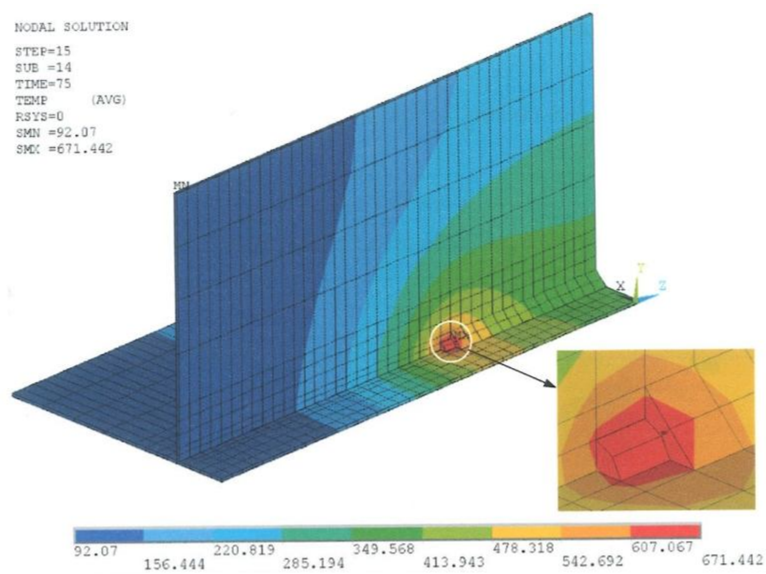


Fig. 5 Temperature field in time 75 s

Fig. 5 is a graphical representation of the temperature field at the time of 75 s from the start of welding. At that time, the movable volume source located at a distance of 75 mm from the beginning. At the time and place of the steady welding process with maximum temperature of 671,442 °C and minimum temperature of 92,07°C. The maximum temperature is in the area of the moving heat source. In this area there is to fuse welding and filler material if their mutual mixing, after cooling resulting weld joint. Detail in Fig. 5 shows the HAZ, which is very broad, which is mainly caused by the good thermal conductivity of aluminium.

Figure 6 shows the temperature field at the time of 900 s. At this time, the welding process is completed and the cooling by natural convection in air. At the time of 900 s is a uniform temperature field throughout the sample volume and sample uniformly cooled down to a temperature of 22,281 °C.

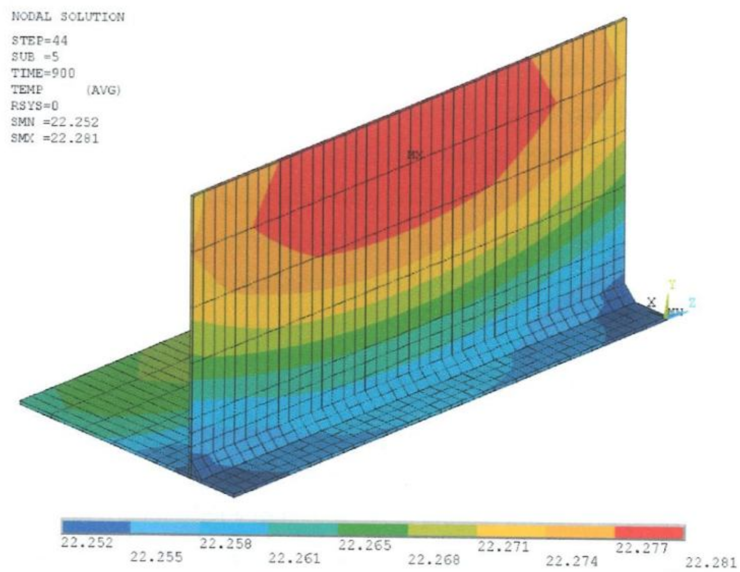


Fig. 6 Temperature field in time 900 s

Graphic representation temperature calculated during the numerical simulation is shown in Fig. 7. Shown waveforms temperatures are in the nodes that disposition correspond to places where they were located thermocouples. The maximum calculated temperature at node 1 was 372,53 °C and node 2 was 375,981 °C.

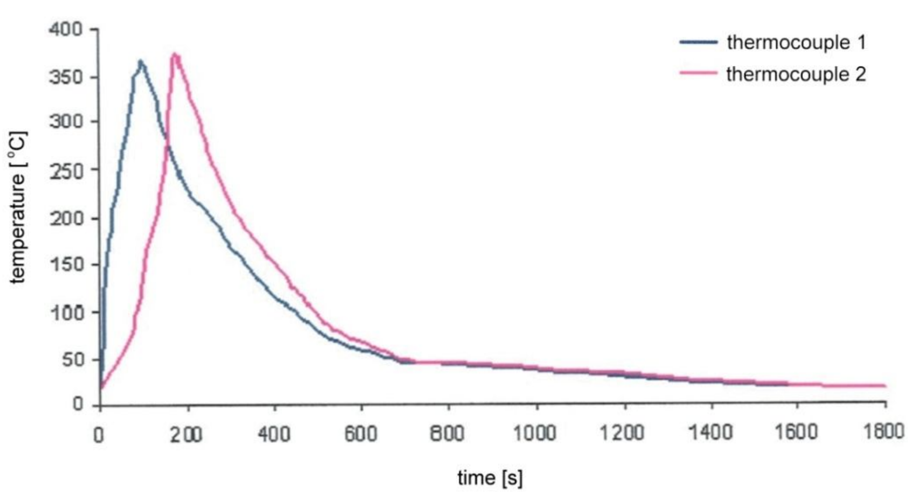


Fig. 7 Graphic representation calculated temperatures depending on the time change

## 5. CONCLUSIONS

Calculated maximum temperature values in the nodes imposition of thermocouples in the numerical simulation are about 40 °C higher than those measured in the experiment. One of the causes of deviations is difficult obtaining material and thermo-physical properties of aluminium depending on the temperature change. Properties are available in the graphical view, where could lead to deviations in the readings values. Also deviation of the measured values might occur due to imperfect contact between material welding and thermocouples.

Experimental solving problems arising in various fields of engineering technology is now very often replaced by a numerical solution by computer simulation using FEM. Substitution of experimental solutions numerical simulation allows examination of the issue on a larger scale and increasing flexibility and prediction of the models.

## 6. ACKNOWLEDGEMENTS

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