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FEM SIMULATION OF THERMAL CYCLES DURING LASER WELDING OF ALUMINIUM

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Abstract: The submitted paper deals with the simulation of thermal cycles during laser welding of aluminum sheets using Finite Element Method (FEM). After the design and creation of the simulation model, the simulation results were verified by the thermal cycles measured during the experiment on real samples. Verification has shown that, despite the differences that have resulted from some simplifications, the proposed model corresponds to the actual behavior of the material used during the laser welding process.

KEYWORDS: laser welding, aluminum, FEM simulation, thermal cycles, ANSYS

1 Introduction

At present, welding of aluminum alloy products is increasingly joined using modern welding processes: Friction Stir Welding [1, 2] and Laser Beam Welding. Laser welding is a process in which a concentrated heat source at the point of action causes an intense heating of the material to high temperatures. The local melted area heats the surrounding part of the welded material and significantly affects its properties. During the laser welding process, the temperature of the metal varies greatly from the ambient temperature to the evaporation temperature of the metal at the point of heating in a very short time. Such a high temperature gradient causes structural and volume changes in the base material. The welding process is defined as the action of a quantity of point heat sources on the individual bulk elements of the base material during the heating process. The heat fields generated by the welding process can be solved by several methods [3]:

- experimentally: by measuring the temperature of a given location using thermocouples,
- Finite Element Method (FEM): modeling and simulation of the welding process [3].

2 Experimental details

The simulation of thermal cycles during laser welding using FEM was designed and implemented using the ANSYS software package. Thermal analysis was solved as a non-linear task. The simulated process was defined according to the actual laser welding parameters, which corresponded to the process parameter of the welding experimental sample. The geometric model characterizes the dimensions and shape of the welded component. Since our aim was to determine the thermal cycles in the welding area and in the heat-affected zone (HAZ), at this point the mesh density of the model was increased (Fig. 1). The reality of the defined thermophysical properties of the model determines the achieved simulation results. The properties that affect the laser beam welding process include: the specific weight, specific heat capacity, thermal conductivity, but also the absorption coefficient and the heat transfer coefficient. Since this is a nonlinear task, it is necessary to enter these properties into ANSYS

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software as a function of temperature. The mentioned properties (Tab. 1) were drawn from available literature [4, 5].

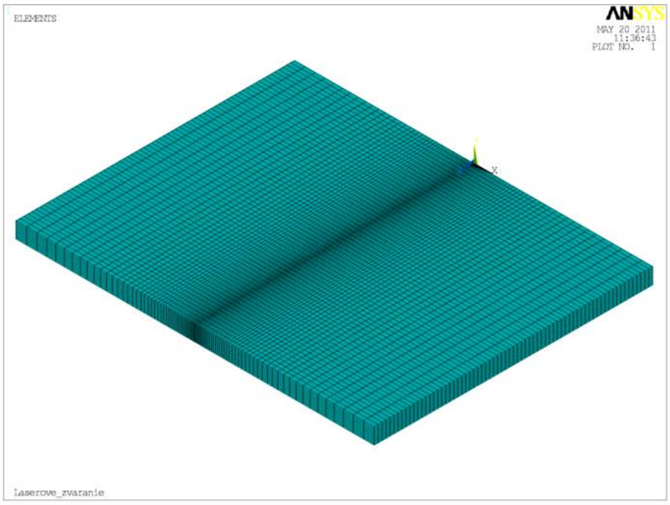

Figure 1 The model divided into elements

Table 1 Dependence of density, specific heat capacity and heat conductivity coefficient from temperature for Al 99.5%.

T [°C]	25	100	200	300	400	500	600
ρ [kg/m^3]	2702	2685	2662	2640	2617	2594	2571
Cp [J/(kg^1.K^1)]	905	904	990	1030	1070	1100	1150
λ [W/(m^1.K^1)]	211	91	92	96	99	103	
T [°C]	660.2	660.2	700	800	900	1000	
ρ [kg/m^3]	2558	2380	2366	2331	2296	2261	
Cp [J/(kg^1.K^1)]	1180	1180	1180	1180	1180	1180	
λ [W/(m^1.K^1)]	211	91	92	96	99	103	

Absorption of laser beam by material is a basic prerequisite for laser welding. Determination of absorption is very demanding since it is a non-stationary process and the value of the absorption coefficient during the process is not constant. For aluminum alloy EN AW - 1050A, the coefficient of absorption is very small, according to [6], A = 0.034. Also, reflection is very high when using Nd: YAG lasers with a wavelength of λ = 1064 nm, up to R = 98.4%. Therefore, before the experiment, the surface of the sample was roughened, resulting not only in the removal of the oxide layer but also in an increase in the absorption coefficient. Heat transfer is a physical phenomenon that occurs at the interface of two substances (metal, air) with different temperatures to transfer heat from a higher temperature substance to a lower temperature substance. In our case, it is a combination of free heat transfer to an unlimited space (natural convection) and heat transfer by radiation:

$$h_c = h_k + h_r \tag{1}$$

where h_c is the overall heat transfer coefficient (W/(m^2.K^1)),
h_k – heat transfer coefficient for free convection (W/(m^2.K^1)),
h_r – heat transfer coefficient by radiation (W/(m^2.K^1)).

When calculating the heat transfer coefficient, we proceeded from [3]. The heat transfer coefficient is determined from the critical equations derived from the theory of similarity and dimensional theory. For calculating the coefficient of heat transfer by convection into an unlimited space, it is based on the following equation:

$$Nu = C.[Gr.Pr]^n \tag{2}$$

where Nu is the Nusselt criterion,

Gr – Grashof criterion,

Pr – Prandtl criterion,

C – constant,

n – exponent.

Initial conditions were determined based on the course of the experiment. The sample had at the initial measurement time (t = 0) a temperature at ambient temperature of T = 20 °C, so the initial temperature of the model was T = 20 °C at simulation. According to the boundary condition of 2nd order, the laser beam thermal flux was simulated. Throughout the time the heat source was applied to the material, the constant density of the heat flux was considered. Using the boundary condition of 3rd order, free cooling of the sample surface to ambient air temperature was taken into account. In this case, heat transfer is a combination of free convection and radiation. Accurate defining of the temperature source (shape and size) for simulation of welding is one of the main prerequisites for obtaining real simulation results. In the calculations, a Goldak double ellipsoidal heat model, which is used for most hot melt welding [3, 7]. Calculation of heat input according to Goldak has the form:

$$q_{(x,y,z,t)} = \frac{6.\sqrt{3}.f.Q_b}{a.b.c_{1,2}\eta.\sqrt{\eta}} e^{\frac{3.x^2}{a^2}}.e^{\frac{3.y^2}{b^2}}.e^{\frac{3.(z-v(\tau-t))^2}{c_{1,2}^2}} \tag{3}$$

$$f = f_1 + f_2 = 2 \tag{4}$$

where Q_b is the power delivered during welding (W),

η - coefficient of effectiveness (-),

v – welding speed (m/s),

$f_{1,2}$ - the constants affecting the flow of energy into the material (-),

x, y, z - coordinates that indicate the position of the heat source over time t (m),

a, b, $c_{1,2}$ - melt area parameters (m).

The aim of the experiment was to measure thermal cycles during laser welding of thin aluminum sheets using thermocouples (Fig. 2). Temperatures were measured according to time in the HAZ at different positions of the thermocouple relative to the welding axis. In the direction of the welding axis, the thermocouples were placed at the same distance (z = 35 mm). At this distance, it can be assumed that the non-stationary temperature field is already quasi-stationary (it is assumed that the maximum temperature is stabilized). In a direction perpendicular to the welding axis, measurements were made at the following distances: x_1 = 1.5 mm, x_2 = 4.44 mm, x_3 = 5.03 mm, (Fig. 2). During welding, the temperature measured on the bottom of the sheet metal (the root side of the weld). The measured values were then evaluated using the MATLAB computer software.

The experiment (welding and measuring of thermal cycles) was carried out with a Nd: YAG laser with a maximum output of P = 4400 W. The laser beam was driven from the optical fibers into the SCANSONIC-ALO 3 adaptive laser head, which was mounted on the KUKA industrial robot. The minimum laser beam spot size was ∅d = 0.6 mm. The K-type (Chromel-Alumel) thermocouple was made of wire ∅d = 0.254 mm in diameter and welded to the sheet metal by a capacitor welding. For the experiment, aluminum sheets of type EN AW 1050 A with a thickness of h = 2 mm were used, the chemical composition of which is shown in Tab. 2. The sheets were cut to 90 x 70 mm plates. The sheets were then cleaned with toluene before welding. The surface of the top on which the laser beam was applied was brushed with a brush with stainless bristles to increase absorption (decrease reflection) of the laser beam by the material and remove the oxide layer.

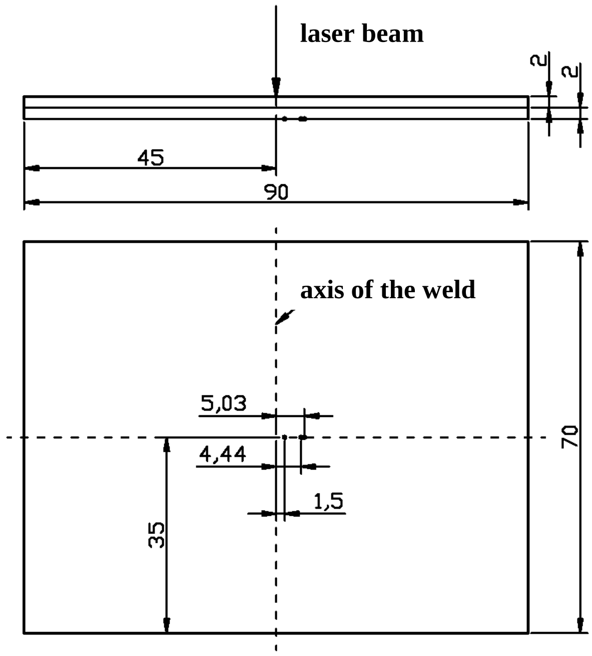

Figure 2 Sample dimensions with position of thermocouples

Table 2 Chemical composition of sheet metal EN AW 1050 A [8]

Al [%]	Si [%]	Fe [%]	Cu [%]	Mn [%]	Mg [%]	Zn [%]	Ti [%]	other [%]
99.5	0.25	0.4	0.05	0.05	0.05	0.07	0.05	0.03

The setting of the process parameters during welding was as follows: laser power: 4 kW, welding mode: continuous mode, wavelength: 1064 nm, mode: TEM 00, welding speed: 25 mm/s, shielding gas: He 5.0, flow rate: 9 l/min, laser beam spot size: 0.6 mm (focussed on the surface of the material). Thermal cycle measurements were performed on three samples at the same welding parameters. These measured values were subsequently verified by thermal cycling simulation results. The biggest problem with the verification was the determination of the laser beam absorption coefficient by the material used (after brushing). As other comparisons showed, the highest match of measurement results with thermal cycle simulation was achieved by choosing the absorption coefficient A = 67%. In Fig. 3 is a graphical representation of the course of temperature fields at time t = 2 s (at that time it is assumed to be a quasi-stationary one). In Fig. 4 shows the verification of measured and simulated temperature cycles. From the temperature cycles, an extremely rapid heating of the material through the laser beam from the ambient temperature to the maximum temperature T_{max} at the measuring site was found.

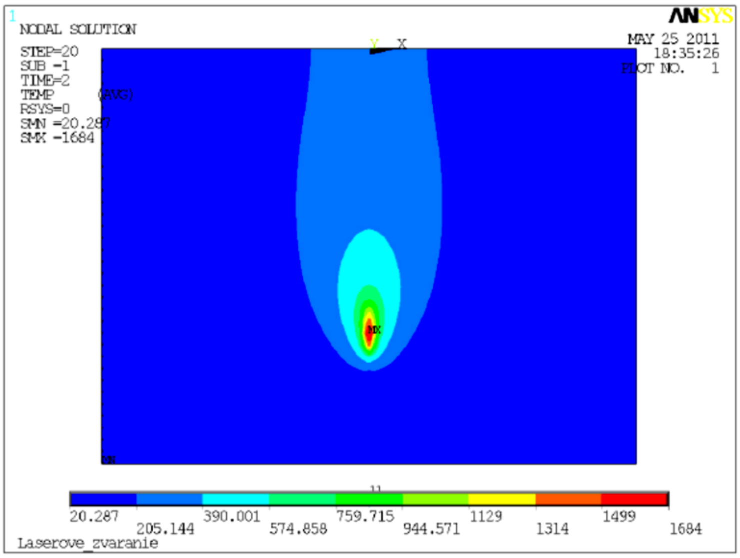

Figure 3 Run of temperature fields at t = 2 s (absorption coefficient A = 67%)

For distance x_1 = 1.5 mm (Fig. 2), this time is t_1 = 1.2 seconds. For distances x_2 = 4.44 mm and x_3 = 5.03 mm it is time $t_2 = t_3$ = 1.5 seconds. Also, a high cooling rate of material is seen (Tab. 3). Differences of measured and simulated temperature cycles are small in the heating area (~15° C). Larger differences occurred during free cooling of the material (Tab. 3).

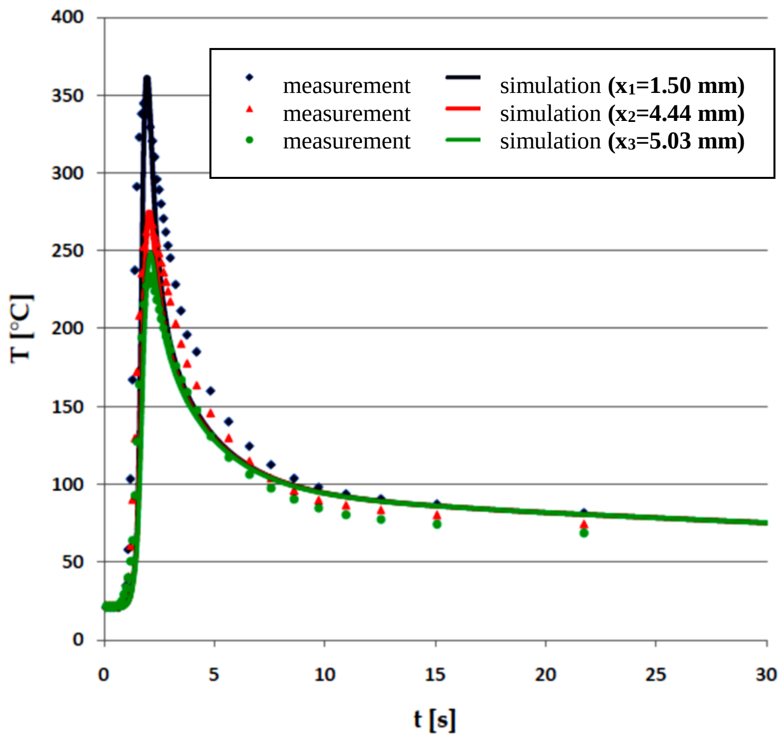

Figure 4 Comparison of simulated and measured thermal cycles

Table 3 Comparison of measured and simulated temperatures, heating and cooling rate

Distance / value obtained	x_1 = 1.5 mm		x_2 = 4.44 mm		x_3 = 5.03 mm	
	simulated	measured	simulated	measured	simulated	measured
T_{max} [°C]	360.9	345.1	274.4	267.6	248.2	233.5
$T_{t=5s}$ [°C]	133.4	159.8	131.9	145.9	131.1	130.7
$T_{t=10s}$ [°C]	95.1	97.9	94.9	89.8	94.8	84.6

Heating rate for T_{max} [°C/s]	300.1	287.6	182.9	178.4	165.5	155.7
Cooling rate over t=5s [°C/s]	73.3	59.9	41.9	49.1	35.4	40.4

CONCLUSION

The following conclusions can be drawn from the results:

- It was not possible to determine the exact value of the absorption coefficient from the input quantities that influence the process of heating the material with the laser beam, nor was it possible to measure it in our conditions or to compare it with the results of work published in the area. Therefore, this value was determined approximately to match the results of the simulation with the measured values of the temperature cycles. A more precise determination of the absorption coefficient can be obtained by measuring with a spectrophotometer. The results obtained, taking into account the laser radiation absorption A = 67%, show a fairly good match between the measured and simulated thermal cycles (Tab. 3): at the maximum temperature T_{max}, the deviation was in the range of 2.5% to 6.0%, in the cooling phase after 5 seconds ($T_{t=5s}$) the deviation ranged from 2.1 to 16.5% and after 10 seconds ($T_{t=10s}$) in the range of 2.9 to 10.5 %.

- The proposed model with the above mentioned simplifications corresponds to the actual behavior of the welded material during the laser beam welding process. Based on this simulation, the laser welding process can be further optimized.

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