FEM NUMERICAL ANALYSIS OF THERMAL FIELD DISTRIBUTION AND EXPERIMENTAL STUDY OF CIRCUMFERENTIAL LASER WELDING OF THIN-WALLED ALUMINUM ALLOY PIPES

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Abstract

This paper addresses the FEM numerical analysis of thermal field distribution in a thin-walled aluminum alloy pipe subjected to circumferential welding with a laser beam as a source of heat. The paper presents constitutive equations describing the studied phenomenon. Computation results were compared to the experimental welding results. Welding process was performed on the TRUMPF CO_2 laser, model TruFlow6000. The temperature ahead of the moving laser beam front was measured by the optical pyrometer. Pyrometer indications confirm that there is a sufficient level of correspondence between the numerical analysis and the actual results.

Keywords: Laser welding, FEM analysis

1. INTRODUCTION

The low melting point (940 K) and high thermal conductivity (180 W/mK) of aluminum alloys [1] significantly affect their weldability. The listed properties of the material necessitate the use of concentrated heat sources. The application of the FEM method should be accompanied with an appropriate voltage selection necessary to heat the workpiece. The voltage value is determined by the thermal conductivity of the material, in the case of aluminum it should range from 22.7V to 24.5V (depending on the welding position). To ensure the correct course of the process and its accuracy the voltage drop in the grid should not exceed 0.5 V [2].

In the course of the alloy welding aluminum does not change its colour (until it reaches the melting point), which allows determining the heating temperature and the heat affected zone range [3, 4]. Therefore, in the case of the TIG method, the welding current selection and the operator's experience have a significant impact on the final result and the quality of the welded joint. In both methods a negligence during the process may result in the workpiece burn through.

Similarly, laser welding of aluminum alloys is problematic. The high reflectivity of the surface results in the low absorption of the laser radiation power. This coefficient can be increased through sanding or anodizing the surface [5, 6]. Moreover, the laser welding process is automatic and its control is limited.

In the case of circumferential welding of thin-walled pipes one can observe a phenomenon of heat accumulation occurring in the workpiece. In consequence, the process parameters need to be modified in the course of its duration so that the temperature in the weld pool is constant. In the case of laser technology certain devices offer the possibility to use variable radiation power during welding.

This article presents a numerical simulation of temperature distribution on the circumference of laser welded pipe and a laser penetration experiment (a welding process simulation), during which the actual temperature distribution was measured.

2. NUMERICAL MODEL OF LASER WELDING PROCESS

The numerical model was developed with the application of the Ansys Fluent 15 package. The paper presents a set of basic equations describing the material melting and solidification models and a k-ε model of turbulent flow depicting the liquid metal movements in a weld pool [7], [8], [9]. The software under consideration uses a parameter known as “liquid fraction coefficient” resulting in the appearance of an interface zone in the calculations regarding the melting processes of alloy metals. This coefficient, adopting the value of 0 for the solid phase and 1 for the liquid phase is defined by the equation:

$$\beta = \begin{cases} 0, & T < T_s \\ 1, & T > T_l \\ (T - T_s)/(T_l - T_s) & T_s < T < T_l \end{cases} \tag{1}$$

where: T - temperature, T_s -solidus temperature, T_l - liquidus temperature.

It was assumed that the boundary condition at the place of laser beam operation takes the following form:

$$-\lambda_{eff} \frac{\partial T_s}{\partial \vec{n}} = I_L \cdot \alpha \left(T - T_\infty\right) - \sigma \varepsilon_p \left(T^4 - T_\infty^4\right) - pu(t) L_v \tag{2}$$

where: I_L - heat flux density generated by laser, L_v - heat of fusion, n - versor, α - heat exchange coefficient, ε_p - emissivity, σ - Stefan-Boltzmann constant.

It was adopted that beyond the laser beam impact range the heat transfer to the environment has convective and radiative nature as described by the equation:

$$-k \frac{\partial T_s}{\partial \vec{n}} = \alpha \left(T - T_\infty\right) + \sigma \varepsilon_p \left(T^4 - T_\infty^4\right) \tag{3}$$

The material parameters change with temperature in the course of the process, which should be taken into account for the simulation to be reliable [10]. In the FEM programme the change of parameters with temperature was predetermined according to the following diagrams (**Figures 1 - 2**). The FEM analysis of temperature distribution was conducted with adopting the beyond conditions and assumptions.

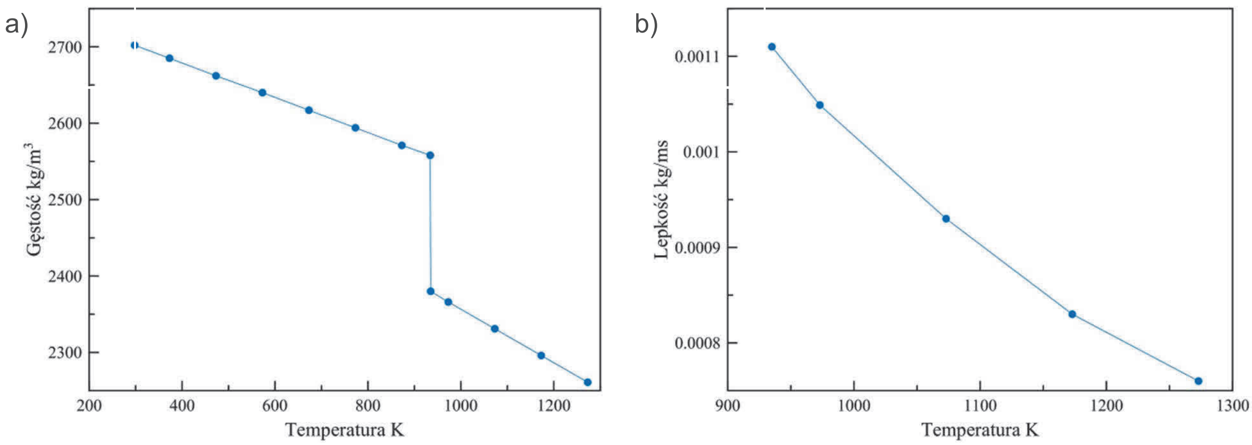

Figure 1 Changes of: a) aluminum density and b) aluminum viscosity with temperature [1]

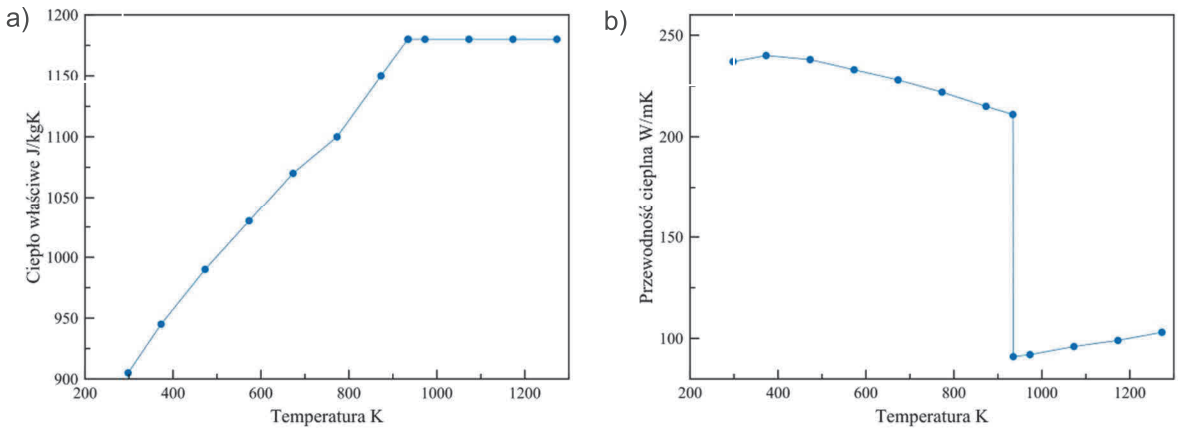

Figure 2 Changes of: a) aluminum specific heat and b) aluminum thermal conductivity with temperature [1]

3. FEM ANALYSIS OF LASER WELDING OF A THIN-WALLED ALUMINUM PIPE

The assumptions outlined in the previous section provided a basis for constructing a discrete pipe model with the following dimensions: external diameter d = 30 mm, wall thickness g = 0.9 mm, length l = 300 mm. The remaining process parameters used in the calculations were as follows: the melting point ΔT_s = 940 K, the absorption coefficient A = 0.2, the heat source power (laser beam) P = 2500 W, the thermal conductivity coefficient λ = 180 W / mK, the thermal diffusivity coefficient κ = 8 x 10-5 m^2 / s, the laser spot diameter on the workpiece surface d_p = 1.1 mm, the workpiece rotational speed ω = 34 rpm. The total time of the heat source operation necessary for the circumferential heating of the workpiece was t =1.2 s (depending on the external diameter of the workpiece and the rotational speed). In order to shorten the time of numerical calculations a symmetry model along the movement path of the laser beam was applied.

The calculation grid shown in **Figure 3** consists of over one million cubic cells. The calculation grid was condensed in the place where the largest temperature gradients occur, i.e. directly by the route of the laser beam movement. A time step of 2 × 10^{-4} s was adopted to meet the convergence criteria for the continuity, energy and momentum equations as well as for *k-ε*.

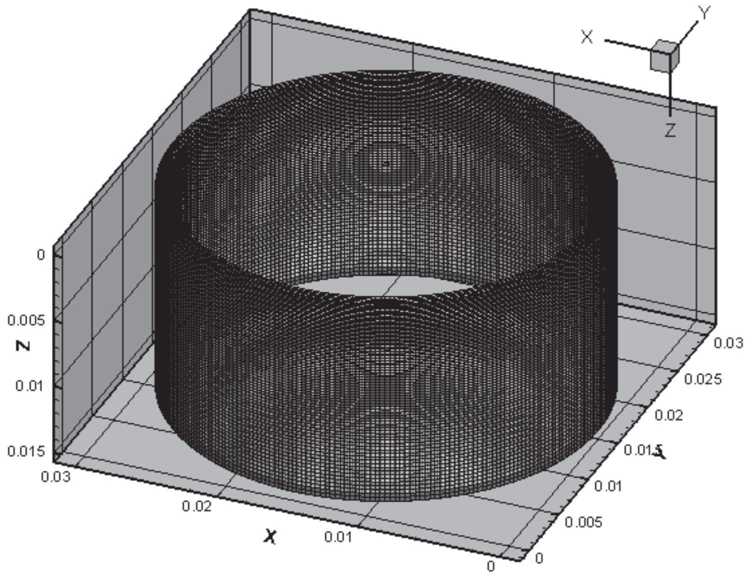

Figure 3 Grid of the workpiece under consideration developed in the *Ansys Fluent 15* programme

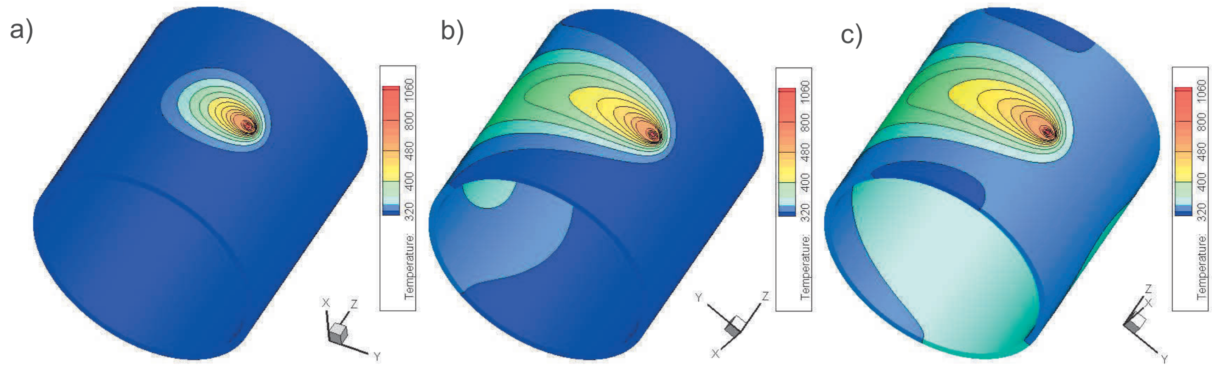

Figure 4 Isotherm distribution during the different phases of the process, a) shortly after the commencement of the process t = 0.2 s, b) in the middle of the process t = 0.6 s, c) the completion of t = 1.2 s

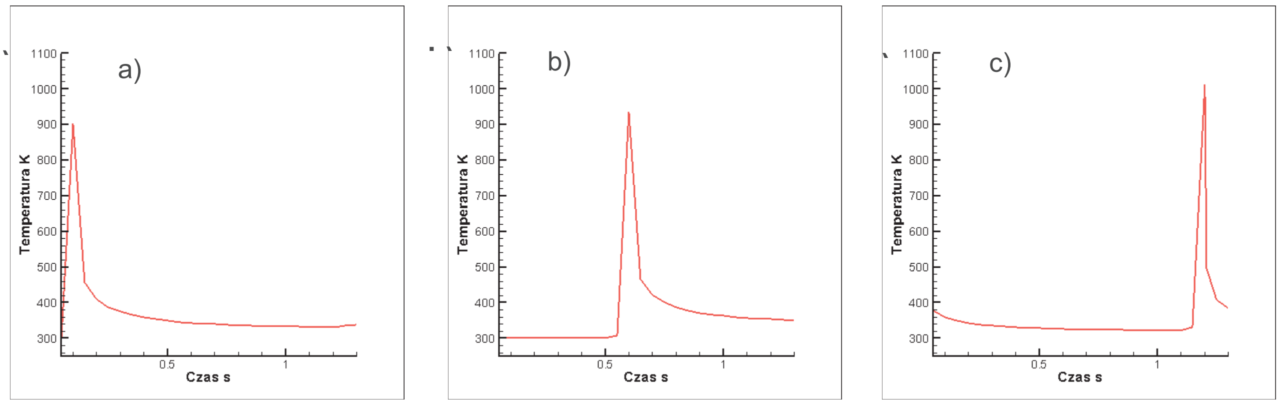

Figure 5 Temperature change in the pool during different phases of the process: a) 0.1 s, b) 0.6 s, c) 1.2 s.

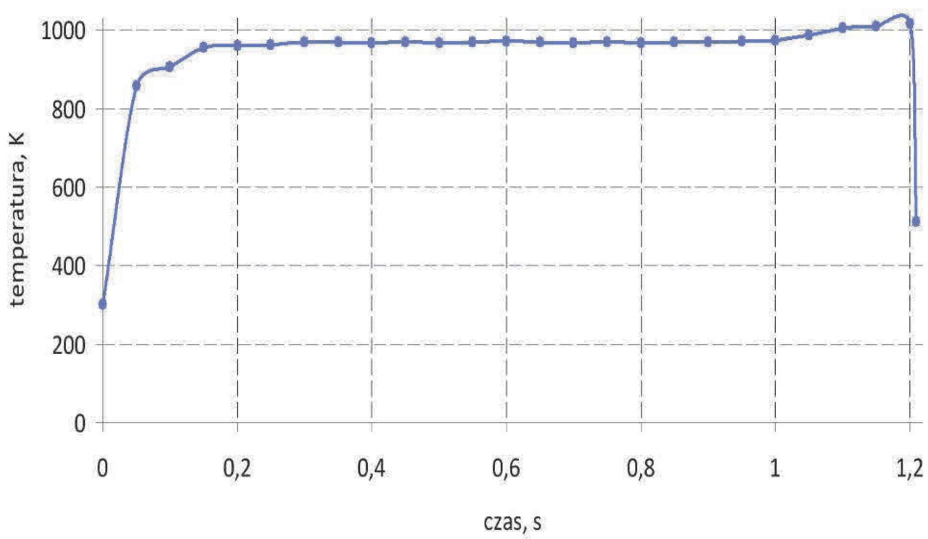

Figure 6 Temperature change in the pool during the welding process (the FEM analysis)

The FEM simulation was performed for the developed procedure. The isotherm distribution in the workpiece in selected process phases is presented in **Figure 4**. **Figure 5** shows temperature changes in the weld pool for the presented distributions. The FEM analysis provided the basis for calculating the pool temperature in the course of the entire process as presented in **Figure 6**.

4. LASER WELDING EXPERIMENT

The actual workpiece was subjected to the conduction welding test in order to verify the FEM analysis. The TRUMPF CO_2 laser, model TruFlow 6000, generating a wavelength of 10.6µm was applied for the experiment. The resonator is integrated with the LASERCELL 1005 system equipped with a pipe positioner. A thin walled aluminum pipe (99.9999 %) was subjected to welding. The pipe surface was roughened to reduce its reflectivity (to maximize absorption coefficient A). Argon 99.99 % was used as the shielding gas. The experiment conditions and parameters were chosen to meet the assumptions of the FEM analysis:
- pipe diameter and wall thickness 30 × 0.9 mm - spot diameter on the surface of the workpiece: dp = 1.1 mm
- the power of the laser radiation P = 2500 W - workpiece rotational speed ω=34 rpm.

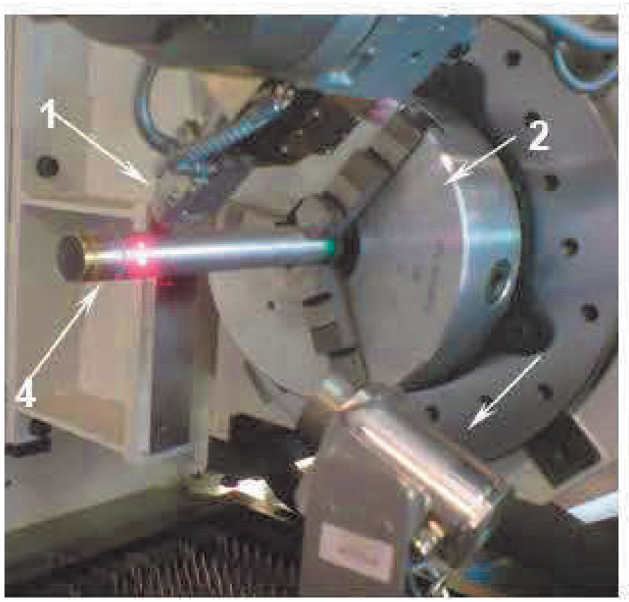

Figure 7 Research station view: 1 - laser head, 2 - positioner, 3 - optical pyrometer, 4 - workpiece

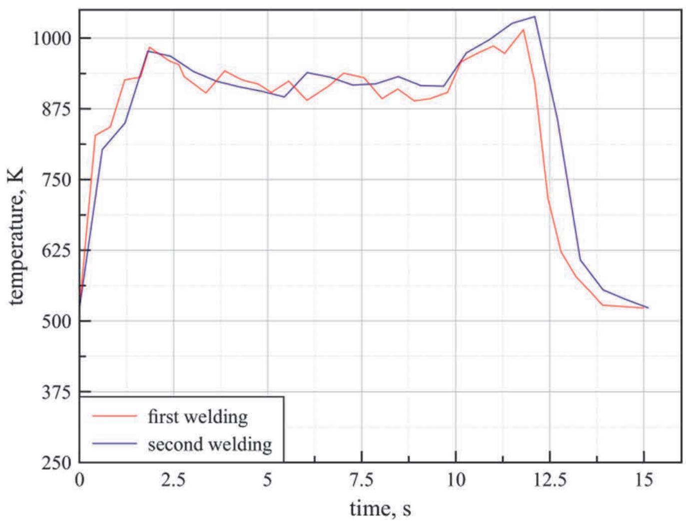

Figure 8 Temperature change in the pool during the welding process (experiment).

In the course of the process the weld pool temperature was recorded by means of the monochromatic OPTRIS pyrometer model G5H. The research station is shown in **Figure 7**. Changes of temperature during the experiment for two independent penetrations are presented in **Figure 8**. In both cases (the FEM analysis and the experiment) in the initial phase the temperature in the pool rises to approx. 1000 K. This temperature permits the welding process. In the case of the FEM analysis the temperature stabilizes at that level in the course of the process. In the case of the experiment the temperature remains in the range of from 900 to 1040 K. It is probably related to the variable absorption coefficient of laser radiation, depending on the surface temperature of the workpiece. In the final phase of the process one can observe a slight rise in temperature to a level of approx. 1020 K (FEM) and approx. 1040 K (experiment). This is due to the heat accumulation in the workpiece. After the process completion the temperature drops rapidly to approx. 530 K in both cases.

5. CONCLUSIONS

1) The use of FEM analysis allows calculate the process parameters in laser welding of thin-walled aluminum pipes with a good degree of accuracy. The difference between the values obtained by experiment and by simulation was in our case less than 10 %.

2) The results obtained from the numerical analysis permit a satisfactory determination of the maximum temperatures reached by the workpiece subjected to the operation of a heat source in the form of a laser beam. Hence, it is possible to avoid the material damage during the process.

3) Numerical analysis is significantly more complicated and long-lasting than analytical calculations it is also characterized by high accuracy of the obtained results [11].

4) Despite the use of variable material parameters the results obtained by the numerical method differ slightly from those obtained during the actual process. This may be due to the variable absorption capacity of the surface. In the presented model a constant value of absorption capacity was assumed.

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