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PYTHON-BASED CALCULATION AND DISPLAY OF TEMPERATURE FIELD DISTRIBUTION IN ARC WELDING

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Abstract

Welding is a crucial manufacturing process used in various industries, and it involves heating two or more metal parts to their melting point and then joining them together. The process of welding is complex, and the resulting microstructure and mechanical properties of the metal depend on various factors such as temperature, heating rate, cooling rate, and the type of metal being welded. Temperature is one of the most critical factors that influence the welding process, as it directly affects the microstructure and mechanical properties of the metal. Understanding the temperature fields in welding is essential for optimizing the process and improving the quality and performance of welded products. This research focuses on analyzing the temperature field distribution during arc welding, which is a common welding technique used in various industries. The objective of this study was to conduct a detailed analysis of three different types of temperature fields and develop a user-friendly Python program to calculate and display the temperature field distribution for each type of analysis. The three types of temperature fields analyzed in this study were for moving point heat source for half infinite body, moving line heat source for thin plates, and instant surface heat source. The Python program developed in this research provides an accessible tool for welders and engineers to better understand and control the welding process. The program calculates and displays the temperature field distribution in the form of interactive 2D and 3D graphs, where the temperature is plotted against length, width, and depth coordinates, as well as the velocity of the moving heat source. The program also calculates several key parameters from the temperature fields, including the temperature cycle, cooling rate, cooling time, maximum temperature, and the width of the heat-affected zone. The ability to control the welding process can lead to improved quality and performance of welded products, making this research a valuable addition to the field of welding engineering.

Keywords: Python programming, moving heat source, temperature field graphs, welding process, metal microstructure

1. Introduction

Welding is the process of joining two or more similar or dissimilar materials by melting or pressure, with or without adding additional material, in order to obtain a homogeneous welded joint. Welding was first documented around 3000 BC. In 1881, Auguste De Meritens used the heat of a short circuit of electric energy to join contact plates on batteries. Throughout history, a multitude of different welding methods have been developed, some of the most well-known being MIG (Metal Inert Gas), MAG (Metal Active Gas), TIG (Tungsten Inert Gas), and MMA (Manual Metal Arc Welding). Welding generally achieves temperatures close to the melting point of the material, resulting in extremely strong joints, but it can also cause numerous problems if not performed under controlled conditions. Today, welding is one of the most commonly used ways of joining metals [1].

Welding involves significant heating that affects the microstructure and mechanical properties of the base metal [2]. The direction and amount of heat spread in the metal being welded are directly related to the residual stresses and deformations that occur during cooling. In steel, it is crucial to pay attention to the cooling time between 800 °C and 500 °C, as this is where the most significant microstructural changes occur. Due to these reasons, it is necessary to predict how heat spreads in the metal. One way is to use an analytical mathematical model that relates temperature to other welding parameters [3].

In the first half of the 20th century, Daniel Rosenthal published the first literature that explained how the heat flow of a moving heat source behaves according to a mathematical model [4]. Rosenthal was the first person to apply Fourier's law to a moving heat source, resulting in the first mathematical model of a heat source with homogeneous distribution [2]. The biggest problem with his solution is that all welding energy is concentrated in one point, meaning that his mathematical model did not take into account the shape of the molten metal area or the depth of penetration [5]. Today, there are three main categories of analytical solutions that can describe welding: the solution based on the Gaussian error function (1D), Rosenthal's solution (2D and 3D), and integral functions.

Analytical solutions require significantly less computing power than numerical solutions. However, analytical solutions are often imprecise because various assumptions and simplifications are made in analytical mathematical models [6]. For example, Rosenthal's mathematical model assumes that the heat source is point-like, surface heat losses are neglected, convection in the molten metal area is neglected, the thermal properties of the material are taken as constant, the latent heat of fusion is neglected, and the amount of exchanged heat does not change over time. Also, analytical solutions are related to simple metal geometry and do not take into account discontinuities in the material.

This paper will focus on heat distribution in arc welding, specifically explaining Rosenthal mathematical model with graphical results.

2. Mathematical model

2.1. Daniel Rosenthal was the first to apply Fourier's law to moving heat sources and laid the foundation for analyzing temperature fields in welding. His mathematical model made the following assumptions [4]:

- Heat flow is constant.
- The heat source is a point.
- Heat loss from the surface is negligible for a semi-infinite body.
- Convection in the melting zone is neglected.
- Temperature properties are constant.
- Latent heat of fusion (melting) is neglected.

Rosenthal's equations form the basis of mathematical models for analyzing moving heat sources.

Three different mathematical analytical models describing a moving heat source will be used in this work.

The three cases that will be described and used in the program are:

- Point heat source on a thick plate.
- Linear heat source on a thin plate.
- Linear heat source moving at high speed (or instantaneous planar source) on a thin plate.

Point heat source on a thick plate

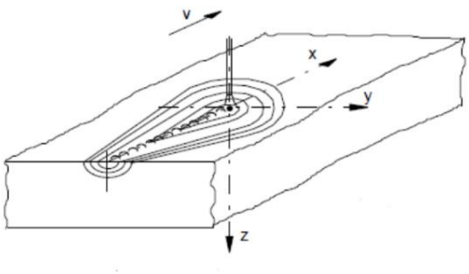

Figure 2.1. Moving point source on a thick plate

Equations for a moving point source traveling on the surface of an infinite body:

$$\vartheta(x,y,z)=\frac{q}{2\pi\cdot\lambda\cdot r}\cdot\exp\left[-\frac{v}{2a}\cdot(x+r)\right] \tag{2.1}$$

$$r=\sqrt{x^2+y^2+z^2} \tag{2.2}$$

$$\vartheta(x,y,z)=\frac{q}{2\pi\cdot\lambda\cdot\sqrt{x^2+y^2+z^2}}\cdot\exp\left[-\frac{v}{2a}\cdot\left(x+\sqrt{x^2+y^2+z^2}\right)\right] \tag{2.3}$$

Where is:
v – heat source velocity, m/s
$q = U\,I\,\eta$ – heat source power, W
a – thermal diffusivity of the material, m^2/s
λ – thermal conductivity, W/(m K)

Moving linear heat source on a thin plate

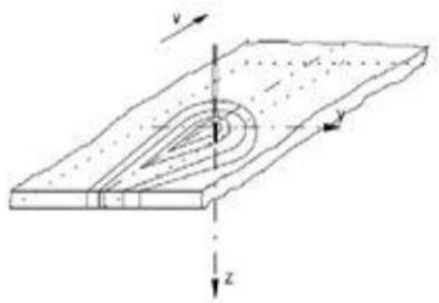

Figure 2.2. Moving linear heat source on a thin plate

$$\vartheta(x,y)=\vartheta(r,x)=\frac{q}{2\pi\cdot\lambda\cdot\delta}\cdot\exp\left(-\frac{v\cdot x}{2a}\right)\cdot K_0\cdot\left(r\cdot\sqrt{\frac{v^2}{4a^2}+\frac{b}{a}}\right) \tag{2.4}$$

Where is:
δ – plate thickness, m
b = 2a/($c\rho\delta$) – coefficient of temperature drop intensity due to heat dissipation to the surroundings, s^{-1}

K_0 – Modified Bessel function of the second kind, zero order

Instantaneous planar heat source

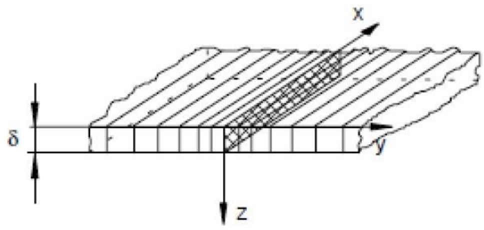

Figure 2.3. Instantaneous planar heat source

A moving linear heat source traveling at high speed transforms into an instantaneous planar heat source:

$$T(y_0,t)-T_0=\frac{q}{v\cdot\delta\cdot\sqrt{4\pi\cdot\lambda\cdot\rho\cdot c\cdot t}}\cdot\exp\left(-\frac{y_0^2}{4a\cdot t}\right) \tag{2.5}$$

Where:
y_0– position on the y-axis of the observed point, m
c – specific heat capacity, J/(kg K)
t – time, s

Calculation of cooling time from 800 °C to 500 °C:

$$t_{8/5}=\frac{E^2\cdot\eta^2}{4\pi\cdot\lambda\cdot\rho\cdot c\cdot\delta^2}\cdot\left[\left(\frac{1}{500-T_0}\right)^2-\left(\frac{1}{800-T_0}\right)^2\right] \tag{2.6}$$

Calculation of heat affected zone:

$$\check{S}_{ZUT}=y_{700}-y_{1500}=\frac{1}{\sqrt{2\pi\cdot e}}\cdot\frac{q}{v\cdot\delta\cdot\rho\cdot c}\cdot\left(\frac{1}{700-T_0}-\frac{1}{1500-T_0}\right) \tag{2.7}$$

Calculation of instantaneous cooling rate:

$$\frac{dT}{dt}=-\frac{q}{2v\cdot\delta\cdot\sqrt{4\pi\cdot\lambda\cdot\rho\cdot c\cdot t^3}} \tag{2.8}$$

3. Results

In the graphs shown in the user interface of the program, the *x*-axis represents the axis that extends in the direction of the weld, with positive values located in front of the heat source. The *y*-axis is the axis that extends perpendicular to the direction of the weld, with positive values extending to the right if the observer is in front of the weld. The *z*-axis extends in the depth of the weld, with positive values located in the direction of the metal. In the following text, point heat source results will be shown.

An analysis of the dependence of temperature on the *x* variable with the parameter value of *y* shows that the temperature increases as the observation point gets closer to the heat source, both along the *x*-axis and the *y*-axis. At the parameter value of *y* = 0.015 m, it can be observed that the temperature increases almost linearly as we approach the heat source from the back. The smaller the parameter value, i.e., the closer the observation point is to the heat source, the greater the temperature gradient. When comparing graphs for different *z* values, it can be observed that the graphs increasingly differ as the value of the *y* parameter decreases.

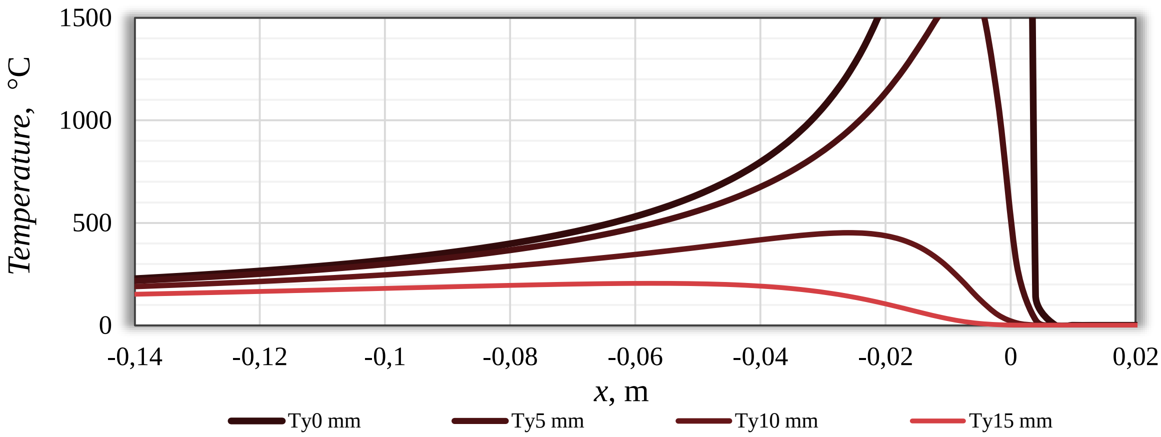

Figure 3.1. Temperature field *q = f(x,y)* with parametric value *y* for *z* = 0 mm

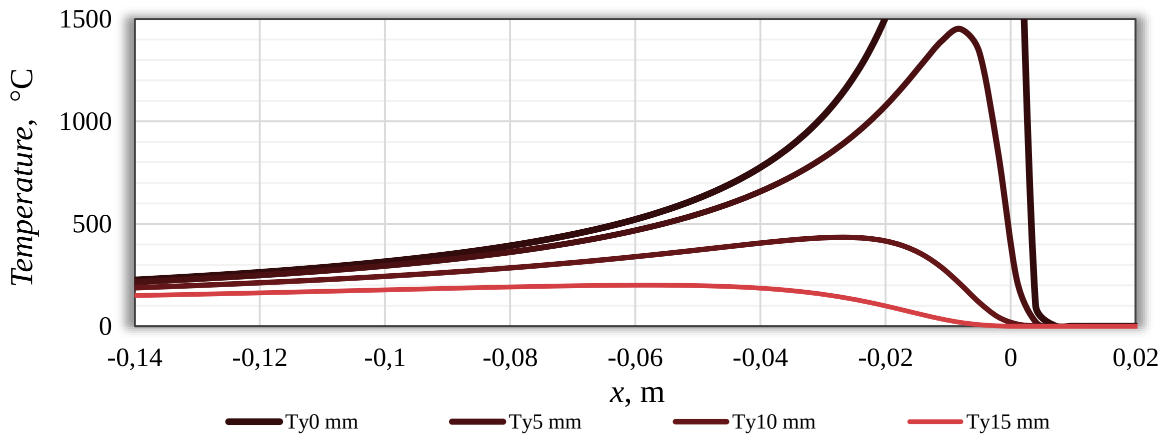

Figure 3.2. Temperature field *q = f(x,y)* with parametric value *y* for *z* = 2 mm

An analysis of the dependence of temperature on the *y* variable with the parameter value of *x* shows that the temperature exponentially increases as the value of the *y* variable approaches the heat source or 0. The mentioned graph is symmetrical with respect to the temperature axis. As the parameter value of x approaches zero, the change in temperature along the *y*-axis becomes greater until it reaches the melting point. The graph for the value of *z* = 0.002 m differs minimally from the graph for the value of *z* = 0 m, i.e., the temperature distribution changes only by 2 mm within the metal, and the temperature distribution on the surface where the heat source is located is very similar.

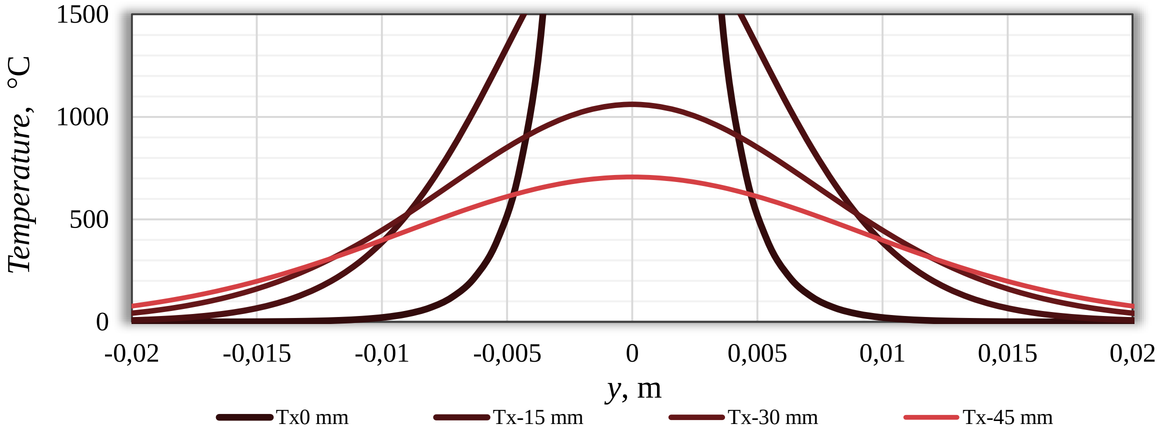

Figure 3.3. Temperature field *q = f(x,y)* with parametric value *x* for *z* = 0 mm

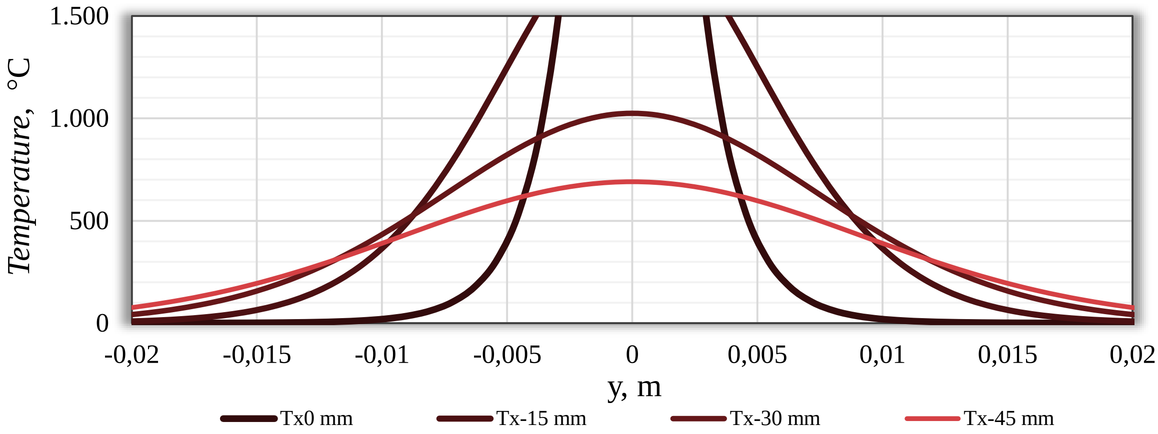

Figure 3.4. Temperature field *q = f(x,y)* with parametric value *x* for *z* = 2 mm

An analysis of the dependence of temperature on the x variable with the parameter value of v shows that the temperature exponentially increases as the speed of the point heat source decreases. The graphs for the values of z = 0 m and z = 0.002 m are very similar.

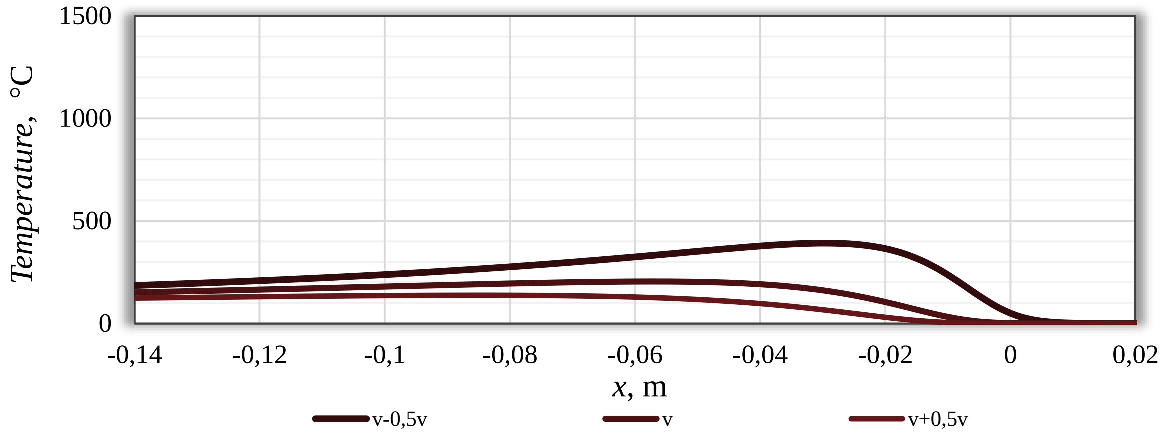

Figure 3.5. Temperature field $q = f(x,y)$ with parametric value v for z = 0 mm and y = 15 mm

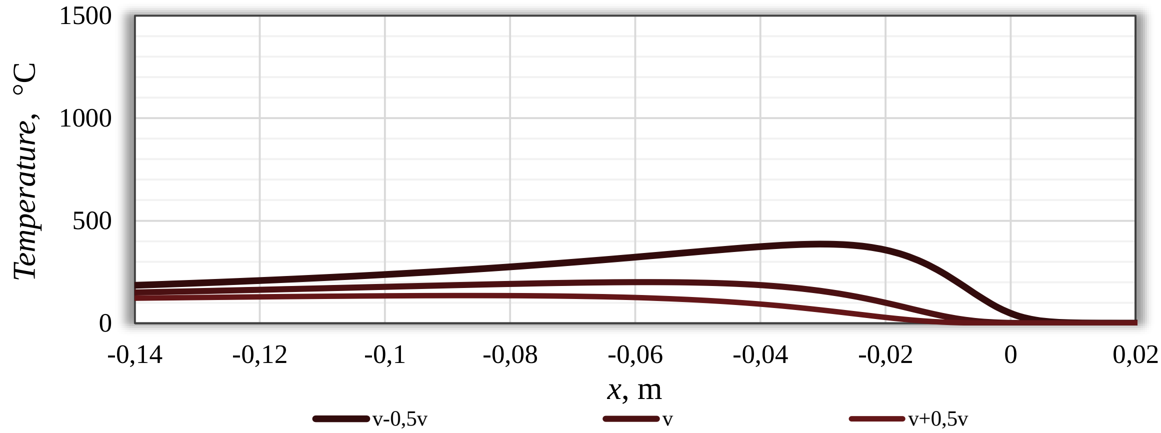

Figure 3.6. Temperature field $q = f(x,y)$ with parametric value v for z = 2 mm and y = 15 mm

4. Discussion

In all types of analysis, it can be seen that the temperature increases exponentially as it gets closer to the heat source. The graphs show that the maximum temperature value is defined as the melting temperature, and the graph is "cut off" there, meaning that it is horizontal. This is not because such a state is defined in the equation, on the contrary, according to the equation, the temperature would tend to reach very high values, but it is because it is defined in the program code that converts all temperature values that are higher than the melting point of the material to the melting point values [7]. This is one of the drawbacks of Rosenthal's equations, as it does not take into account the pool of molten material or the convection that occurs there. For example, if a value of 1700 °C is obtained by the equation, and the material's melting point is 1500 °C, the program code will put that value at 1500 °C to bypass the equation's limitation. The three-dimensional graph in the analysis of a moving point heat source is shown as a set of points, not as a surface because in that way it is possible to get the coordinate of each point with the mouse, which would not be the case with a surface. If the user wants to obtain a graph with higher density that more resembles a surface, they can simply increase the density of points on the x and y axes. This will put more strain on the computer, and if the certain number of points is exceeded (e.g., over 150 for both axes), the program may stop working.

After welding, the cooling of the metal is of utmost importance. By reducing the temperature in the metal, the microstructure that is directly related to the properties of the metal changes. Knowing the width of the heat-affected zone and the temperature changes near the weld, it is possible to determine the probability of crack formation and the amount of residual stresses at certain points in the metal. This part of the metal needs to be very well controlled during and after welding because it undergoes changes in the microstructure of the metal, and thus changes in the mechanical properties. The toughness and hardness of the metal change depending on the time i.e. cooling rate. By changing the cooling rate, we can find the optimal ratio of hardness and toughness (measured by impact fracture energy) for certain metal operating conditions. If we cool the metal at the wrong temperature, catastrophic failure may occur during operation [8].

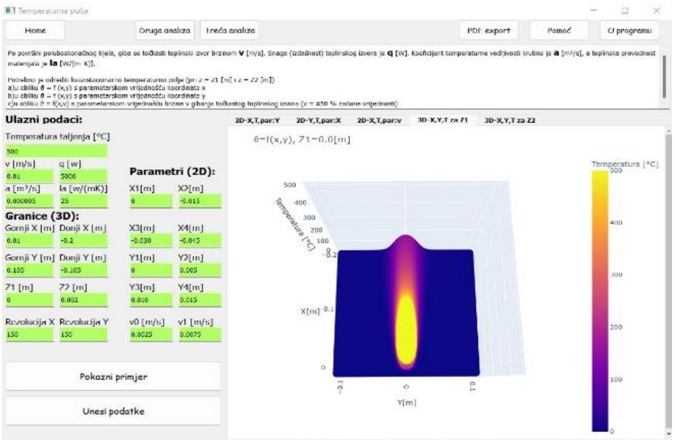

Figure 4.1. Graphical user interface of Python program

5. Conclusions

Welding is one of the most commonly used methods for joining metals. During welding, the metal melts, and there is a significant increase in temperature near the welding point. During cooling, there is a change in the microstructure, which directly affects the mechanical properties of the metal, especially toughness and hardness. The rate of temperature change, especially in the range of 800 °C to 500 °C, is very important for the final microstructure of the metal. Temperature distribution in welding is important for controlling the welded joint and can be described by analytical equations of temperature fields.

The analysis of temperature fields is based on analytical Rosenthal's equations of moving temperature fields. The equations used allow for quick approximate results. The downside of using these equations is the large number of assumptions that are not true for the actual case of heat transfer in welding. The accuracy of the results could be increased by using numerical methods of finite volumes compared to Finite Volume methodsThe downside of using FVM methods is a more complex code that uses larger computer resources, which greatly depend on the number of finite elements. Almost all modern programs for analyzing temperature fields use FVM methods (ABAQUS, ANSYS Fluent, OpenFOAM, Nastran, etc.).

The results of the Python program analysis of temperature fields show that the temperature value increases exponentially as the observation point gets closer to the heat source, and the temperature gradient increases as we approach the source. The value also increases as the heat source's movement speed decreases. The current cooling time is increasing as the preheating temperature increases. The current cooling rate is higher as the starting temperature of cooling is higher. The shape of the temperature cycle curve is similar if we observe points of the same coordinates but different preheating temperatures. This is because preheating temperatures have small values compared to the melting temperature of the metal.

The program for analyzing temperature fields developed in this thesis allows the user to choose the type of analysis and quickly obtain results in the form of interactive graphs that can be exported. In the future, it is expected that programs will be developed to analyze temperature fields during welding, which will be easier to use and will soon be available to welders on smartphones. The use of cameras and object recognition will provide an approximate solution for heat propagation and warn of critical points.

6. References

[1] Author(s): Marimuthu, P.; Latha, B.: An Overview of Welding and Welding Safety, *Journal of Industrial Pollution Control Volume: 31*, 2015., str.250-256

[2] Kou, S.:Welding metallurgy, John Wiley & Sons, 2003.

[3] Barac A., Živić M., Holik M., Končić R., Samardžić I.: Comparison of Experimental and Analytical Solutions of Temperature Field in a Submerged Arc Welding, 2019.

[4] Rosenthal, Daniel: Mathematical Theory of Heat Distribution During Welding and Cutting, *The Welding Journal*, 1941., str.220-234

[5] Goldak, J. A., Chakravarti, A., & Bibby, M.: A new finite element model for welding heat sources, *International Journal of Heat and Mass Transfer*, 1984., str.233-243

[6] DebRoy, T. : The science of welding, *CRC Press*, 2003.

[7] https://github.com/Ivor22/Temperaturna_polja

[8] Dunđer Marko: Utjecaj brzine hlađenja na tvrdoću i žilavost mikrolegiranih čelika, Disertacija, 2005.