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EFFICIENCY ESTIMATION OF A CAPACITIVE DISCHARGE WELDING PROCESS IN THERMOCOUPLES

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Abstract. *Determining the thermal input of a welding process is essential to improve the quality of the procedure. With the knowledge of the exact amount of heat used in the process, it is possible to control the equipment so that there is no excess or lack of energy. When there is an excess of energy in the process, the material can deteriorate or oxidize, losing its mechanical properties. The presence of oxidation also affects mechanical properties, which may lead to a rupture of the thermocouple during measurement applications. On the other hand, if there is a lack of energy, the junction of the materials becomes weak and can crack. In this work, inverse problem techniques are used to model and estimate the transient heat rate provided to a welding process accomplished by a capacitive discharge, in K-type thermocouple. An inverse heat conduction problem (IHCP) is that in which the boundary conditions or input parameters of the problem are unknown. To solve it, information of temperatures measured experimentally over time at some accessible point in the domain is used. Since the welding process under study is fast, obtaining temperature data in the regions of interest is tough. In addition, measuring the heat flux in the melt pool using a heat flux transducer, for example, would also be difficult. For this reason, it is essential to apply inverse heat transfer analysis, which can assess unknown or difficult-to-measure parameters. This experimental investigation of thermal effects is carried out using the software COMSOL® and the Specification Function Method (SFSM), which sequentially computes the heat flux at each time interval. To solve the IHCP in order to estimate the heat flux history, the SFSM searches for a heat flux that minimizes an objective function, which compares the temperature measurements taken close to the welding region with the numerical solution. Moreover, the efficiency of the welding process is also evaluated once the total energy employed is known by calculating the energy stored in the capacitor bank. The technique used to estimate the input power was efficient when compared with experimental temperature data.*

Keywords: *heat conduction, inverse problem, welding process, capacitive discharge, optimization*

1. INTRODUCTION

Various engineering materials and processes are affected due to exposure to high temperatures. One example is the welding process, which needs high temperatures to take place. As high temperatures change as mechanical properties and agents of materials, with this, oxidation of the materials to be welded can occur. Oxidation can alter a thermoelectric capacity of thermocouples. The consequence of these changes is a reduction in the accuracy and precision of temperature requirements.

Knowing the energy required in the welding process results in advantages such as better process efficiency, longer material life, and accurate temperature measurements.

The inverse heat conduction problem plays an important role in complex studies, such as the welding process and other manufacturing processes, where it is difficult to obtain satisfactory results with experiments alone. The inverse problems are used to estimate an unknown parameter, such as the actual heat rate provided during the process, from the temperature history measured experimentally within the domain.

One of the first works on inverse problems employing heat transfer was presented by Stoltz (1960), who presented a method to determine the heat flux on the surface of spheres during the quenching process. The Specification Function Method was proposed by Beck *et al*. (1985) to minimize noise in the temperature data presented by Stoltz (1960). This method does not require a lot of computational time and is robust to the noise present in the data.

Silva *et al.* (2012) estimated the surface heat flux of an AISI 304 stainless steel sample, using the inverse problem techniques of the Golden Section, Brent, Specification Function, Tikhonov Regularization and Variable Metrics. The authors concluded that all techniques were in agreement with the experimental temperatures. The Specification Function and Tikhonov Regularization techniques had a lower computational cost than the other techniques.

Brito *et al*. (2015) analyzed the thermal aspects in the operation of the cutting tool in the machining process. Due to the difficulty of obtaining process data with the tool in motion, they used the inverse problems by the Specification Function technique to determine the temperature field and the heat flux in the tool region.

Dourado *et al*. (2018) compared three inverse problem techniques: the Golden Section method with Time Travellling Regularization, the Specification Function Method, and the Iterative Sequential Function Specification Method. In order to estimate the heat flux in a three-dimensional problem in heat transfer. He concluded that for his problem the iterative techniques (Time Travellling Regularization and Iterative Sequential Function Specification Method) presented better results, but longer computational times.

In this paper it is proposed to use inverse problem techniques, together with the COMSOL Multiphysics software, to estimate the energy used in the capacitive discharge welding process, to obtain the welded joint in K-type thermocouples. The MATLAB program, with the technique of the Iterative Specification Function, was used to estimate the heat rate from experimentally measured temperatures in regions close to the weld joint. The thermal model considered is non-linear, as the thermal properties are temperature-dependent.

2. METHODOLOGY

2.1 Thermal model

The model domain is composed of three subdomains: A wire composed of Alumel, a wire composed of chromel and a solder sphere composed of a mixture of chromel and alumel. Each subdomain has distinct thermal properties, in addition to distinct convective properties. The heat diffusion equation for a nonlinear three-dimensional problem with phase change can be expressed as:

$$\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right)+\frac{Q(t)}{V}=\rho\frac{\partial H(T)}{\partial t} \tag{1}$$

where k is the thermal conductivity, T is the temperature, ρ is the density and t is the time. The enthalpy function can be defined as:

$$H=\int c dT+fL \tag{2}$$

where c is the specific heat, L is the latent heat and f is the Heaviside function, defined as a function of the melting temperature Tm. The function $\theta(T)$ is used to define the phase transition region, when $\theta(T)$=0 the domain is in the solid state, if $\theta(T)$=1 the domain is totally in the liquid state. $\theta(T)$ is modeled using the Heaviside function:

$$\theta(T)=\begin{cases}0, & T>Ts\\ 1, & T<T_L\\ 0.5+0.9375\left(2*\frac{T-T_m}{\Delta T}\right)-0.625\left(2*\frac{T-T_m}{\Delta T}\right)^3+0.1875\left(2*\frac{T-T_m}{\Delta T}\right)^5, & T_S<T<T_L\end{cases} \tag{3}$$

The heat flux, represented by $Q(t)$, acts uniformly on the sphere of volume V.

The thermal problem is subject to convection and radiation boundary conditions:

$$-k(T)\frac{\partial T}{\partial \eta}(x,y,z,t)=h(T)(T-T_\infty)+\sigma\varepsilon(T)(T^4-{T_\infty}^4) \tag{4}$$

where η is the normal direction, h is the convection heat coefficient, σ is the Stefan-Boltzmann constant, ε is the emissivity and T_∞ is the ambient temperature. The convection heat transfer coefficient h was defined constant for the thermocouple wires as 15 W/m² and for the welded joint the correlation defined by Incropera *et al*. (2008) for a sphere, such as:

$$Nu_D=2+\frac{0.589Ra_D^{1/4}}{\left[1+\left(\frac{0.469}{Pr}\right)^{9/16}\right]^{4/9}} \tag{5}$$

where Ra_D is the Rayleigh number, Nu_D is the Nusselt number and Pr is the Prandtl number.

The calculation of the three-dimensional temperature distribution was performed using the Finite Element Method through the commercial program COMSOL Multiphysics. A tetrahedral mesh with 54000 elements was generated. The thermophysical properties, specific mass, conductivity $k(T)$ and specific heat $c(T)$ considered for Alumel and Chromel were obtained from Buttsworth (2001), in addition, emissivity values of 0.1 for chromel and 0.6 for alumel were obtained from Sasaki *et al.* (1994).

$$c_{cromel}(T) = 0.1786 * T + 394.3 \quad \text{[J/kgK]} \tag{6}$$

$$k_{cromel}(T) = 0.01912 * T + 12.11 \quad \text{[W/mK]} \tag{7}$$

$$c_{Alumel}(T) = 0.0712 * T + 500.8 \quad \text{[J/kgK]} \tag{8}$$

$$k_{Alumel}(T) = 0.02981 * T + 18.42 \quad \text{[W/mK]} \tag{9}$$

The thermal properties in the phase transition zone are calculated as the weighted average of the solid/liquid fraction represented by the $\theta(T)$ in Eq. 3.

It was considered, approximately, that the sphere representing the welded joint is formed by 50% of Alumel and 50% of Chromel. Thus, the thermophysical properties in this subdomain are obtained by averaging the properties of the metals that make up the thermocouple.

Figure 1 shows the geometry of the thermocouple with welded joint, which was used in the three-dimensional thermal model. In this model, the welded end of the T_0 initial temperature thermocouple is subjected to a transient heat source, caused by a capacitive discharge. This heat flux fuses the two entwined ends, where phase transformation occurs and a solder sphere is formed.

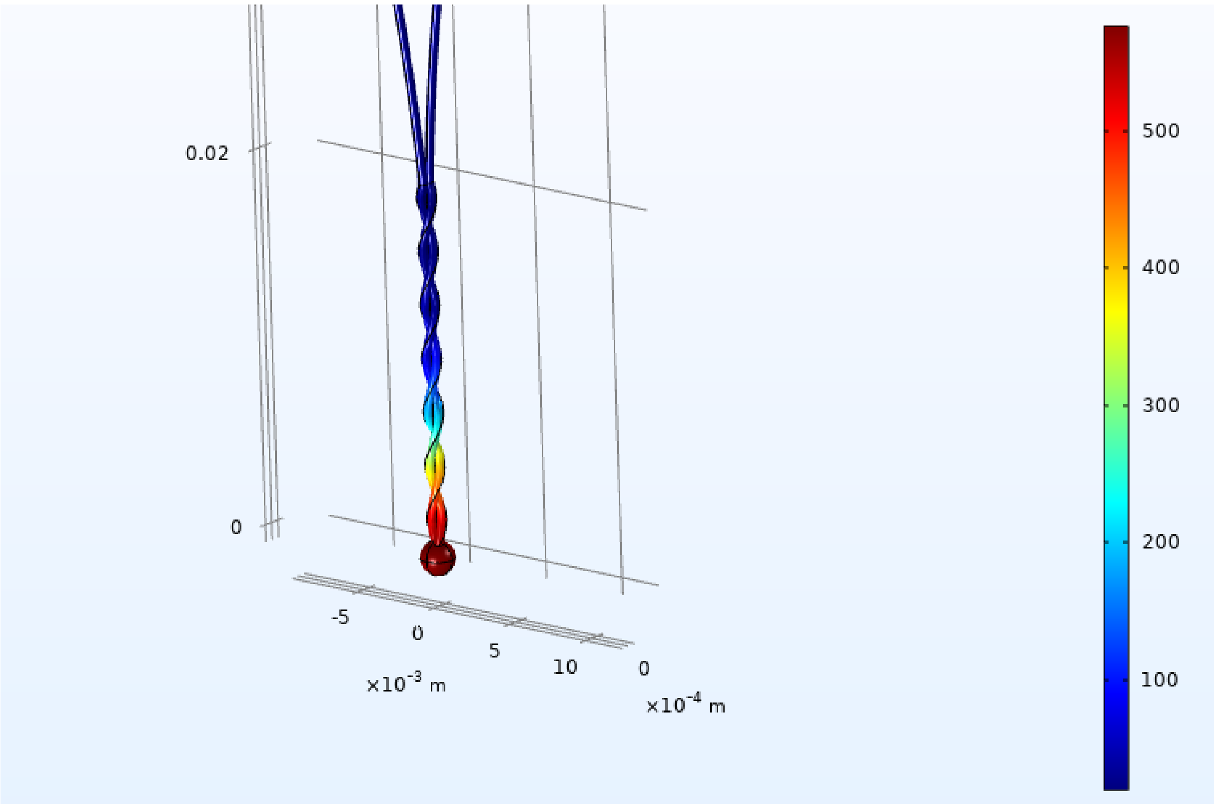

Figure 1. Tree-dimensional thermal model

2.2 Experimental Procedure

For the application of the inverse problem technique, experiments were necessary, which were performed in the Heat Transfer Laboratory of the Federal University of Itajubá.

The bench used to carry out the experiments is shown in Figure 2. A type K 30 AWG thermocouple was welded, through a capacitive discharge welding equipment, in a type K 24 AWG thermocouple 4mm away from the end of the latter. The 30 AWG thermocouple was connected to a 34980A data acquisition that was controlled by a microcomputer. The 24 AWG thermocouple welding was performed, the welding result is shown in Figure 3, and the temperature data, shown in Figure 4, were obtained.

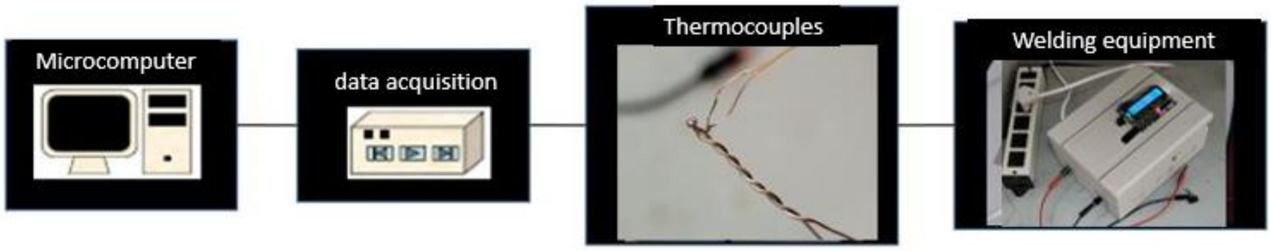

Figure 2- Assembly scheme of the experimental bench used in carrying out the experiments

Figure 3. Welded thermocouple

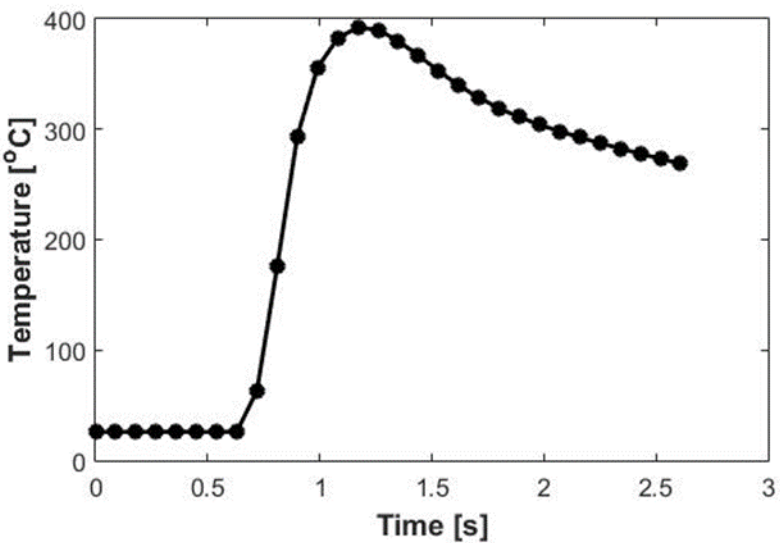

Figure 4- Curve of the experimental temperature distribution in the welding process.

2.3 Iterative Sequential Function Specification Method (SFSM)

The SFSM Interative is a technique based on the Gauss Minimization Method with regularization in future times (Beck and Arnold, 1977), capable of solving non-linear inverse heat conduction problems.

The vector T is considered a vector of observations with size n, dependent on another vector with unknown parameters β of length p, when a variation of Δb is applied to this vector, the temperature at a point in the domain can be approximated through the Taylor series :

$$T|_{b+\Delta b} \approx T|_{b} + \left.\frac{\partial T}{\partial \beta}\right|_{b} \Delta b \tag{10}$$

Equation (11) represents the sensitivity matrix, which represents the gradient of Eq. (10).

$$\boldsymbol{X_\beta} = \frac{\partial \boldsymbol{T}}{\partial \boldsymbol{\beta}} = \begin{bmatrix} \frac{\partial T_1}{\partial \beta_1} & \frac{\partial T_1}{\partial \beta_2} & \cdots & \frac{\partial T_1}{\partial \beta_{np}} \\ \frac{\partial T_2}{\partial \beta_1} & \frac{\partial T_2}{\partial \beta_2} & \cdots & \frac{\partial T_2}{\partial \beta_{np}} \\ \vdots & \vdots & \ddots & \\ \frac{\partial T_{no}}{\partial \beta_1} & \frac{\partial T_{no}}{\partial \beta_2} & \cdots & \frac{\partial T_{no}}{\partial \beta_{np}} \end{bmatrix} \tag{11}$$

The inverse problem is solved by minimizing Eq. (12).

$$S = (Y - T)^T - (Y - T) \tag{12}$$

Substituting Equations (10) and (11) in Eq. (12), and minimizing it for Δb, results:

$$\Delta b = \left(X_\beta^T X_\beta\right)^{1} X_\beta^T (Y - T/_b) \tag{13}$$

For the inverse problem studied, the parameter β has only one component, which is the welding power $Q(t)$, so we have $\Delta b = \Delta Q$. For each time step M, the increment ΔQ must be computed until Eq. (14) reaches convergence.

$$Q_M^{(i+1)} = Q_M^{(i)} + \Delta Q_M^{(i)} \tag{14}$$

2.4 Quantity of Energy Stored in the Capacitor Bank

According to Halliday *et al.* (2014) when there is an association of capacitors in parallel, each capacitor has the same potential difference. In this case, the total electrical charge stored in the association is the sum of the charge of all capacitors.

The stored energy equation can be defined as:

$$W = C * \frac{V^2}{2} \tag{15}$$

where W is the stored energy, C is the total capacitance and V is the voltage applied to the capacitor bank.

The capacitive discharge welding equipment is composed of three 22000 µF capacitors totaling a total capacitance of 66000 µF, which are subjected to a voltage of 40 V, so the total energy stored in the capacitor bank is 52.8J.

3. RESULTS

In this section, the result of the estimation of the welding power and time obtained by the Iterative SFSM technique together with COMSOL is presented.

The power was estimated using a smoothing parameter, r, of 3 future time steps. Figure 5 presents the result of the estimated power using the Iterative Specification Function Method. The estimated maximum power was 37.8 W, the power reaches its maximum value between the times of 0.63 and 0.72 seconds and returns to zero at the time of 0.92 seconds.

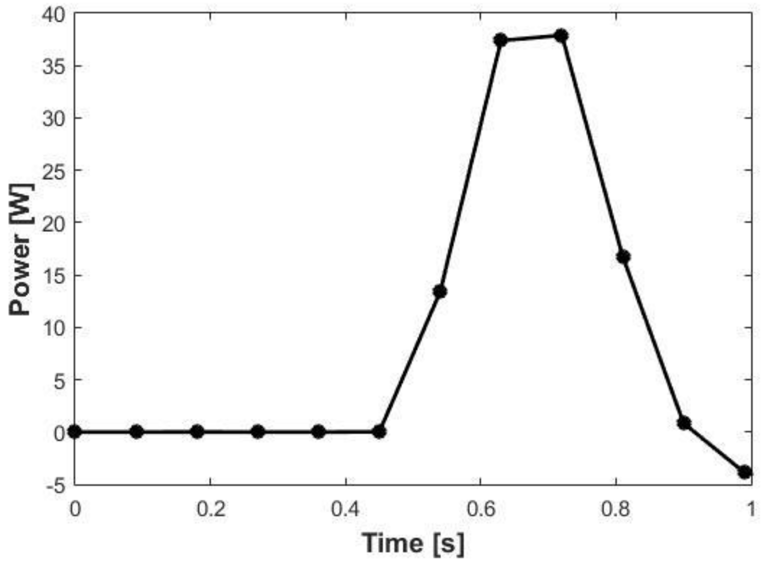

Figure 5. Estimated power as a function of time by the Iterative Specification Function Method.

In Figure 6 the relative error of convergence of the applied method is presented, the method converges to errors smaller than 0.001, so for all time steps the convergence was reached.

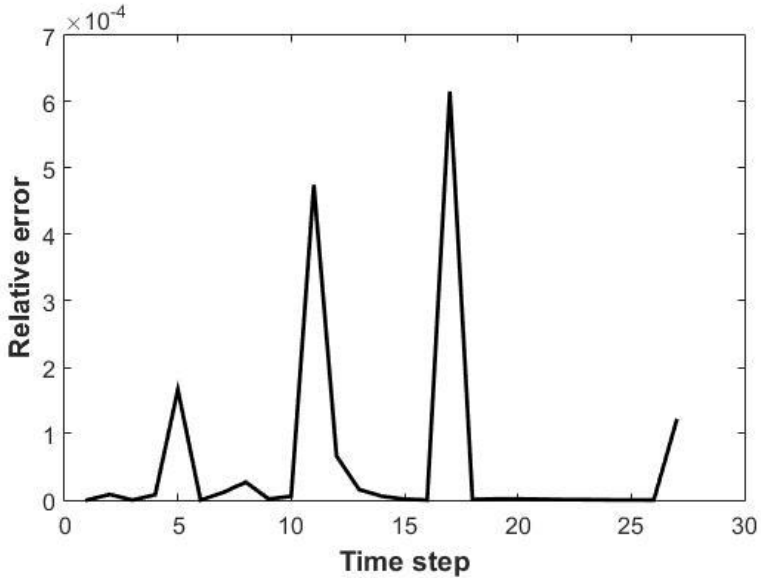

Figure 6. Relative error

Figure 7 shows the comparison of experimentally measured temperature data and temperatures estimated from the estimated power. The temperature values obtained experimentally are very close to those calculated. The residual values between the experimental and estimated temperatures are represented with the dashed line in the graph shown in Figure 7. The maximum temperature residual obtained is 16 °C, with an average of 0.16 °C and deviation of 4.8 °C .

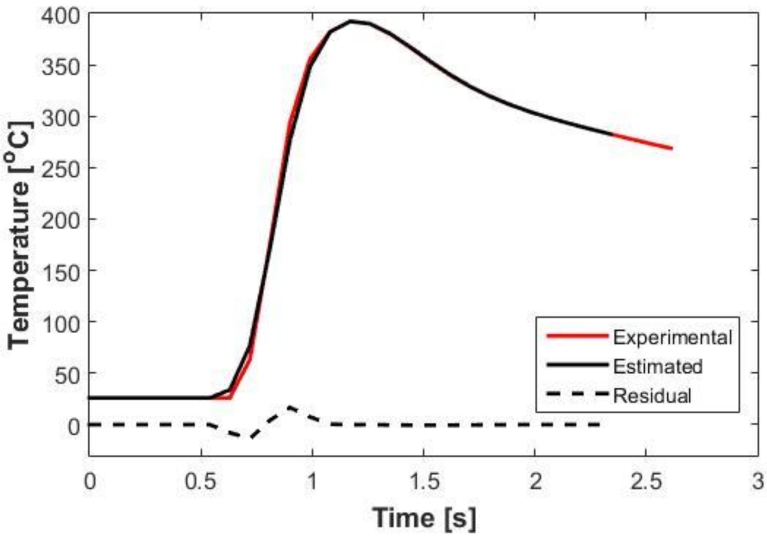

Figure 7. Estimated, experimental temperature and residual temperature.

To calculate the efficiency, the energy generated by the heat flux estimated in Joules was used, calculated by the cross-hatched area in Figure 8. And it is obtained by the integral of the power estimated by the time of the welding process by capacitive discharge. The calculated energy value was 9.5293J.

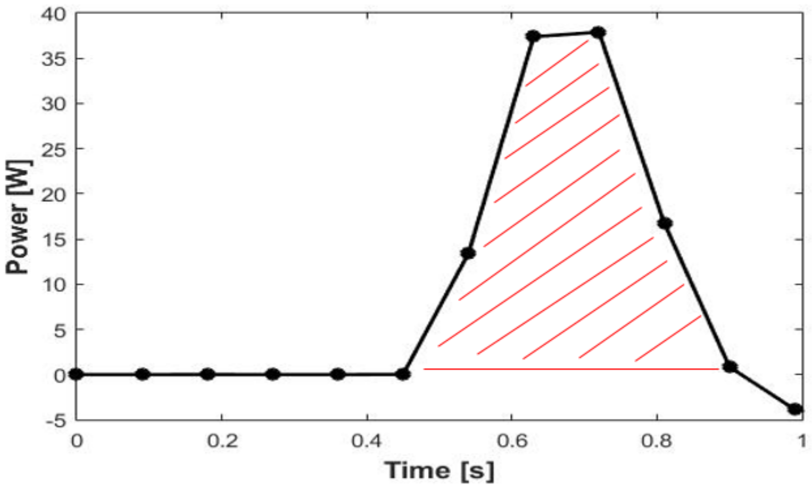

Figure 8. Energy used in the welding process.

Efficiency is given as:

$$\eta = \frac{E}{W} \tag{16}$$

where η is the efficiency, E is the energy consumed by the heat flux and W is the total energy stored in the capacitor bank.

The average efficiency value calculated for the capacitive discharge welding process was 0.18048. The heat flux time produced by the capacitive discharge was estimated at 0.47s. With the energy generated by the heat flux of 9.5293J, it was possible to make a weld sphere with a diameter of 1.83mm, which is effective for using the thermocouple. The low efficiency of the process can be explained by the large dissipation of energy by light and noise during the process.

4. CONCLUSIONS

This work presented an inverse problem technique to estimate the power of the capacitive discharge welding process. The Iterative Sequential Function Specification method was able to estimate the power used in the process, which resulted in good results in the comparison of experimental with estimated temperature data.

The use of COMSOL allowed to make adjustments in the boundary conditions in order to obtain a thermal model close to reality, this was essential so that the model data could be compared with the experimental data.

The suggestion for the next papers is to replicate the method used in the welding of other types of thermocouples, such as T-type, E-type, J-type, and others, which are made of materials different than those studied in this work.

5. ACKNOWLEDGEMENTS

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