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Thermal Circuit Model of the Pulse DC Sintering System Container During Cooling

*[1]Tuba Yener,[2] Suayb CagriYener, and [3]Resat Mutlu

[1]Department of Materials and Metallurgy Engineering, Sakarya University, Sakarya, Turkey
[2]Department of Electrical and Electronics Engineering, Sakarya University, Sakarya, Turkey
[3]Department of Electronics and Telecom. Eng., Namik Kemal University, Corlu, Tekirdag, Turkey

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Abstract

Pulse DC Sintering System (PDCS) is a cheap and quick way of producing different types of materials. After sintering of the sample, the cooling of the PDCS container is needed before taking it out. The sample production time is the sum of the sintering and the cooling time. Therefore, estimation of the sample cooling time must be made accurately to model sample production. Its container dimensions and the material, it is made of, determines its temperature during cooling. In this paper, a thermal circuit which models a pulse DC sintering system container during cooling is given. Its thermal circuit model is made assuming that some heat leaks from the steel container to the cooper bars, the copper bars and the container all have natural convection and also radiate heat to cool down. The thermal model is described with a set of nonlinear state-space equations. The state-space equations are solved numerically using Runge-Kutta 4 method. The time required to make the sample cool down to ambient temperature is calculated using simulations. The temperatures of the container and the copper bars of an PDCS system are measured to find the experimental cooling time. The results are compared. The PDCS thermal model is able to verify the experimental results. It has also been experimentally shown that the cooling time is not dependent on the sample type produced for the examined PDCS system. Such a model can be easily implemented in an engineering software which aims to model the sample production process of the PDCS system and can also be used for its optimization considering its physical parameters such as dimensions, electrical and mechanical constants etc.

Keywords: Material Production, Pulse DC Sintering, Thermal Circuit Model

Darbeli DC Sinterleme Sistemi Konteynerinin Soğumasına Yönelik Termal Devre Modeli

*[1]Tuba Yener,[2] Suayb Cagri Yener, and [3]Resat Mutlu
[1]Department of Materials and Metallurgy Engineering, Sakarya University, Sakarya, Turkey
[2]Department of Electrical and Electronics Engineering, Sakarya University, Sakarya, Turkey
[3]Department of Electronics and Telecom. Eng., Namik Kemal University, Corlu, Tekirdag, Turkey

Öz

Darbe DC Sinterleme (PDCS), darbe genlik modülasyonlu doğru akım kullanarak farklı tipte malzemelerin ucuz ve hızlı biçimde üretilmesini sağlayan bir yöntemdir. Bu yöntemde numunenin sinterlenmesinden sonra, PDCS konteynerinin soğuması gerekir. Toplam üretim süresi sinterleme ve soğuma süresinin toplamıdır. Bu nedenle, numune üretim zamanını modellemek için numune soğuma süresinin belirlenmesi gereklidir. Kalıp boyutları ve üretilen malzeme, soğuma sırasındaki sıcaklığı belirler. Bu çalışmada, soğuma sırasındaki elektrik akım destekli sinterleme sistemi konteynerini modelleyen bir termal devre sunulmuştur. Isı devresi modeli, çelik konteynerden bakır baralara ısı transferi olduğu; bakır baralar ve konteynerin soğuma için doğal taşınıma sahip yayınım ile ısı yaydığı yaptığı kabulüyle oluşturulmuştur. Termal model, doğrusal olmayan durum-uzay denklemleri ile tanımlanmış ve denklemler numerik olarak Runge-Kutta 4 metodu kullanılarak çözülmüştür. Numunenin ortam sıcaklığına kadar soğuması için gereken süre simülasyonlar kullanılarak hesaplanmıştır. Elde edilen sonuçlar, konteyner ve bakır bara sıcaklıkları

*Corresponding Author: Department of Materials and Metallurgy Engineering, Sakarya University, Sakarya, Turkey

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deneysel olarak ölçülen bir PDCS sisteminden elde edilen sonuçlarla karşılaştırılmıştır. Deneysel olarak, soğuma süresinin, incelenen PDCS sistemi için üretilen numune tipine bağlı olmadığı da gösterilmiştir. Böyle bir model, PDCS sisteminin numune üretim sürecini modellemeyi amaçlayan bir algoritmaya ve bunu gerçekleyecek donanıma kolayca uygulanabilir. Ayrıca önerilen model; boyutlar, elektriksel ve mekanik sabitler vb. fiziksel parametreleri dikkate alarak gerçekleştirilebilecek optimizasyon süreçlerinde kullanılabilir.

Anahtar Kelimeler: Malzeme üretimi, Darbeli DC Sinterleme, Termal Devre Modeli

1. INTRODUCTION

Pulse DC sintering system (PDCS) is a method which enables the production of different material types by using mechanical load and electric current to strengthen the inter-particle bonding and to intensify bonding [1–10]. Prediction of process time of sample production is an important PDCS parameter [1–4]. Finding the cooling time of a PDCS device is very important to predict the sample production time or the process time since the sintering of the sample may also continue during cooling. Therefore, a method is needed to predict/calculate the cooling time. Heat transfer equations written for zero internal heat production describe also the cooling of the PDCS system. However, their solutions are not analytically possible due to the fact that the system having nonlinear mechanical and the heat transfer equations coupled together and also having irregular boundaries making their solution not possible. A PDCS system for a complete analysis can be analyzed using numerical methods Finite elements (FEM), Boundary elements (BEM) or Finite differences (FD) methods. However, programs which uses Finite elements (FEM), Boundary elements (BEM) or Finite differences (FD) methods are expensive and also takes time to input the system parameters or physical dimensions and they also require some practice [11, 12]. This paper examines the cooling of such a PDCS device using lumped-parameter thermal circuit model. First, the biot number for copper bars and steel container are calculated and it is shown that it is possible to use the lumped parameter circuit to model the PDCS system, the thermal circuit parameters are calculated, and the dynamic model of the thermal circuit including radiation and convection loss and the power transferred from container to the copper bars are made. Since the thermal circuit due to the radiation loss is also nonlinear, Simulink^{TM} toolbox of MATLAB^{TM} is used to simulate the dynamic system during cooling. The cooling time is estimated from the simulation data. Then, experiments are performed to measure cooling time of the PDCS system for two intermetallic samples. Finally, the experimental and simulated cooling times are compared.
This paper is arranged as follows. In the second section, the PDCS system is introduced; the thermal circuit model and its state-space equations are given. In the fourth section, the experimental data acquired during cooling is given and the results obtained from simulations and experiments are compared. The paper is finished with the conclusion section.

2. PDCS SYSTEM THERMAL CIRCUIT MODEL

Heat transfer model of the PDCS system during cooling is derived in this section. During cooling, the dissipated power density per volume is zero. Considering the convection and radiation losses, a lumped parameter thermal circuit model of the PDCS system is done.

2.1. PDCS System

Let’s consider heating mechanism of the PDCS system given in Figure 1. It consists of a cylindrical cut container made of 1% carbon steel at whose middle cross-section, the sample covered with graphene is placed, two cylindrical stiffs made of 1% carbon steel which are used to press the sample from the bottom and above, the copper bar electrodes above and below the stiffs which are used for electrical connection to sources. Copper bar electrodes are actually longer than the ones shown in Figure 1. However, for modeling purposes, only the rectangular parts of the electrodes are considered.

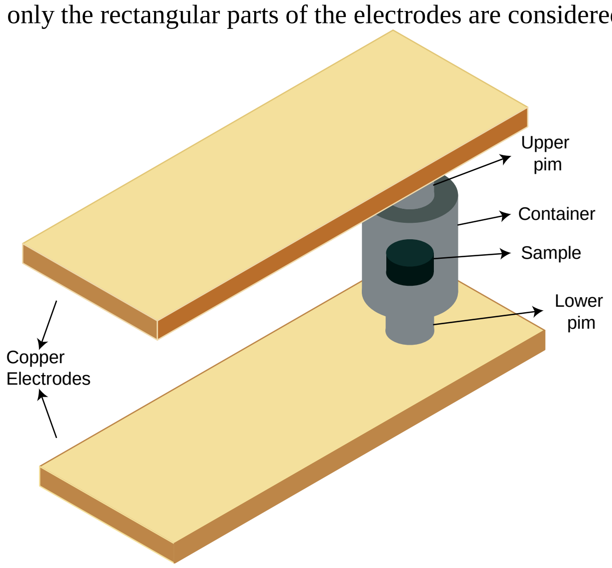

Figure 1. The PDCS System.

2.2. Thermal Conductivity of Steel

The thermal conductivity of carbon steel data is taken from [13] and it is modeled as

$$k_S(T) = p_1T^2 + p_2T + p_3 \quad (1)$$

Using the data and the least squares method, the coefficients are found as p1 = 4.0534e-006, p2 = -0.010813and p3 = 36.566.The steel thermal conductivity is to be used to model between the container and the copper bars.

2.3. Calculation of an Equivalent Biot Number

We have predicted that most of the heat transfer dynamics from copper and steel container are governed by convection and radiation. The steel and copper thermal resistances are nonlinear circuit elements. Therefore, their temperature can be assumed as uniform. In this paper, an equivalent Biot number which takes not only the convection but also the radiation is considered. It is defined as

$$Bi = \frac{\textit{Convection and radiation from the surface of the object}}{\textit{The conduction from throuhout the object}} \quad (2)$$

Since the radiation is temperature dependent, we take a maximum temperature of 1000 ^{0}C for the steel container to calculate its equivalent Biot number and it is found less than 0.1. For copper bars, we have assumed they have the symmetric temperature distribution by respect to container and we take a maximum temperature of 200 ^{0}C for the copper bars and their equivalent Biot number is also found to be less than 0.1. Therefore, their temperature can be assumed to be uniform Therefore, the PDCS system can be treated simply as a lumped parameter problem, for which Bi < 0.1 and for which it is seldom necessary to solve the conduction equation, i.e., convection and radiation is the rate controlling process [14]..Because of this, the temperatures of both the copper bars and the steel container can be assumed to be uniform.

2.4. Lumped-parameter Thermal Circuit

The thermal circuit shown in Figure 2 is considered in this paper. The thermal circuit is a simple approximation to the heat transfer model. The sample is placed at the container center which can be insulator, intermetallic etc. The copper and the steel sections, whose thermal conductivities are quite high, conduct heat very well. The container has a low thermal conductivity since it is made of steel. It has also a higher electrical resistance than the copper electrode bars. Also, it has a small area for convection and radiation. Its higher electrical resistance, its lower thermal conductivity and its smaller contact cross-section results in its temperature getting greater than the copper electrodes, which has a better thermal and electrical conductivities and a larger cross-section for convection and radiation, during heating. Because of these reasons, the container stores a significant amount of thermal energy due to having a high temperature although its volume or mass is quite less than the copper electrodes. The copper electrode bars also store considerable amount of energy due to its higher volume despite its temperature being lower than the container. The ambient medium is air which does not flow. Therefore, the system losses heat due to both natural convection and radiation loss. The air temperature is assumed to be constant at room temperature and its convection constant is taken from [14] for the case that the air flow speed is zero. It is assumed that the container and the copper bars have homogenous initial temperatures. There is a temperature gradient between the copper bars and the container throughout the steel stiff sections staying outside the container. The thermal circuit model of the PDCS container is given in Figure 2 and the circuit elements are explained below.

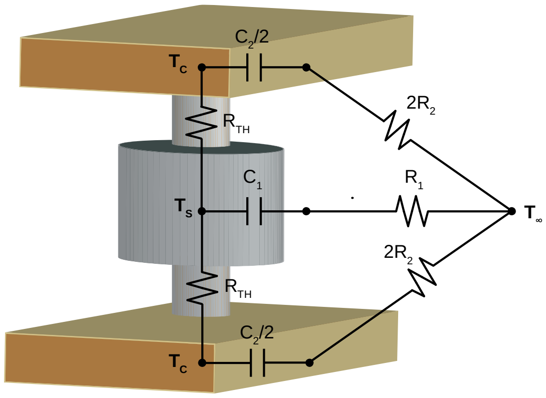

Figure 2. The lumped parameter thermal circuit model of the PDCS system during the cooling.

In the thermal circuit, R1 is the nonlinear thermal resistance which models both the radiation and convection loss from container and stiffs to the ambiance, R2 is the nonlinear thermal resistance which models both the radiation and convection loss from copper bars to the ambiance, RTH is the thermal resistance of the stiffs, C1 is the thermal capacitance of the PDCS container and the stiffs, C2 is the thermal capacitance of the copper.

2.5. The State-space Model of the Lumped-parameter Thermal Circuit

Considering conservation of the energy and submitting object physical parameters such as area, surface, thermal conductivity etc., the state-space model of the lumped-parameter thermal circuit can be written as

$$\rho_S V_S C_S \frac{dT_S}{dt} = -A_S\left(k_{SB}\varepsilon_S T_S^4 + h_C\left(T_S - T_\infty\right)\right) + \frac{2\left(T_S - T_C\right)}{R_{TH}} \quad (3)$$

$$\rho_C V_C C_C \frac{dT_C}{dt} = -A_C\left(k_{SB}\varepsilon_C T_C^4 + h_C\left(T_C - T_\infty\right)\right) - \frac{2\left(T_S - T_C\right)}{R_{TH}} \quad (4)$$

Where T_S is the container temperature in Kelvin, T_C is the copper bars' temperature in Kelvin, T_∞ is the ambient temperature, k_{SB} is the Stephan-Boltzman constant, ε_S is the emissivity of the steel, ε_C is the emissivity of the copper bars, h_C is the natural air convection constant, A_S is the container area, V_S is the container volume, ρ_S is the steel density, C_S is the specific heat of the steel, V_C is the copper bar volume, ρ_C is the copper density, C_C is the specific heat of copper, and R_{TH} is thermal conductance of the stiff section between the container main body and a copper bar. The container stiffs are made of steel and their thermal conductivity is a function of temperature. Therefore, the thermal resistance, R_{TH} of the inter-stiff sections staying between the container and the copper bars is modelled as temperature-dependent resistance:

$$R_{TH} = \frac{h_{stifft}}{k_S(T)A_{stifft}} \quad (5)$$

The sample volume is less than container volume. So is the heat capacity of the sample. Therefore, its effect in the thermal dynamics is ignored:

$$\rho_S V_S C_S \ll \rho_{Sa} V_{Sa} C_{Sa} \quad (6)$$

For the system used in this study, the copper bars have a higher heat capacitance than the container has. They lose heat due to convection since it is surrounded by air and also by radiation.

Due to the high heat capacitance and also the heat lost from the container to the copper bars, copper bar temperature rises a little above the initial value while the container temperature keeps falling down. When the copper bars' and container temperatures becomes equal, the copper bars' and container temperatures start falling down together At the beginning since container temperature is a lot higher than the room temperature and the system has natural cooling and radiation loss. Since the radiation loss is proportional to the fourth power of the temperature, the convection heat loss is less than the radiation heat loss when sample is hot at the beginning. The thermal circuit model also requires the initial temperatures of the copper bars beside the initial temperature of the container.

3 SIMULATIONS and COMPARISON OF THE RESULTS

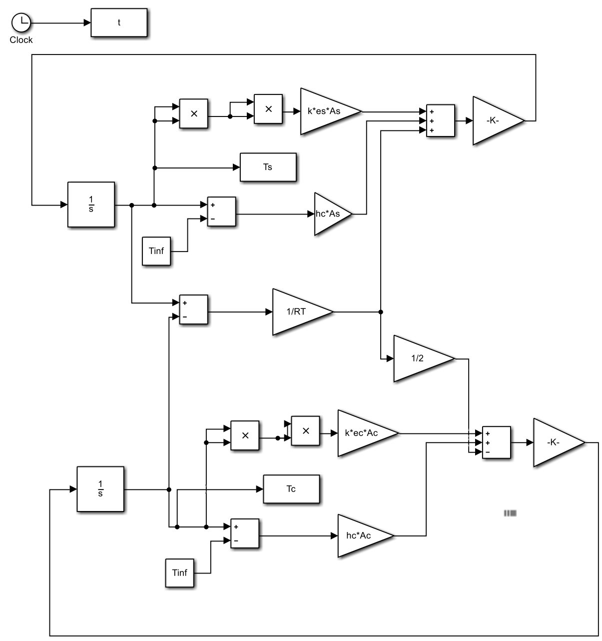

Figure 3. Simulink block diagram of the PDCS thermal circuit during cooling.

Since the differential equations describing thermal circuit equations are nonlinear, they require numerical solutions. That's why numerical analysis of the PDCS system is performed using SimulinkTM toolbox of MatlabTM. A Simulink block diagram shown in Figure 3 is made to solve this nonlinear equation. During simulations, container inner radius, outer radius and height are taken as 16.5mm, 9mm, 23mm, respectively. Radius of both upper and lower pins are taken as 9mm. Their total height is taken as 27mm and it is assumed that they were stretched out equally, 2mm below and 2mm above.

The reult obtained with the Simulink model is compared with the real cooling data obtained using IR thermometer after sintering process. The simulation and experimental cooling characteristics with respect to time for 926˚C initial condition are shown in Figure 4.

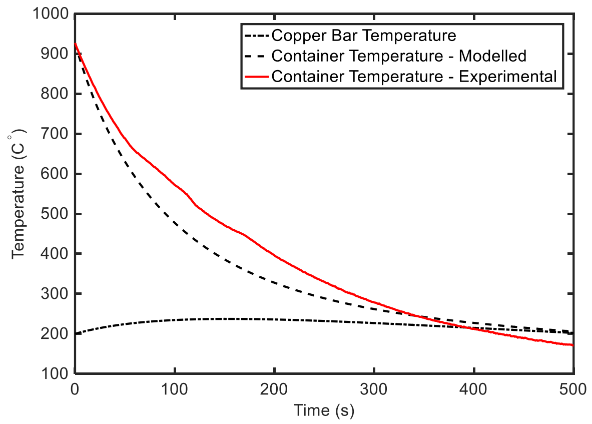

Figure 4. PDCS container temperature vs time by simulations for 926˚C initial condition.

We defined the cooling time as the time the container temperature falls down to 200 ^{0}C and at this temperature the hydraulic press is opened and the container is released. For an initial container temperature of 926^{0}C, the cooling time is found around 500 seconds. The simulation and the experimental cooling times are almost same. Therefore, the lumped parameter thermal model of the PDCS system can successfully be used to predict the sample cooling time for different initial container temperatures. It has been also found from the several experiments made with intermetallic and insulator samples that the cooling time is almost independent on the sample type produced for the reported PDCS system and this verifies the assumption made in the Section 0. For high steel temperatures, the steel stiff resistances must be estimated well or their temperature dependency must be modeled accurately for a good estimation of the cooling time.

4. CONCLUSIONS

For a method like resistive sintering, it is very important to estimate the sample production time which is the sum of the sintering time and the cooling time. In this study, first a thermal circuit model of the PDCS system is made. Nonlinear Thermal resistances resulting from, radiation and convection losses, and conduction are used in the thermal circuit. Thermal resistances and thermal capacitances of the PDCS container, the inter-stiff sections, and copper bars are also calculated using material properties and physical dimensions. It is also highlighted that only the inter-stiff sections' thermal resistances, which connect the container to the copper bars are of importance and the temperature dependence of the rest of the thermal resistances in the PDCS system is not of importance since the biot numbers are less than 0.1. The cooling time is estimated by simulations. Second, the temperature of the PDCS system container is measured experimentally, after real sintering processes, during cooling intervals. The cooling time is also calculated from experiments. It has been found that the cooling time is almost independent on the sample type produced for the reported PDCS system since the sample volume is much less than the container volume, its effect on cooling time is negligible since the solids have almost the same specific heat capacitance. And third, the results of the proposed thermal circuit model in this study are compared to that of the real experimental data. It has been shown that the simulation and experimental results are in good agreement and our model is able to predict cooling time with acceptable error. We leave estimation the sintering time for the future work since it is much more difficult to estimate than the cooling time due to the internal heat produced in the PDCS container.

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