**Effects of die geometry and insulation on the energy and electrical parameters analyses of spark plasma sintered TiC ceramics**

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**A B S T R A C T**

This work conducts a numerical simulation to investigate the temperature and electric current distribution during the spark plasma sintering (SPS) process using the finite element method (FEM) carried out in COMSOL Multiphysics software. The main goal is to optimize the SPS process for titanium carbide (TiC) ceramics, with a particular focus on the effects of insulation and die geometry (height and thickness). For the TiC material, the ideal sintering temperature is set at 2000 °C. The study analyzes eight case studies, involving a base case, an insulating case, and six cases with various thicknesses and heights, to evaluate the effectiveness of the suggested optimization. The results show that using insulation on the die surface reduces heat transfer from the die surface significantly, which leads to a 63% decrease in input power consumption when compared to the basic scenario. Based on a correlation study between energy and electricity, increasing die thickness raises the cross-sectional area of the electric current, which raises the amount of electric power required to attain the 2000 °C sintering temperature. The results indicate the temperature distribution in the sample is more sensitive to changes in die height than to changes in die thickness.

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**Abbreviation**

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
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<tbody>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>UHTCs</td>
<td>Ultra-high temperature ceramics</td>
</tr>
<tr>
<td>SPS</td>
<td>Spark plasma sintering</td>
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<tr>
<td>TS</td>
<td>Two-step</td>
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<tr>
<td>HfB2</td>
<td>Hafnium diboride</td>
</tr>
<tr>
<td>Al2O3</td>
<td>Aluminium oxide</td>
</tr>
<tr>
<td>B4C</td>
<td>Boron carbide</td>
</tr>
<tr>
<td>HP</td>
<td>High pressure</td>
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<table>
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<tr>
<th>Symbols</th>
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<tr>
<td>UHP</td>
<td>Ultra-high pressure</td>
</tr>
<tr>
<td>TiC</td>
<td>Titanium carbide</td>
</tr>
<tr>
<td>ZrB2</td>
<td>Zirconium diboride</td>
</tr>
<tr>
<td>h</td>
<td>Height</td>
</tr>
<tr>
<td>t</td>
<td>Thickness</td>
</tr>
<tr>
<td>RMS</td>
<td>Root-mean-square</td>
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<tr>
<td>ECR</td>
<td>Electric contact resistance</td>
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**Keywords**

- Spark plasma sintering
- UHTC
- Electrical analysis
- Energy optimization
- Titanium carbide
- Simulation

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1. Introduction

1.1. Background of research

Ultra-high-temperature ceramics, known as UHTCs, are advanced materials that have unique features, particularly when exposed to extreme temperatures [1, 2]. These materials are gradually attracting attention as durable candidates for a wide range of industrial applications that require resistance to harsh environments, high mechanical strength, and extreme temperatures [3–7]. UHTCs have become known for their remarkable thermal stability, exceptional mechanical properties, and compliance with a wide range of substances [8–14]. The manufacturing of UHTCs is almost a challenge due to their low self-diffusion caused by covalent bonding, weak sinterability, and high melting temperature [15–17]. It tends to being challenging to achieve a balance between improved sinterability and controlled grain growth. Preserving fine-grain structures and optimizing the synthesis process are two of the main challenges associated with conventional powder metallurgy methods, such as hot pressing, in the manufacturing of metal [18, 19]. The SPS method simultaneously applies both external pressure and electric current to the material during the sintering process. Applying high pressure during the sintering process is one of the major advantages of using SPS. This eliminates porosity and voids, leading to a more effective synthesis process. External pressure is applied. Because it directly influences the mechanical and thermal properties of materials, accurate control of grain development is essential for numerous metallurgical applications. SPS offers this control and fine-grained microstructures—which are frequently necessary in a variety of technical applications—through a distinctive combination of rapid heating and brief holding times [20–27]. SPS has several advantages over conventional methods. In particular, rapid heating and short holding time reduce processing time. In addition, SPS operates at lower sintering temperatures, which helps with energy conservation and preserves the integrity of temperature-sensitive materials. In contrast to traditional powder metallurgy techniques, SPS presents a promising alternative that could enhance ceramic synthesis while effectively controlling grain size [28–32]. Compared to the conductive heat transport used in conventional sintering systems, using volumetric heating rates caused by the Joule effect enables a rapid increase in temperature. This phenomenon increases the mass transport mechanisms responsible for sintering processes, resulting in a higher consolidation rate and less grain coarsening. This restriction in grain coarsening improves the mechanical and physical properties of the final sintered parts, including enhanced mechanical strength and structural integrity [33–35].

Although the experimental method is utilized, the determination of the temperature distribution in spark plasma sintering can be accomplished by the utilization of finite element modeling, which is helpful. The process can be managed and optimized with the help of this strategy, which takes into consideration the interrelated phenomena that are involved.

1.2. Literature survey

Considering the preceding discourse, it is evident that a research initiative is currently underway to optimize the SPS process by implementing insulation and die geometry optimization. Research in this area is extensive and delves into several facets, including the simultaneous application of external pressure and electric parameters, a broad range of optimization procedures, design methodologies, and various configurations. Scholarly articles addressing the optimization of the SPS process have increased significantly in recent years. Therefore, to determine the research gaps in the studies, we will conduct a comprehensive review of them so that the present study may contribute to filling the research gaps.

Via the present research on Spark Plasma Sintering by Zhang et al. [36], the thermal-electric-mechanical model is introduced by a detailed and comprehensive model prototype. The result showed that there was a radial temperature of 155 °C and an axial of 24 °C. Computer simulations obtained stress gradients, which were compared with theoretical ones (0.9699). Finally, to improve the efficiency of the device by considering the temperature, they suggested a reduced...
diameter for the die. With the approach to temperature measurement in SPS, researchers can enhance the efficacy and reliability. Nöthe et al. [37] conducted a finite element model and a customized setup for in-depth analyses of spark plasma sintering. A testing environment interacting with a finite element model was constructed that enabled thorough analysis. Being small, this setup generates aperture currents, an arbitrary waveform, pressure variations, and dilatometry readings at the same time. They also found temperature dependence from contact resistances and furnace configuration and unequal currents caused by uneven interfacial contacts between the foil and specimen. As well, they found the potential variance in currents due to imperfect contacts at graphite foil and specimen interfaces. Semenov et al. [38] applied a numerical modeling method to investigate the early stages of sintering of a particle assembly under spark plasma sintering on a microscopic scale. The fully laminated thermo-electro-mechanical problem, which takes into account the grain boundaries and the transport at surfaces, is solved using the staggered method. Ranjbarpour Niari et al. [39] use numerical simulations to study the spark plasma sintering process of HfB2. Electrical conductivity is one of the main properties of HfB2 that allows for the uniform distribution of the flow during sintering and gives it an advantage over other non-conductive ceramics. The combination of the Joule effect in thermal distribution proves HfB2 to be exclusive, indicating chances for better and more moderated SPS approaches in materials science and process manufacturing, especially pertinent to industrial applications when targeting electrical conductivity.

Bagheri et al. [40] highlight the importance of numerical simulations in investigating and optimizing the SPS process for TiC samples. By solving governing equations for heat conduction and electric current distribution, the study successfully achieves the desired sintering temperature of 2000 °C. They reported a radial temperature gradient of 80 °C in the TiC sample. Although their reports indicate that the maximum temperature occurs at the die and punch interface, where the cross-section is minimum and current density is highest, as a result, heat generation via Joule heating phenomena is highest. Sakkaki et al. [41], in a numerical simulation, investigated the temperature and electric current distribution via the FE method in the SPS process of the ZrB2 and Al2O3 samples. They attempt to clarify the temperature and electric current distribution via the FE method in the spark plasma sintering process when an electric current passes through the material. For each point, the temperature distribution can be obtained by solving the Maxwell and electric charge conservation equations. In addition, the heat diffusion equation has to be solved to determine the temperature distribution. Furthermore, the need to link and concurrently solve these equations is emphasized due to the temperature-dependent properties involved. Eq. 1, which is based on Ref. [41], describes the Maxwell equation:

### 1.4. Organization of the paper

This paper adheres to the following sections within a meticulously structured framework:

The methodology and solution method are presented in section 2. Sections 3 and 4 present the findings and discussions. An overview of the correlation study between electrical power and thermal losses is given in section 5. Lastly, section 6 presents the conclusions.

#### 2. Methodology

##### 2.1. Geometry

The geometry of the SPS system, which was used in the numerical simulation, is shown in Fig. 1. The device consists of spacers, graphite punches, and upper and lower electrodes. Water current cools both the lower and upper electrodes, which are made of Inconel. The presented numerical simulation attempts to evaluate the effect of die geometry on energy consumption in the SPS process, namely die thickness (t) and height (h).

##### 2.2. Mathematical formulation of geometric relationships

Due to the Joule heating phenomenon, heat is produced during the spark plasma sintering process when an electric current passes through the material. For each point, the temperature distribution can be obtained by solving the Maxwell and electric charge conservation equations. In addition, the heat diffusion equation has to be solved to determine the temperature distribution. Furthermore, the need to link and concurrently solve these equations is emphasized due to the temperature-dependent properties involved. Eq. 1, which is based on Ref. [41], describes the Maxwell equation:

\[
\nabla \cdot \mathbf{E} + \frac{1}{\sigma} \cdot \mathbf{J} = 0
\]

where \( E, J, U \) and \( 0 \) are the electric field, the current density, the electric potential, and the electrical conductivity of the materials, respectively.

The energy equation in cylindrical coordinates is represented by Eq. 2.

\[
\rho C_p \frac{\partial T}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r k_T \frac{\partial T}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( k_T \frac{\partial T}{\partial \theta} \right) = q_i
\]

### 1.3. Contributions of this paper

In response to the identified research gaps within the domain of SPS research, the presented context involves:

- correlation analysis;
- investigation of radiant heat transfer with a particular focus on the die surface.

#### 1.4. Organization of the paper

This paper adheres to the following sections within a meticulously structured framework:

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### 2. Methodology

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\[
\nabla \cdot \mathbf{E} = \nabla \cdot \mathbf{J} = \mathbf{0}
\]
\[ q_i = J_i E \]  \hspace{1cm} (3)

where \( E \) is the electric field.

Hereafter, the expression for electric current in cylindrical coordinates is conventionally denoted as Eq. 4:

\[ \frac{1}{\rho} \frac{\partial \rho_i}{\partial r} + \frac{\partial \rho_i}{\partial z} = 0 \]  \hspace{1cm} (4)

The parameters are as follows: “\( r \)” represents the radial coordinate, “\( z \)” is the axial coordinate, \( \rho_i \) is the radial component of current density, and \( \rho_z \) is the axial component of current density.

Setting the RMS values for voltage and current intensity is necessary for calculating power dissipation in heating tools. The passion of the electrical signal is measured by these RMS values, to demonstrate the amount of energy lost as heat. Determining these is essential for accurately calculating the heating tool’s power dissipation. A certain equation must be used to calculate the RMS voltage value [43]. This process step is of extreme importance since it makes it possible to take into account the effective voltage and current values, which are vital for accurately determining the power used by heating equipment. Using RMS values provides a more accurate representation of power usage since it offers a metric that takes into account both the amplitude and time-varying properties of electricity.

Due to the lack of space, the additional fundamental relationships between energy and electrical parameters, such as voltage, electric current, and electric power, are not shown. However, a complete definition of these relationships can be found in [44–46]. Hence, the equation governing the determination of the RMS value of voltage is articulated as follows in Eq. 5:

\[ U_{\text{RMS}} = \sqrt{\frac{1}{P} \int_{t-T}^{t} u^2(t) \, dt} \]  \hspace{1cm} (5)

The integral term \( \int_{t-T}^{t} u^2(t) \, dt \) calculates the square of the voltage waveform \( u \) over a time interval from \( t - T \) to \( t \), where \( t \) is the present time, and \( T \) is the period considered for calculating the RMS value. The division by \( P \) signifies that the voltage waveform’s power is divided by the period \( T \). The RMS voltage is a measure that considers both amplitude and the waveform’s temporal characteristics, facilitating accurate power calculations and equipment assessment.

### 2.3. Characteristics of materials

The electrical and thermal properties are closely related to the thermoelectric problems. The temperature range in the sintering process is large, so it is important to take the temperature dependence of the material properties into account. Table 1 lists the characteristics of the materials.

### 2.4. Parameters for boundaries and initial states

The governing equations necessitate corresponding boundaries and initial conditions for a comprehensive solution. The applying boundary conditions in this paper are presented in Fig. 2, where electrical insulation is implemented on the outer surfaces of the device (depicted by brick red and yellow lines in Fig. 2). When applying an electric potential, the upper surface is connected to the ground. In contrast, the lower surface is grounded (i.e., \( V = 0 \)). As observed in Fig. 2, water flows over both the upper and lower surfaces, undergoing convective heat transfer, which is mathematically described by Newton’s cooling law as Eq. 6:

\[ q_i = h_i (T_i - T_w) \]  \hspace{1cm} (6)

### Table 1. The properties of different parts of the SPS system as functions of temperature (T in Kelvin).

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat capacity (J.kg(^{-1}).K(^{-1}))</th>
<th>Density (kg.m(^{-3}))</th>
<th>Thermal conductivity (W.m(^{-1}).K(^{-1}))</th>
<th>Electrical resistivity ((\Omega).m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>(34.27+2.72\times10^{-4}\times T^2)</td>
<td>(1.9\times10^3-1.414\times10^2\times T)</td>
<td>(82.85-0.06\times2.56\times10^{-5}\times T^2)</td>
<td>(2.14\times10^{-5}-1.34\times10^{-8}\times T+4.42\times10^{-12}\times T^2)</td>
</tr>
<tr>
<td>Inconel</td>
<td>(344+0.25\times T)</td>
<td>(8.43\times10^5)</td>
<td>(0.0157\times T+10.09)</td>
<td>(9.82\times10^{-7}+1.6\times10^{-10}\times T)</td>
</tr>
<tr>
<td>TiC</td>
<td>(803+5.744\times10^{-7}\times T-5.427\times10^{-9}\times T^2-23.685\times10^{-12}\times T^2)</td>
<td>(4930)</td>
<td>(9.8\times10^5\times T+23.994)</td>
<td>(1/(6\times10^{-10}\times T+4\times10^{-7}))</td>
</tr>
</tbody>
</table>

Remark: (J.kg\(^{-1}\).K\(^{-1}\)): Joule per kelvin per kilogram; (kg.m\(^{-3}\)): kilogram per cubic meter; (W.m\(^{-1}\).K\(^{-1}\)): watts per meter-kelvin; (\(\Omega\).m): ohm-meter.
Adapted from Ref. [47], the convection coefficient for both upper and lower surfaces is considered to be $h_c = 880 \text{W.m}^{-2}\text{.K}^{-1}$ [48]. The sintering setup operates within a vacuum environment; therefore, heat losses from the side walls are exclusively considered radiation. The heat transfer through the radiation mechanism can be mathematically expressed as in Eq. 7:

$$q_r = \sigma_{e}e\left(T_e^4 - T_s^4\right)$$ (7)

As per Refs. [48, 49], the material emissivity values are set at 0.8 [50] for graphite and 0.67 [51] for Inconel. It is proposed to apply a thermal contact layer with a thickness of 0.1 mm and a thermal conductivity of 0.04 W.m$^{-1}\text{.K}^{-1}$ [49] at the interface between Inconel and the spacer (see Fig. 2). It is noteworthy that Manière et al. [52] observed that when temperatures exceed 800 °C and pressures surpass 50 MPa, the ECR becomes negligible. Given that the working pressure in this study is approximately 100 MPa, the ECR is presumed to be zero. Furthermore, the sintering temperature is set at 2000 °C [53, 54].

### 3. Solution methodology

The finite element method is a powerful computational tool that is utilized to analyze and solve engineering problems. The model-governing equations are solved with the help of the finite element method, which is accomplished with the software COMSOL Multiphysics (version 6.14). Engineering problems can be analyzed and solved with the help of finite element modeling (FEM), which is a powerful computational technique [55]. In an accurate simulation, it is necessary to choose a suitable mesh size. Fig. 2 illustrates the mesh that was applied, which contains triangular elements. To conduct a more accurate analysis, the sample section takes into consideration a smaller mesh size. Ultimately, 1430 elements are chosen for this research project, which investigates a variety of mesh sizes to establish mesh independence.

### 4. Results and discussion

This research effort attempts to clarify how insulation and geometrical characteristics (thickness and height) affect the amount of energy used in the SPS process. In this paper, the variations in the TiC sample die's thickness and height are investigated, and the power required to reach the constant sintering temperature (2000 °C) is calculated. Optimizing the SPS process becomes related to a better understanding of the temperature distribution, the effect of die geometrical characteristics, and the use of insulation during the SPS process. These approaches give an accurate understanding of the modified die's energy usage as well as its electrical characteristics, including power, voltage, and current.

#### 4.1. Validation analysis

The presented numerical simulation validation was verified by comparing temperature distributions in a computational area that was the same as Pavia et al. [53], the results of which are presented in Fig. 3. Referring to Fig. 3, there is a good agreement between Pavia et al. [53] investigation results. Thus, the proposed numerical method can be used to simulate the sintering process of a TiC sample.

#### 4.2. Analysis of radial temperature distribution based on thickness and height of die

The radial temperature distribution in the sample along die thickness and height is illustrated in Figs. 4 and 5, respectively. In both cases, the temperature gradient from the sample center to the die surface exhibits a decreasing trend. As shown in Fig. 4, the changes in the temperature gradient from the center to the edge of the sample ($r = 18$) are similar. This is because the heat generated in the core of the sample is dissipated into the surroundings, resulting in a decreased temperature gradient from center to edge.
In Fig. 5, the temperature pattern is similar to Fig. 4. According to Fig. 5, the die experiences a lower temperature difference with an increase in the height of the sample die. Also, in the sample, the slope of the temperature reduction decreases with the increase in the height of the die. The radial temperature distribution has a significant effect on the final sample microstructure. A sample with a smaller temperature difference tends to have more uniform mechanical and microstructural properties. Additionally, as depicted in Fig. 5, in contrast to die thickness variations, die height alterations induce modifications in the temperature distribution pattern. To achieve a uniform temperature distribution, it is necessary to choose either a die with a lower thickness or a die with a higher height [54]. Upon comparing both Fig. 4 and Fig. 5, it becomes evident that to achieve a more uniform temperature distribution, selecting a die with greater height and reduced thickness proves to be effective in the optimization process. Therefore, a die with a shorter height and reduced thickness is the preferred option for optimizing temperature distribution.

### 4.3. Temperature contours analysis

To find out the correlation between electric current lines and temperature distribution in all components, the temperature contour and electric current lines for the study cases were derived. To conduct a comparative study, all temperature distribution contours and electric current lines were projected symmetrically. In each figure, the right side of the symmetry axis corresponds to the electric current lines, while the left side corresponds to the temperature distribution contour. In all cases, the interface between the punch and the spacer exhibits the maximum current density, as shown in Figs. 6–8. This occurrence is attributed to the reduced cross-sectional area of the current path from the spacer to the punch. Consequently, this phenomenon contributes to generating maximum temperatures in this area. The central region of the system consistently exhibits the highest temperature across all cases. A gradual decrease in the temperature gradient is obvious as it moves away from the center. All analyzed cases consistently identify this characteristic pattern of temperature distribution and electric current lines.
4.3.1. Effect of die insulation

Fig. 6 shows the electric current lines and temperature distribution contour of the base and insulated cases. In both the insulation case and the base case, the distribution pattern of electric current lines remains unchanged. The temperature distribution in the punch, sample, and die, however, indicates a good level of uniformity when compared to the base case because of the insulated case's surface insulation and a lack of heat losses from the die surface. In the base case, the temperature differential between the surface of the die and the center of the sample is 246 °C. This temperature differential, nevertheless, is only 0.3 °C in the insulated sample. In addition to reducing the amount of electrical power needed for the SPS process and reducing thermal energy losses, this decrease in temperature difference causes the sample's temperature to be more uniform, which improves the sample's mechanical and micromechanical characteristics.

4.3.2. Effect of die height

Fig. 7 shows the temperature distribution contour and electric current lines based on die height variation. According to Fig. 7,
The height of the die greatly affects the pattern of electric current line distribution. A shorter die height decreases the pass cross-sectional area of the electric current in the die, leading to a higher electric current in the sample. Increasing the die height increases the cross-sectional area of the passing electric current, therefore generating more heat. The die with a higher height shows a higher temperature than a die with a shorter height, as shown in Fig. 5. Further, the electrical current line density in the punch and sample is greater than in a die with a larger height; as a result, the punch temperature and heat generation around the sample increase. In a die with a shorter height, where heat generation is lower, the temperature difference between the sample and the die is higher. This leads to more heat transfer from the sample to the die via the conductive heat transfer mechanism, resulting in a more non-uniform temperature distribution in the sample. Hence, selecting the optimal die height minimizes sample heat loss and temperature differences.

Fig. 7. Temperature distribution contours and electric current lines for the various die height.

Fig. 8. Temperature distribution contours and electric current lines for the various die thickness.
Table 2. Electric current, voltage, and power consumption at different heights and thicknesses.

<table>
<thead>
<tr>
<th>Case study</th>
<th>Profile</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Base</td>
<td>17 t (mm) 60 h (mm)</td>
<td>5.07</td>
<td>5684.6</td>
<td>28.82</td>
</tr>
<tr>
<td>2 Insulation</td>
<td>17 t (mm) 60 h (mm)</td>
<td>2.99</td>
<td>3498</td>
<td>10.45</td>
</tr>
<tr>
<td>3</td>
<td>17 t (mm) 30 h (mm)</td>
<td>4.27</td>
<td>3714.4</td>
<td>15.86</td>
</tr>
<tr>
<td>4</td>
<td>17 t (mm) 40 h (mm)</td>
<td>4.62</td>
<td>4288.5</td>
<td>19.81</td>
</tr>
<tr>
<td>5</td>
<td>17 t (mm) 50 h (mm)</td>
<td>4.89</td>
<td>4936</td>
<td>24.13</td>
</tr>
<tr>
<td>6</td>
<td>10 t (mm) 60 h (mm)</td>
<td>4.85</td>
<td>5207.3</td>
<td>25.25</td>
</tr>
<tr>
<td>7</td>
<td>15 t (mm) 60 h (mm)</td>
<td>5.01</td>
<td>5577.5</td>
<td>27.94</td>
</tr>
<tr>
<td>8</td>
<td>20 t (mm) 60 h (mm)</td>
<td>5.12</td>
<td>5791.5</td>
<td>29.65</td>
</tr>
</tbody>
</table>

Remark: V: volt; A: ampere; kW: kilo Watt.

4.3.3. Effect of die thickness

Fig. 8 delivers the temperature distribution contour and electric current lines based on the effect of die thickness. In all cases, the maximum current density and the maximum temperature variation are similar to the previous section that was discussed. Fig. 8 shows that an increase in die thickness results in a higher current density within the die due to the expanded cross-sectional area. Also, a die with an increased thickness shows a more uniform distribution of current lines than a thinner die. The higher current density in the thicker die also leads to elevated heat generation, resulting in increased heat losses and a non-uniform temperature distribution in the die. The lower current density in the sample within the thicker die reduces Joule heating compared to the thinner die. These observations highlight that employing a die with the optimal minimum thickness minimizes heat loss and reduces temperature differences in the die.

4.4. Correlation energy and electrical analysis

Table 2 shows the electrical and energy analysis results (current, voltage, and power consumption) at different thicknesses and heights. Considering that the sintering temperature (at the sample's center) has been maintained constant in the simulation in all cases, different electric power consumptions have been calculated to achieve this fixed temperature (2000 °C). This highlighted the importance of optimizing the geometrical parameters. Furthermore, the voltage, current, and power consumption in the base case are 5.07 V, 5684.6 A, and 28.82 kW, in that order. In the insulated case, these values fall to 2.99 V, 3498 A, and 10.45 kW, which represents a 63% reduction in electrical power consumption due to radiation heat transfer from the die surface. This indicates that preserving the system from radiation heat transfer reduces electrical power consumption, which lowers the energy required to power the system.

The insulated case exhibits considerably less electric power consumption than the other cases, according to the results. Fig. 9 compares the increase in power savings in the insulation mode to the other cases. The power reductions are 34%, 47%, 56%, 58%, 62%, and 64%, respectively, when comparing the insulated case 3 to case 8. This is because insulation reduces heat losses through radiation heat transfer.

The power consumption in terms of die thickness is shown in Fig. 10. The electric power consumption curve is depicted using three distinct thicknesses (t = 10 mm, t = 15 mm, and t = 20 mm) and a constant height (h = 60 mm). Results indicate that as die thickness increases, it also increases electric power consumption. These three thicknesses require, in order, 25.25, 27.94, and 29.65 kW of electric power.

Fig. 9. Percentage of power saving in insulated mode compared to case studies 3 to 8.
Fig. 11 shows electric power consumption based on the die different height at a constant thickness (t = 17 mm). The electric power consumption for h = 30 mm, h = 40 mm, and h = 50 mm is 15.86, 19.81, and 24.13 kW, respectively. As is obvious, increasing die height led to a higher electric power consumption requirement.

Electric power and radiation flux are directly related to each other, so the level of electric power affects the radiant flux. An analysis delineating the changes in radiant heat flux has been provided using Figs. 12 and 13. Fig. 12 displays the radiated heat flux from the entire device's wall surface for various cases. The radiant heat flux is 21.46 kW in the base state and reduces to 5.51 kW in the insulation state. For cases 3 to 8, these values are 10.3, 13.6, 17.41, 18.44, 20.71, and 22.17 kW, respectively. Fig. 12 clearly shows that selecting larger height and thickness of the die increases the radiation heat transfer from all device surfaces. Additionally, Fig. 13 shows the radiant heat flux from the die surfaces of the device. The radiant heat flux is 10.356 kW in the base case and becomes zero in the insulation case (where heat transfer is negligible). For cases 3 to 8, these values are 4.48, 6.3, 8.25, 9.28, and 10.08 kW, respectively. The die surfaces account for approximately 50% of the heat losses from all device surfaces. Insulating the die surface nearly eliminates the heat loss from the surface. At a constant die height, radiation heat loss increases with a larger die thickness.

5. Correlation analysis of thermal losses and electrical power

A correlation analysis between heat losses and electrical power is useful for achieving optimal conditions. Since the amount of heat loss is directly related to the electrical power, minimizing thermal losses will reduce the input electrical power. The larger thickness of the die results in an increase in the pass cross-sectional area for electric current. As a result, the Joule heating mechanism generates more heat. This leads to an increase in the die temperature and the radiation heat transfer rate, as illustrated in Fig. 4. This leads to a rise in total radiant heat losses. To compensate for heat losses and reach the desired temperature of 2000 °C, more electrical power is required as thermal losses rise (see Fig. 10). At constant thickness, the magnitude of radiation heat losses rises with an increase in die height. This is attributed to the simultaneous increase in radiation surface and the passing cross-sectional area of the electric current, increasing the die surface temperature (see Fig. 5). Therefore, an increase in die height requires higher input electrical power (see Fig. 10). Based on numerical simulation, it is determined that the utilization of insulation in the entire surface of the device necessitates a voltage of 1.66 V and a current of 1980 A. Consequently, this results in a reduction of the required input electrical power to 3.28 kW.
6. Conclusions

A key factor that affects the mechanical properties and microstructure of the sintered samples is the temperature distribution during the sintering process. The main source of heat generation in the SPS process is Joule heating. The electric current density and energy conservation equations were numerically solved using the finite element method in order to determine the temperature and electric current distribution. In the present work, the temperature and electric current distribution during the TiC sample sintering process were simulated numerically using COMSOL Multiphysics software, and the SPS process for TiC samples was optimised by investigating the effect of die geometry (height and thickness) and insulation application. The results showed that the input power consumption was significantly reduced by 63% when compared to the non-insulated case, highlighting the usefulness of insulation in enhancing the SPS process's energy efficiency. Consequently, the effects of the height and thickness of the die were investigated in order to optimise the SPS process. As a result, temperature uniformity is more sensitive to variations in die height than to variations in die thickness. The correlation study between current lines and temperature distribution revealed useful insights into the relationship between electric current and temperature distribution. The results indicated that an increase in die thickness resulted in an increase in the electric current's cross-sectional area, which in effect changed the quantity of electricity required to attain the sintering temperature of 2000 °C.

CRediT authorship contribution statement

Milad Sakkaki: Project administration, Supervision, Validation, Visualization, Methodology, Software, Formal analysis, Investigation, Writing - Review & Editing, Resources.

Milad Foroutani: Visualization, Investigation, Writing-original draft, Software, Data Curation, Resources, Validation.

Peyman Zare: Validation, Writing - Review & Editing, Supervision, Software, Formal analysis, Resources.

Fig. 12. Radiative heat flux from all surfaces of the SPS device in different cases.

Fig. 13. Radiative heat flux from die surfaces of the SPS device in different cases.
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Declaration of Ai and Ai-assisted technologies in the writing process

During the preparation of this work, the authors used AI and AI-assisted technologies to improve the readability and language of the work. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the publication’s content.

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