Thermal Debinding Kinetics of Gelcast Ceramic Parts via a Modified Independent Parallel Reaction Model in Comparison with the Multiple Normally Distributed Activation Energy Model

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ABSTRACT: This work aims to provide useful insights into the thermal debinding kinetics of gelcast ceramic parts, especially for debinding kinetics prediction involving heat preservation. Debinding experiments were conducted in a differential thermogravimetric analyzer at five heating rates (5, 8, 10, 15, and 20 °C/min) in the temperature range of 35–900 °C under an air atmosphere. The conversion ($\alpha$) and pyrolysis rate ($d\alpha/dT$) data were simulated using a modified independent parallel reaction (IPR) model and a multiple normally distributed activation energy model (M-DAEM). Their validity was assessed and compared by checking the agreement between the experimental results and the prediction capability. The results showed that both the modified IPR model and M-DAEM had high predictability for thermal debinding kinetics under linear heating conditions. The fitting quality parameters (Fit) were less than 1.406 and 1.01%, respectively. The activation energies ($E_i$, $i = 1, 2, 3, 4,$ and $5$) calculated by the M-DAEM ranged from 153.312 to 217.171 kJ/mol. The relationships between $E_i$ and $d\alpha/dT$ were a function of the conversion rate. The $E_i$ values were $E_1(\alpha) = 116.750 + 11.153\alpha - 26.772\alpha^2 + 4.362\alpha^3$ kJ/mol, $E_2(\alpha) = 139.595 - 66.162\alpha + 75.702\alpha^2 - 38.041\alpha^3$ kJ/mol, $E_3(\alpha) = 190.854 + 135.758\alpha - 214.801\alpha^2 + 116.093\alpha^3$ kJ/mol, $E_4(\alpha) = 64.068 + 280.086\alpha - 380.270\alpha^2 + 264.724\alpha^3$ kJ/mol, and $E_5(\alpha) = 188.257 - 77.086\alpha + 74.129\alpha^2 - 48.669\alpha^3$ kJ/mol, respectively. However, it is noteworthy that the $\alpha$ and $d\alpha/dT$ curves predicted by the modified IPR model with a deviation of less than 8% were better than those predicted by the M-DAEM for the linear thermal debinding process with the holding stage. Accordingly, it is believed that the proposed modified IPR model is suitable for describing the thermal debinding kinetics involving the heat preservation of gelcast green parts.

1. INTRODUCTION

With the continuous expansion of the application field of ceramic materials, higher requirements have been put forward for the shape, size, and forming accuracy of ceramic components. Gelcasting technology has been confirmed to be the most effective method to achieve near net shaping of ceramic products with larger sizes and more complex shapes because it can improve the deformation shrinkage and post-processing difficulties of traditional ceramic green body molding methods. Thermal debinding is one of the key steps in gelcasting. If it is not properly controlled, the green body is prone to cracking, collapse, and other defects due to the rapid release of pyrolysis gas and local pressure surge, which will adversely affect the performance of ceramic parts. To avoid these problems, multistage thermal insulation is often adopted to control the pyrolysis rate of polymers. Therefore, an accurate analysis of thermal degreasing kinetics is indispensable. Currently, the research on thermal debinding kinetics mainly focuses on the use of single-reaction models and model-free methods. Yan et al. used the Coats–Redfern method to study the thermal debinding kinetics of copper green parts prepared by the three-dimensional (3D) printing method and obtained the kinetic parameters and reaction order ($n = 1$). Salehi et al. investigated the pyrolysis kinetics of the binder in the thermoplastic processing of YSZ ceramics by three model-free methods: Ozawa–Flynn–Wall, Kissinger–Akahira–Su–nose (KAS), and Friedman. Their findings suggest that the KAS and Friedman models tested produce consistent results and allow dependable prediction of the degreasing kinetics. However, these studies usually regard the pyrolysis process as a...
single-reaction stage, which may not be suitable for the problem of multiple pyrolysis peaks in the binder or gel systems. Practically, typical binder systems are usually composed of several types of binders, and the degreasing process usually has multiple reaction steps. For example, Gal et al.22 studied the thermal debinding behavior of Si3N4 prepared by powder injection molding based on the first-order reaction kinetic model. In their study, the thermal decomposition behavior of the binder was divided into two sigmoids. The master decomposition curve of the feedstocks was established to help optimize the thermal debinding process. Similarly, polymers formed from some gel systems often exhibit multiple pyrolysis peaks, and the pyrolysis reaction does not follow a single mechanism function.23–25 This problem widely exists in the fields of biomass and coal pyrolysis. For instance, Torres-Sciancalepore et al.24 studied the kinetic and thermodynamic behavior of the pyrolysis of quince waste and pectin-free quince waste after extraction. It was found that the pyrolysis process followed a multiple-step mechanism with three different steps. Parthasarathy et al.25 investigated the O2 gasification behavior of camel manure. The decomposition of the camel manure occurred in three stages: dehydration, decomposition of hemicellulose and cellulose, and oxidation of fixed carbon. The abovementioned models have difficulty accurately describing these complex combustion and pyrolysis processes. Currently, the multiple normally distributed activation energy model (M-DAEM) and the multistage parallel reaction model (M-PRM) have been reported to be effective models to analyze this complex process. Lin et al.26 researched the copyrolysis kinetics of bagasse, sewage sludge, and their mixtures by means of the M-DAEM. Sun et al.27 explored the combustion kinetics of organic matter in Huadian oil shale by introducing the M-PRM. Their research showed that the predictions of the abovementioned kinetic models well

Table 1. Reactant Characteristics Used in This Experiment

| function          | raw materials       | amount     | purity   | manufacturer                      |
|-------------------|---------------------|------------|----------|-----------------------------------|
| components        | Si₃N₄              | 22.5 g     | ≥99.9%, d₅₀ = 1.0 μm | Ube Industries Ltd., Japan       |
|                   | Al₂O₃              | 2 g        | ≥99.9%, d₅₀ = 0.5 μm | Sumitomo Chemical Co., Ltd., Japan |
|                   | AlN                | 2.8 g      | ≥99.9%, d₅₀ = 2.0 μm | Aladdin Industrial Co., Ltd., China |
| sintering additives| Y₂O₃              | 0.9 g      | ≥99.9%, grade fine | H.C. Stark, Germany              |
| monomer           | CeO₂                | 1.8 g      | ≥99.9%, d₅₀ = 5.0 μm | Aladdin Industrial Co., Ltd., China |
| cross-linker      | DMAA (N,N-dimethylacrylamide) | DMAA + MBAM 12.4 wt % | ≥99.4% | Kowa Co., Ltd., Japan             |
| cross-linker      | MBAM (N,N′-methylenbisacrylamide) | (DMAA/MBAM = 16:1) | ≥99.0% | Shenzhen Highrun Chemical Industry Co. Ltd., China |
| dispersant        | NH₄PAA (ammonium polycrylate) | 1.0 wt % | ≥99.0% | Aladdin Industrial Co., Ltd., China |
| catalyst          | TEMED (N,N,N′,N′-tetramethylethylene-diamine) | 1.0 wt % | ≥98.0% | Aladdin Industrial Co., Ltd., China |
| initiator         | APS (ammonium persulfate) | 1.0 wt % | ≥98.0% | Aladdin Industrial Co., Ltd., China |
| pH adjuster       | NH₃·H₂O (ammonia water) | 25% | 25% | Shuncheng Chemical Materials Co., Ltd., China |

Figure 1. Schematic representation of the gelcasting process toward the fabrication of a ceramic green body.
matched the experimental results. However, there are few reports on the kinetics of thermal debinding involving the thermal insulation process.

In this work, an M-DAEM and a modified independent parallel reaction (IPR) model were used to study the nonisothermal kinetics and the kinetics related to heat preservation of gelcast ceramic green bodies during debinding. The applicability of the two models was compared, and the kinetic parameters were estimated. It was anticipated to achieve an effective description and accurate prediction of thermal debinding kinetics and to provide an effective theoretical basis for the optimization of the thermal debinding process.

2. EXPERIMENTAL SECTION AND METHODS

2.1. Sample Preparation. In this study, the target green gelcast ceramic part is Y-α-SiAlON, where \( m = 1.5 \) and \( n = 0.75 \) according to the general chemical formula \( \text{Y}_m/3\text{Si}_{12−(m/n)}\text{Al}_{(n/m)}\text{O}_{16−n} \). The samples were prepared from commercial powders as precursors according to Table 1. Here, Si₃N₄, Al₂O₃, and AlN powders were used as reactants, and Y₂O₃ and CeO₂ powders were added as sintering additives. Of note, the AlN powder is prone to a hydrolysis reaction in the aqueous solution, leading to the flocculation of the suspension. To obtain hydrolytic resistance, the surface modification of AlN was implemented according to the method reported by Li et al. A low-toxicity aqueous gel was used to form a 3D network structure for the in situ immobilization of solid powders.

A schematic representation of the gelcasting process leading to the fabrication of ceramic green bodies is shown in Figure 1. As depicted in Figure 1, the process includes the preparation of a mixed powder slurry and gelling agent solution, casting, demolding, drying, and debinding. The specific experimental process can be found in our previous research.

2.2. Characterization Technique. The thermal debinding experiments were performed in a differential thermogravimetric (DTG) analyzer STA-449F3 Jupiter of Netzch, with which the TG and DTG curves were recorded under dynamic conditions in the range of 35–900 °C. The nonisothermal TG experiments were performed in an air atmosphere with a flow rate of 40 mL/min at various heating rates of 5, 8, 10, 15, and 20 °C/min. The insulation treatment runs were performed in one stepwise program, where the temperature was held at 250 or 400 °C for 120 min at a heating rate of 10 °C/min.

2.3. Kinetic Analysis Using Different Models.

2.3.1. Kinetic Theory. In nonisothermal kinetic analysis, the pyrolysis rate is expressed as

\[
\frac{d\alpha}{dt} = k(T)f(\alpha) \quad \text{or} \quad \frac{d\alpha}{dT} = \frac{k}{\beta} \exp\left(-\frac{E}{RT}\right)f(\alpha)
\]

where \( \alpha \) is the conversion (0< \( \alpha < 1 \)), \( d\alpha/dt \) is the pyrolysis rate, \( k(T) \) is the Arrhenius rate constant and \( k(T) = k_0 \exp\left(-E/RT\right) \), \( f(\alpha) \) is the reaction mechanism function, \( k \) is the pre-exponential factor, \( \beta \) is the heating rate and \( \beta = dT/dt, E \) is the apparent activation energy, \( R \) is the universal gas constant, and \( T \) is the temperature.

The integration of eq 1 is usually described as

\[
G(\alpha) = \int_0^\alpha \frac{d\alpha}{f(\alpha)} \approx \frac{k}{\beta} \int_0^T \exp\left(-\frac{E}{RT}\right) dT \approx \frac{kE}{\beta R} p(y)
\]

where \( p(y) \) is the temperature integral \[ y = E/(RT) \], \( p(y) = -\int_y^\infty \exp(-\gamma) d\gamma \] (eq 2).

2.3.2. M-DAEM. Assume that the polymer in the green body contains \( m \) independent species that follow a first-order reaction. Therefore, the pyrolysis process of the polymer can be considered a weighting of the independent reactions of the \( m \) pseudo components, and the pyrolysis reaction kinetics of each pseudo component can be described by the DAEM. Then, the standard equation of the M-DAEM can be expressed as

\[
\frac{d\alpha(T)}{dT} = \sum_{i=1}^m c_i \int_0^\infty \frac{k_i}{\beta \sqrt{2\pi} \sigma_i} \exp\left(-\frac{k_i}{\beta \psi(E_i, T)}\right) f_i(E) dE
\]

where \( c_i = 1, 2, \ldots, m \) are the pre-exponential factors, \( \beta \) is the heating rate, and \( \psi(E_i, T) \) is the reaction mechanism function.

The integration of eq 1 is usually described as

\[
f_i(E) = \frac{1}{\sigma_i \sqrt{2\pi}} \exp\left(-\frac{E - E_i^2}{2\sigma_i^2}\right)
\]

Figure 3. \( f(E) \) curves of the five pseudo components calculated by the M-DAEM at a heating rate of 5 °C/min.
Table 2. Degradation Temperature of Three Peaks in DTG Curves at Different Heating Rates

| heating rates (°C/min) | peak 1 (°C) | peak 2 (°C) | peak 3 (°C) | height (peak 1) (%/°C) | height (peak 2) (%/°C) | height (peak 3) (%/°C) | maximum mass loss (%) |
|------------------------|-------------|-------------|-------------|------------------------|------------------------|------------------------|-----------------------|
| 5                      | 239         | 328         | 459         | 0.17                   | 0.41                   | 0.11                   | 10.23                 |
| 8                      | 247         | 337         | 463         | 0.25                   | 0.59                   | 0.17                   | 9.67                  |
| 10                     | 252         | 343         | 474         | 0.31                   | 0.74                   | 0.19                   | 10.05                 |
| 15                     | 260         | 350         | 477         | 0.49                   | 1.10                   | 0.31                   | 9.59                  |

Table 3. Kinetic Parameters Calculated Using the M-DAEM

| polymer                  | c_i          | k_i (min⁻¹)  | E_i (kJ/mol)  | σ_i (kJ/mol)  |
|--------------------------|--------------|--------------|---------------|---------------|
| pseudo component 1       | 0.156        | 2.582 × 10¹¹ | 153.312       | 4.814         |
| pseudo component 2       | 0.251        | 2.582 × 10¹¹ | 179.887       | 2.766         |
| pseudo component 3       | 0.149        | 2.582 × 10¹¹ | 190.190       | 6.007         |
| pseudo component 4       | 0.381        | 2.582 × 10¹¹ | 208.171       | 36.607        |
| pseudo component 5       | 0.047        | 2.582 × 10¹¹ | 217.171       | 3.725         |

According to the IPR model, polymer decomposition in the green body can be described by several independent parallel first- or n-th-order reactions. Each one corresponds to the decomposition of the different constituents of macromolecular chains within the polymer. The IPR model can be expressed as

\[
\frac{dm_i}{dt} = -\sum c_i \frac{d\alpha_i}{dt} = k_i \exp \left( -\frac{E_i}{RT} \right) (1 - \alpha_i)^n
\]

(9)

where \(m_i\) is the observed mass at time \(t\), and \(m_0\) is the initial mass.

3. RESULTS AND DISCUSSION

3.1. TG and DTG Analysis. Figure 2 shows the TG and DTG curves of the green body during debinding at heating rates of 5, 8, 10, and 15 °C/min. The maximum degradation temperature of each peak and the maximum mass loss in the DTG curve under different heating rates are presented in Table 2. Figure 2 and Table 2 show that there are three main peaks in the DTG curves ranging from 200 to 600 °C.
corresponding to the pyrolysis stages of DMAA/MBAM polymers. With an increase in the heating rate, the maximum pyrolysis temperature of each peak also increased and shifted to the high-temperature region, resulting in a hysteresis phenomenon. This was due to the fact that the polymer underwent different pyrolysis rates at different heating rates, leading to an increase in its pyrolysis temperature range. It can be noted that this phenomenon was very general, which was closely in agreement with the study of Parthasarathy et al.30 and Al-Rumaihi et al.39 At 900 °C, the final mass loss of the sample was approximately 10.23, 9.67, 10.05, and 9.59% at heating rates of 5, 8, 10, and 15 °C/min, respectively.

3.2. Kinetic Analysis Using the M-DAEM. Through the DTG analysis mentioned in Section 3.1, the dominant region of DMAA/MBAM polymer pyrolysis consisted of three main pyrolysis peaks. Therefore, the entire pyrolysis process could be considered the summation of the reactions of at least three pseudo components. Practically, the precipitation of residual moisture during the low-temperature drying process (<200 °C) cannot be ignored. In addition, the secondary reaction of the residual carbon could also be triggered in the late stage of pyrolysis. Finally, it is hypothesized that the DMAA/MBAM polymer contains five independent pseudo components that follow first-order reactions.

The $f(E)$ curves of the DMAA/MBAM polymer in the green body debinded in the air atmosphere are shown in Figure 3. The component contents of the five pseudo components and their pyrolysis kinetic parameters ($E_i$, $k_i$, and $\sigma_i$) are presented in Table 3. As shown in Figure 3 and Table 3, $E_i$ ranged from 153.312 to 217.171 kJ/mol, $k_i$ was $2.582 \times 10^{11}$ min$^{-1}$, and $\sigma_i$ ranged from 2.766 to 36.607. Pseudo component 1 had the lowest activation energy and therefore underwent thermal degradation reactions first. Pseudo component 5 had the highest activation energy, and its pyrolysis reaction required the largest activation energy; thus, the reaction was relatively difficult. The order of the standard deviation $\sigma_i$ of the activation energy was 4 > 3 > 1 > 5 > 2, indicating that the activation energy distribution of pseudo component 4 was the widest, and the activation energy distribution of pseudo component 2 was the narrowest.

The comparison of $\alpha$ and $d\alpha/dT$ curves obtained based on the M-DAEM with the experimental data is shown in Figures 4 and 5. The fit (%) of the $\alpha$ curves calculated by the M-DAEM was less than 1.406%. The fitted models presented show good agreement with the experimental data. All of the matched peaks were optimized according to the generalized reduced gradient algorithm performed using Microsoft Excel. Therefore, the M-DAEM was very suitable for describing the kinetic behavior of green bodies during the debinding process. In Figure 5, the pseudo components were named from 1 to 5 according to the peak temperatures from smallest to largest. The larger the value, the more stable the pseudo component; thus, the reaction process requires higher temperature and energy.

3.3. Kinetic Analysis Using the Modified IPR Model. The IPR model has been proven to be a promising method to fit DTG curves with multi-decomposition peaks. As reported in

![Figure 3](https://example.com/fig3.png)

**Figure 3.** The $f(E)$ curves of the DMAA/MBAM polymer in the green body debinded in the air atmosphere.

![Figure 4](https://example.com/fig4.png)

**Figure 4.** Experimental and model-calculated conversion rates $\alpha$ under an air atmosphere obtained with the M-DAEM (a) 5, (b) 8, (c) 10, and (d) 15 °C/min.

![Figure 5](https://example.com/fig5.png)

**Figure 5.** The pseudo components were named from 1 to 5 according to the peak temperatures from smallest to largest. The larger the value, the more stable the pseudo component.
the work of Yousef et al.40 The TG/DTG experimental data of membranes were fitted using an IPR model with high predictability. Our previous study showed that the pyrolysis reaction of the DMAA/MBAM gel system satisfies the mechanism function of the SB model.35 Therefore, in the IPR model was modified to

\[ f(\alpha) = (1 - \alpha)^{n} \cdot \alpha^{-m} \cdot \left(1 - \ln(1 - \alpha)\right)^{p}, \]

named the modified IPR model, which was developed and applied to study the thermal debinding kinetics. Figure 6 shows fits of the calculated \( \frac{\alpha}{dT} \) curves to the experimental data using the modified IPR model at heating rates of 5, 8, 10, and 15 °C/min. The fitting quality parameters (Fit) of the modified IPR model used for thermal debinding kinetic analysis at different heating rates are presented in Table 5. As illustrated in Figure 6, the pyrolysis domains (the shape and width) of the five pseudo components obtained by the modified IPR model matched the pyrolysis curves of the polymer at different heating rates, which means that the modified IPR model-predicted \( \frac{\alpha}{dT} \) curves well matched the experimental results during the thermal debinding process, and the fitting quality parameter (Fit) was less than 1.01%.

During the degreasing process of polymers under an air atmosphere, in addition to weak bonds, side chain group cracking, depolymerization, and cyclization reactions, there were also oxidative combustion reactions of cracked products and residual carbon and even the formation of new compounds accompanying cross-linking polymerization. The reaction process was very complicated, and the activation energy was constantly changing. Therefore, the dependence relationship between \( E \) and \( \alpha \) of each substage was obtained according to the modified IPR model. The optimum modified IPR model parameters for the five pseudo components are shown in Table 6. The relationships between the activation energies of pseudo components 1 to 5 as a function of the conversion rate were

\[ E_{1}(\alpha) = 116.750 + 11.153 \alpha - 26.772 \alpha^{2} + 4.362 \alpha^{3}, \]

\[ E_{2}(\alpha) = 139.595 - 66.162 \alpha + 75.702 \alpha^{2} - 38.041 \alpha^{3}, \]

\[ E_{3}(\alpha) = 190.854 + 135.755 \alpha - 214.801 \alpha^{2} + 116.093 \alpha^{3}, \]

\[ E_{4}(\alpha) = 64.068 + 280.086 \alpha - 380.270 \alpha^{2} + 264.724 \alpha^{3}, \]

\[ E_{5}(\alpha) = 188.257 - 77.086 \alpha + 74.129 \alpha^{2} - 48.669 \alpha^{3}, \]

Figure 7 shows the relationship between \( E \) and \( \ln(k) \) for each pseudo component during degreasing under an air atmosphere calculated using the modified IPR model. As seen, with an increase in the activation energy \( E \) value, the value of \( \ln(k) \) also increases; except for the low linear correlation coefficient of pseudo component 1, the \( E \) and \( \ln(k) \) of other

![Figure 5](https://example.com/image)
pseudo components showed a strong linear relationship with the linear correlation coefficient of \( R^2 > 0.97 \), which indicates that there existed a kinetic compensation effect between \( E \) and \( k \) of each substage.

### 3.4. Comparison of the Kinetic Models

A comparison between the \( \frac{d\alpha}{dt} \) and \( \alpha \) curves predicted by the modified IPR model and the M-DAEM during the nonisothermal debinding process is illustrated in Figure 8a–c. By comparing the calculated and experimental \( \frac{d\alpha}{dt} \) and \( \alpha \) curves at a heating rate of 20 °C/min, which are plotted in Figure 8a, it is clear that the predicted \( \alpha \) and \( \frac{d\alpha}{dt} \) curves of the two methods were in good agreement with the experimental data for the linear heating thermal debinding process. However, it is noteworthy that the \( \alpha \) and \( \frac{d\alpha}{dt} \) curves predicted by the modified IPR model were better than those predicted by the M-DAEM for the linear thermal degreasing process with the holding stage, as illustrated in Figure 8b,c. The deviation was less than 8%. Overall, the modified IPR model was confirmed to be superior to the M-DAEM due to better fitting results for the insulation kinetics during the thermal debinding process, which is an inevitable step to

**Table 5. Fitting Quality Parameter (Fit) of the Modified IPR Model Used for Thermal Debinding Kinetic Analysis**

| model        | Fit (%) of \( \alpha \) curves |
|--------------|---------------------------------|
| modified IPR | 0.96 0.87 1.01 0.95             |

Figure 6. Experimental and calculated \( \frac{d\alpha}{dT} \) curves by the modified IPR model at different heating rates (a) 5, (b) 8, (c) 10, and (d) 15 °C/min.

**Table 6. Optimum Parameters for the Modified IPR Model of Five Pseudo Components**

| parameters | content | \( c_i \) | peak 1 | peak 2 | peak 3 | peak 4 | peak 5 |
|------------|---------|----------|--------|--------|--------|--------|--------|
| SB model   | \( n \) | 0.711    | 0.711  | 0.711  | 1.050  | 0.711  |
|            | \( m \) | 2.970    | 2.970  | 2.970  | 2.970  | −0.025 | 2.970  |
| \( p \)    |        | −3.761   | −3.761 | −3.761 | 0.134  | −3.761 |
| \( p_1 \)  |        | 22.614   | 22.632 | 34.897 | 13.505 | 26.268 |
| \( p_2 \)  |        | 18.789   | 5.013  | 31.985 | 37.241 | 1.358  |
| \( p_3 \)  |        | −30.541  | −10.764| −50.628| −50.545| −6.552 |
| \( p_4 \)  |        | 16.270   | 5.291  | 27.718 | 30.167 | 4.035  |
| \( p_5 \)  |        | 116.750  | 139.595| 190.854| 64.608 | 188.257|
| \( p_6 \)  |        | 11.153   | −66.162| 135.755| 280.086| −77.086|
| \( p_7 \)  |        | −26.772  | 75.702 | −214.801| −380.270| 74.192 |
| \( p_8 \)  |        | 4.362    | −38.041| 116.093| 264.727| −48.669|

\( E(\alpha)(kJ/mol) \)

| \( p_5 \) | 116.750 | 139.595 | 190.854 | 64.608 | 188.257 |
| \( p_6 \) | 11.153  | −66.162 | 135.755 | 280.086| −77.086 |
| \( p_7 \) | −26.772 | 75.702  | −214.801| −380.270| 74.192  |
| \( p_8 \) | 4.362   | −38.041 | 116.093 | 264.727| −48.669 |
prevent the formation of defects. Furthermore, compared to the M-DAEM, the modified IPR model did not need to solve the quadratic integral function, which greatly reduced the number of calculations. Therefore, the proposed modified IPR model was especially suitable for describing the thermal debinding kinetics involving heat preservation of gelcast green bodies, considering its accuracy, simplicity, and speed of performance.

4. CONCLUSIONS

In this study, the IPR model was modified by replacing $(1 - \alpha_i)^n$ with $f(\alpha_i) = (1 - \alpha_i)^m \cdot [-\ln(1 - \alpha_i)]^p$. Then, the thermal debinding kinetics of ceramic green bodies prepared by the DMAA/MBAM gel system under an air atmosphere were studied using the modified IPR model comparison with the M-DAEM. The relevant kinetic parameters (activation energy and pre-exponential factor) were also calculated. The performed research indicated that the predicted $\alpha$ and $d\alpha/dT$ curves by the modified IPR model and the M-DAEM were both in good agreement with the experimental data for the linear heating thermal debinding process. The fitting quality parameters (Fit) were less than 1.406 and 1.01%, respectively. However, for the thermal debinding process involving heat preservation, the modified IPR model was proven to give better fit and prediction results compared to the M-DAEM, with a deviation of less than 8%. The research results can provide a theoretical basis for the study of thermal debinding kinetics involving thermal insulation measures.

Figure 7. $\ln(k)$ vs $E$ (calculated by the modified IPR model) plot of each pseudo component of the polymer during the debinding process under an air atmosphere.

Figure 8. Comparison of prediction results between the modified IPR model and the M-DAEM for (a) linear thermal debinding process (20 °C/min), (b) insulation process (holding at 250 °C for 120 min), and (c) insulation process (holding at 400 °C for 120 min).
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Notes

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