Effect of powders and binders on material properties and molding parameters in iron and stainless steel powder injection molding process

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ABSTRACT

It is essential to study and optimize multiple objective functions such as binder system design, feedstock, part geometry, mold design, and processing conditions in order to develop a successful powder injection molding process. A powder with different combinations of binder systems and a binder system with different combinations of powder systems were investigated with a combined experimental and simulation study. First, an experimental rheological study was performed to evaluate the influence of the powder/binder combinations on the rheological behavior and thermal stability of carbonyl iron and stainless steel powder injection molding (PIM) feedstocks. Second, based on the characterization of the feedstock, the simulation study revealed that the pressure-related parameters such as wall shear stress, injection pressure, and clamping force were mainly dependent on the binder system and not much on the powder characteristics, in the range of particle attributes studied. Third, to the temperature-related parameters such as melt front temperature difference and cooling time, binder selection is more critical than powder selection. Fourth, for the velocity-related parameter, maximum shear rate, the selection of both powder and binder system is critical in control. It is demonstrated that the simulation study is essential in the development stage for successful PIM.

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1. Introduction

Powder injection molding (PIM) is a manufacturing technology for the net-shape production of small, intricate, and precise metal or ceramic components. The PIM process includes mixing of either metal or ceramic powders with a binder to produce a feedstock, injection molding to form a green part with the desired shape by making the feedstock flow into and fill a mold under pressure, debinding to form a brown part by removing the binder components, and sintering to near full density [1]. Among powdered materials used in PIM, iron, iron alloy, and steels constitute about 43% of the overall material systems used [2].

In PIM, the molding stage is a critical step for forming a desired shape. This step requires specific rheological behavior and thermal properties of the PIM feedstocks. The injection pressure is the driving force for making flow of PIM feedstock during filling stage. The viscosity of PIM feedstock is the most important property to flow behavior. In addition, the thermal properties of PIM feedstock such as thermal conductivity and heat capacity are more important in PIM than in plastic injection molding, because of faster heat transfer from PIM feedstock than from plastic resin [3]. Understanding the rheological behavior and thermal stability of PIM feedstock is key for successful PIM manufacturing. Many experimental data about rheological and thermal characteristics of PIM feedstocks are available in the technical literature [4–8]. But a systematic analysis for the effect of powder and binder system on rheological and thermal characteristics is not common.

Computer simulation of PIM process is important because of the complexity of process and the nonlinearity of the governing equation and material properties. The computer simulation provides a convenient platform to map interactions between the material properties, the processing conditions, and geometric attributes. Recently, Atre et al. [9] reported the classification of output parameter into three categories for the systematic analysis of injection molding process design during PIM. This classification can help the effect of powder and binder system on injection molding process design of PIM.

The purpose of this study was to investigate the influence on rheological behavior and thermal properties of the different selection of iron based powders with several different binder combinations. The rheological and thermal analysis lays a solid foundation for both the numerical prediction associated with the PIM process and the quality of the final products. It is our contention that many frustrations...
encountered in practice can be avoided by more care in the planning stage, as it is now possible with computer simulation tools.

2. Experimental procedures

2.1. Powder

In the present study, we used five different iron and stainless steel (SS) powders; iron [10], carbonyl iron (BASF, Ludwigshafen, Germany) [11], water-atomized 316 L SS (PF-15, ATMIX Corp., Nagano-ken, Japan) [3,12], 430 L SS (Sandvik Osprey Ltd., Neath–Port Talbot, UK), and water-atomized 17-4 PH SS (ATMIX Corp., Nagano-ken, Japan) [13] powders. The characteristics of these powders are reported in Table 1. We measured all data in Table 1 except for data of Powder 1 obtained from reference [10]. To determine the width of distribution $S_w$, we used the following equation

$$S_w = \frac{2.56}{\log(D_{90}/D_{10})}.$$  (1)

Fig. 1 shows SEM micrographs of Powders 2 and 3 which show the shape of powders related to feedstock rheological behavior.

2.2. Binder

In the present study, we used five different binder systems; four wax-polymer based binder systems and one water-soluble agar binder system. The source and composition of the binder systems are given in Table 2. The binder systems were composed of waxes—carnauba wax (CW) or paraffin wax (PW)—as a main component to control viscosity, stearic acid (SA) as a surfactant, and polymers—polypropylene (PP), polyethylene (PE) or ethylene vinyl acetate (EVA)—as backbone components. The binder compositions for Binders 1, 2, and 3 are known from Nanyang Technological University (Singapore), Center for Innovative Sintered Products (CISP) in the Pennsylvania State University (PSU), and Oregon Nanoscience and Microtechnologies Institute (ONAMI) in Oregon State University (OSU), but Binders 4 and 5 are commercial binder systems from CetaTech (Sacheon, South Korea) and Honeywell (Morristown, NJ) so its compositions are unknown.

2.3. Feedstock

The binder was mixed with the powder to form feedstock for molding. In the present study, we used seven different feedstocks from combinations of powders in Table 1 and binder systems in Table 2, as listed in Table 3 with solid loading percentages. Note that Feedstocks 3, 4, and 5 used the same Powder 3 and Feedstock 2, 5, and 6 used the same Binder 2. These feedstocks can be used for discussion of the effect of powders for Binder 2 and the effects of binder systems for Powder 3 on material properties and simulation results. Note that the solid loading percentage of Feedstock 2, 5, and 6 with the same binder system (Binder 2) are all higher than 60% while other feedstocks are relatively low between 45 to 55%.

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**Table 1** Characteristics of powders used in this study.

<table>
<thead>
<tr>
<th>Powder ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder type</td>
<td>Iron</td>
<td>Carbonyl iron</td>
<td>316 L SS (PF-15)</td>
<td>430 L SS</td>
<td>17-4 PH SS</td>
</tr>
<tr>
<td>Vendor</td>
<td>BASF</td>
<td>ATMIX Corp. Osprey Ltd.</td>
<td>ATMIX Corp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production method</td>
<td>Water-atomized</td>
<td>Water-atomized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>Round</td>
<td>Irregular</td>
<td>Spherical</td>
<td>Irregular</td>
<td></td>
</tr>
<tr>
<td>particle size ($\mu$m)</td>
<td>$D_{10}$</td>
<td>1.8</td>
<td>3.7</td>
<td>4.0</td>
<td>3.1</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>10</td>
<td>4.2</td>
<td>8.0</td>
<td>10.0</td>
<td>7.6</td>
</tr>
<tr>
<td>$D_{90}$</td>
<td>8.0</td>
<td>14.4</td>
<td>22.0</td>
<td>15.8</td>
<td></td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>Apparent</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2.85</td>
</tr>
<tr>
<td>Tap</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4.25</td>
</tr>
<tr>
<td>Pycnometer</td>
<td>7.87</td>
<td>7.75</td>
<td>7.93</td>
<td>7.75</td>
<td>7.66</td>
</tr>
<tr>
<td>Width of distribution</td>
<td>–</td>
<td>4.0</td>
<td>4.3</td>
<td>3.5</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**Table 2** Sources and compositions of binder systems used in this study.

<table>
<thead>
<tr>
<th>Binder ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>Nanyang Technological University</td>
<td>CISP, PSU</td>
<td>ONAMI, OSU</td>
<td>CetaTech</td>
<td>Honeywell</td>
</tr>
<tr>
<td>Wax-based binder</td>
<td>PP 20%</td>
<td>PP 25%</td>
<td>EVA 20%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Water-based agar binder</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Composition (wt.%)</td>
<td>CW 10%</td>
<td>CW 57%</td>
<td>CW 69%</td>
<td>PE 15%</td>
<td>PE 10%</td>
</tr>
<tr>
<td>SA 1%</td>
<td>SA 3%</td>
<td>SA 1%</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Reference</td>
<td>10</td>
<td>11, 12</td>
<td>–</td>
<td>9</td>
<td>13</td>
</tr>
</tbody>
</table>

**Table 3** Combination of powders and binder systems and solid loadings for feedstocks used in this study.

<table>
<thead>
<tr>
<th>Feedstock ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder ID</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Binder ID</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Solid loading (%)</td>
<td>45</td>
<td>63</td>
<td>50</td>
<td>53</td>
<td>61</td>
<td>61</td>
<td>55</td>
</tr>
<tr>
<td>Critical solid loading (%)</td>
<td>60</td>
<td>–</td>
<td>–</td>
<td>64</td>
<td>64</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Reference</td>
<td>10</td>
<td>11</td>
<td>–</td>
<td>9</td>
<td>12</td>
<td>–</td>
<td>13</td>
</tr>
</tbody>
</table>

---

(a) Powder 2

(b) Powder 3

Fig. 1. SEM micrographs showing (a) carbonyl iron powder (Powder 2) and (b) 316 L stainless steel powders (Powder 3).
2.4. Material property measurement

The rheological and thermal properties of Feedstocks 2, 3, 4, and 7 were measured at DataPoint (Ithaca, NY) to support the mold filling simulation. The material properties of Feedstock 1 were obtained from the literature [10]. The rheological properties of Feedstocks 5 and 6 were measured by a capillary rheometer (model: Galaxy V 8052; supplier: Kayeness, Morgantown, PA) and thermal properties were estimated based on the rule-of-mixtures approach from individual powder and binder components.

3. Numerical simulation

The commercially available software PIMSolver (CetaTech, Sacheon, South Korea) was used to carry out the simulations in the present study. PIMSolver utilizes the hybrid method of finite element method (FEM) and finite difference method (FDM) for calculating the flow and temperature fields in defined geometries and has been specifically developed and experimentally validated for PIM applications [9]. The software is capable of simulating in two and half-dimension (2.5D) and models the flow in the third dimension as fully developed.

In the present study, a tensile bar geometry was selected and simulated as shown in Fig. 2 with 1598 elements and 942 nodes. The mesh was generated using the meshing tool of PIMSolver. The simulations in the present study only focused on the mold filling stage of the PIM process. The input parameters for this baseline process were divided into three subgroups: feedstock material properties, component geometry parameters, and process parameters. The input process parameters considered in the present study are listed in Table 4. These parameters are based on experience from a typical injection molding process. The switch-over point (SO) was set as a percentage of cavity volume filled to switch from velocity control to pressure control during cavity filling process. Note that we used three different injection temperatures with range of 55 °C to 220 °C to investigate the effect of injection temperature on material properties and simulation results.

The output parameters evaluated in the study were classified into:

- pressure-related parameters: injection pressure, clamping force, and maximum shear stress
- temperature-related parameters: melt front temperature difference and cooling time
- velocity-related parameters: maximum shear strain.

<table>
<thead>
<tr>
<th>Feedstock ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling time (s)</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switch-over point (%)</td>
<td>98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection temperatures (°C)</td>
<td>180 145 100 110 140 140 55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mold-wall temperature (°C)</td>
<td>70 60 40 45 55 55 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The goal of this simulation analysis is to investigate the relationship on the input parameters (powders, binder systems, and injection temperature) that have the greatest influence on the output parameters.

4. Results and discussion

4.1. Material property

4.1.1. Rheological property

Concentrated powder/binder mixtures such as PIM feedstock show a non-Newtonian shear thinning viscous behavior [14]. In this study, the modified-Cross model was used for viscosity \( \eta \) as a function of the effective shear rate \( \dot{\gamma} \) and absolute temperature \( T \):

\[
\eta(\dot{\gamma}, T) = \frac{\eta_0}{1 + (\eta_0 \dot{\gamma}/\tau^*)^{n-1}}
\]

where

\[
\eta_0 = B \exp(T_b / T)
\]

where \( \eta_0 \), \( n \), and \( \tau^* \) denote the zero shear rate viscosity, the power law exponent, the transition shear stress. Note \( B \) and \( T_b \) denote the constant amplitude and the reference temperature in absolute scale for the Arrhenius temperature dependence.

We plotted material parameters of viscosity for all feedstocks listed in Table 3 based on the above viscosity model, as shown in Fig. 3. Fig. 3a shows the plot of material parameters \( T_b \) and \( n \) and Fig. 3b shows the plot of zero shear rate viscosity as a function of temperature.

4.1.1.1. Power law exponent

The power law exponent \( n \) is a material parameter to indicate how sensitive a fluid is to a shear rate. A fluid with \( n \leq 1 \) is called shear thinning or pseudoplastic while a fluid with \( n = 1 \) is called Newtonian. From Fig. 3a, the power law exponent \( n \) is ranging quite widely from 0.2 to 0.5, which indicates that all feedstock in this paper show shear thinning effect due to reduction of friction among binder components (release of polymer chain entanglement) and friction between powder and binder system (particle alignment with streamlines) at high shear rate region [14]. The higher shear thinning means the viscosity drop at the higher shear rate range and it is preferred for cavity filling with less energy for complicated geometry [3] but may also cause higher shear rate gradient and then as a result, powder–binder separation more easily [15].

We could investigate the effects of powder and binder system on the power law exponent \( n \) by comparing Feedstocks 2, 5, and 6, which were prepared from different Powder 2, 3, and 4 with the same binder system (Binder 2) and Feedstocks 3, 4, and 5, which were prepared from different binder system (Binder 3, 4, and 2) with the same Powder 3, respectively. (Note that we used this approach consistently in Section 4.)

- Powder effect: the maximum difference was 0.085 (0.415–0.500)
- Binder effect: the maximum difference was 0.217 (0.198–0.415).

Over range studies, we can conclude that the binder system has a more significant effect on the power law exponent than powder.
4.1.1.3. Zero shear rate viscosity. Operating temperatures as such injection temperature and mold wall temperature are more important in PIM than in conventional plastic injection molding process. Therefore, we compared zero shear rate viscosity at different injection temperatures as listed in Table 4, to further investigate the temperature dependency on the PIM feedstock viscosity. The zero shear rate viscosity includes all temperature dependency parameters based on the modified-Cross model of feedstock viscosity used in this study. The zero shear rate viscosity \( \eta_0 \) for the feedstocks is ranging very widely from 0.59 to 54 kPa·s with wide range of injection temperature from 55 to 220 °C. We calculated the difference of the zero shear rate viscosity between high and low molten feedstock injection temperatures in Table 4, denoted \( \Delta \eta_b \), which ranged from 0.30 to 38 kPa·s. Feedstock 6 shows the least \( \Delta \eta_b \) with operating injection temperature change, which matches with the lowest \( T_b \) from Fig. 3(a). Feedstock 7 with water-based agar binder system (Binder 5) shows the highest \( \Delta \eta_b \).

We investigated the effects of powders and binder systems:

- **Powder effect**: the maximum difference in \( \Delta \eta_b \) was 0.60 kPa·s (0.30 – 0.90 kPa·s).
- **Binder effect**: the maximum difference in \( \Delta \eta_b \) was 3.8 kPa·s (0.90 – 4.7 kPa·s).

We can conclude from the above results that the binder system selection has a more significant effect on the \( \Delta \eta_b \) than powder selection. This result is in contrast to the result on the reference temperature, which is very interesting. The reference temperature or the flow activation energy is more dependent on powder selection but the zero shear rate viscosity in operating range of feedstock injection temperature, which depends on binder system selection, is more dependent on binder system selection.

4.1.2. Thermal property

The thermal conductivity and heat capacity of powders are generally much higher than those of the binder components. Consequently, during solidification, the PIM feedstock cools quickly. As a result, the control of injection temperature and mold wall temperature is much more significant during PIM process than conventional plastic injection molding [9].

Fig. 4 shows the thermal conductivity and heat capacity of all PIM feedstocks. Feedstocks 1 and 7 shows very different thermal properties from other feedstocks possibly due to low solid loading and different binder components (water-based agar binder system), respectively.
4.2. Simulation results

4.2.1. Pressure-related outputs

4.2.1.1. Injection pressure. The material flow of injection molding is pressure driven and the pressure at the injection nozzle rises as the mold cavity begins to fill and continues to do so until the switch-over occurs to change the control mechanism from the position of ram to the pressure of ram. The maximum pressure at the nozzle just before switch-over occurs is called injection pressure, which is an important specification of an injection molding machine. Therefore, the size of an injection molding machine can be selected based on the predicted injection pressure. Improper specification of the injection pressure can result in several types of defects in the molded components such as flash created when pressure in a mold cavity is too high and short shot created when pressure in a mold cavity is insufficient. Other mold filling problems include jetting and formation of weld lines. Consequently, minimum injection pressure, which is the driving force for molding, is best for a good part without a defect.

Fig. 5 shows the injection pressure range of the feedstocks at various injection temperatures listed in Table 4. All the feedstocks display negative slopes in Fig. 5 with injection temperature increase, which indicates that the injection pressure decreases with the injection temperature increases as expected from the rheological study. The predicted injection pressure of feedstocks ranges from 1.5 to 66 MPa. Feedstock 1 shows the lowest injection pressure while Feedstock 7 requires the highest injection pressure for successful cavity filling.

We used two values to investigate the effects of powder and binder system on the injection pressure; one is the predicted injection pressure at the middle point of operating injection temperature range (P) and the other is the difference between the predicted injection pressures at the highest and lowest injection temperatures (ΔP).

- **Powder effect**: maximum difference in P was 2.0 MPa (6.3 – 8.3 MPa) and maximum difference in ΔP was 1.0 MPa (0.48 – 1.5 MPa)
- **Binder effect**: maximum difference in P was 16 MPa (5.7 – 21 MPa) and maximum difference in ΔP was 2.6 MPa (1.5 – 4.1 MPa).

Based on the above observation, we conclude that the selection of binder system is more critical to minimize the injection pressure and its dependency on injection temperature. In comparison, an earlier parameter sensitivity analysis by Atre et al. [9] showed similar results that the strong sensitivity of n and T0 of the modified-Cross model of the feedstock viscosity to injection pressure.

4.2.1.2. Clamping force. The clamping force required is proportionally related to the projected area of a part: the larger the projected area, the more clamping force is needed. This is important for machine selection for a given mold with a given amount of cavities. If the clamping force available is inadequate, then the mold will not close fully and abundant flash can occur. The clamping force aids the holding process and allows for the part to fill and pack properly. Too high a clamping force results in an increase in power consumption and possibly a reduction in mold life. Therefore an optimal range of clamping force exists for any molding situation.

Fig. 6 shows the clamping force for different feedstocks. The clamping force decreases with the temperature increase and ranges from 0.24 to 10 kN. The results of clamping force mostly relate to injection pressure since force equals pressure multiplied by area, with gate size not being a major contributor owing to its small projected area.

As in the case of the injection pressure, we used two values to investigate the effects of powder and binder system on the clamping force. The first value was the predicted clamping force at the middle point of operating injection temperature range (Fc). The second value...
was the difference between the predicted clamping force at the highest and lowest injection temperatures (ΔFC).

- **Powder effect**: maximum difference in FC was 0.29 kN (0.94 – 1.2 kN) and maximum difference in ΔFC is 0.15 kN (0.074 – 0.22 kN)
- **Binder effect**: maximum difference in FC was 2.4 kN (0.81 – 3.2 kN) and maximum difference in ΔFC was 0.43 kN (0.22 – 0.66 kN).

As in the case of the injection pressure, the greater influence to minimize clamping force and its dependency on injection temperature originates from the binder system selection rather than from the powder selection.

### 4.2.1.3. Maximum shear stress

Shear stress is the force between layers of fluid that causes the layers to initiate motion and is proportional to the pressure gradient at each location. A sufficiently high shear stress can create a phenomenon, called shear thinning after the initial Newtonian behavior at lower shear stress region, which can decrease the viscosity of a PIM feedstock. The maximum shear stress is one of the very critical design parameters, which occurs usually at the wall near the gate or in the thinnest part of cavity. Too high a maximum shear stress may result in breaking the molecular structure of binder components and thus reduction of green strength and viscosity reduction.

Fig. 7 shows the maximum shear stress for different feedstocks at their operating injection temperatures, which exhibits very similar to results of injection pressure and clamping force. The maximum shear stress decreases with the temperature increase and ranges from 21 to 800 kPa.

As in the other cases, we used two values to investigate the effects of powder and binder system on the maximum shear stress. The first one was the maximum shear stress at the middle point of the operating injection temperature range (τm). The second one was the difference between the predicted maximum shear stress at the highest and lowest injection temperatures (Δτm).

- **Powder effect**: maximum difference in τm was 30 kPa (120 – 150 kPa) and maximum difference in Δτm is 18 kPa (9.2 – 27 kPa)
- **Binder effect**: maximum difference in τm was 170 MPa (95 – 260 MPa) and maximum difference in Δτm is 18 kPa (21 – 39 kPa).

As in the case of the injection pressure and the clamping force, the greater influence to minimize the maximum shear stress and its dependency on injection temperature originated from the binder system rather than from the powder. However, it should be noted that the temperature dependency on the maximum shear stress (Δτm) was almost the same in both powder and binder effects, which is different from the results of the injection pressure and the clamping force.

### 4.2.2. Temperature-related outputs

#### 4.2.2.1. Melt front temperature difference

In order to produce a defect-free part with uniform and homogenous properties in the flow direction, the melt front temperature difference should be kept to a minimum level. The definition of the melt front temperature difference (MFTD) is the difference between the maximum and the minimum in the melt front temperature (MFT) distribution. Failure to control the uniformity of MFT will result in anisotropic shrinkage and strength evolution during the packing and cooling stages. This anisotropy will cause cracks in the debinding process and severe distortion during the sintering process [16].

Fig. 8 shows MFTD for each feedstock at its operating injection temperatures and its value ranges from 0 to 12 °C. The MFTD increases with temperature increase even in Feedstock 3, 5, and 6, which show very low value of MFT difference. Feedstocks 1 and 7 show relatively higher MFTD compared with other feedstocks. In addition, the two feedstocks show a great temperature dependency on the MFTD. The implications of these observations are that the Feedstocks 1 and 7 may need more careful design of processing window for PIM.

We used two values to investigate the effects of powder and binder system on the MFTD; one was the MFTD at the middle point of operating injection temperature range (mMFTD) and the other was the difference between the predicted MFTD at the highest and lowest injection temperatures (ΔmMFTD).

- **Powder effect**: maximum difference in mMFTD was 1.3 °C (0.010 – 1.3 °C) and maximum difference in ΔmMFTD was 0.65 °C (0.0 – 0.65 °C)
- **Binder effect**: maximum difference in mMFTD was 2.8 °C (0.010 – 2.8 °C) and maximum difference in ΔmMFTD was 1.6 °C (0.010 – 1.6 °C).

As in the case of the pressure-related parameters, the binder system selection has a greater influence on minimizing mMFTD and its dependency on injection temperature, ΔMFTD than from the powder selection.

#### 4.2.2.2. Cooling time

Cooling time is important to ensure a satisfactory part upon ejection. While for production reasons, it is best to select the shortest cooling time, an insufficient cooling time can result with the parts having defects during ejection owing to their low strength. Warpage and sink marks are common problems from parts being ejected while they are too hot. If insufficient cooling time is provided, then the parts may stick to the mold and cause problems with ejector pin marks.

The cooling time is sensitive to a variety of the energy relevant material properties of the feedstock such as feedstock density, specific heat, and viscosity. The cooling time is defined as the time it takes for the feedstock to cool from 400°C to 200°C after injection. To control the cooling time, the cooling time can be minimized by considering the feedstock properties such as the density, specific heat, and viscosity, as well as the injection pressure and temperature. The cooling time is an important parameter to ensure the integrity of the final part, and it is influenced by the feedstock properties as well as the injection conditions.
heat capacity, thermal heat conductivity, and ejection temperature. Other than that, the part thickness among geometrical parameters, and injection temperature and mold wall temperature in processing conditions are the only significant parameters [9].

All feedstocks show a positive slope on Fig. 9 with injection temperature increase, which means the cooling time increase with the injection temperature increase, as expected. Feedstock 1 and 7, which have higher thermal conductivity and heat capacitance, exhibit faster cooling times and these match with the results from the thermal properties study in Section 4.1.2.

In order to investigate the effects of powder and binder system on cooling time, we used two values; one was the cooling time at the middle point of operating injection temperature range (\(t_c\)) and the other was the difference between the predicted cooling time at the longest and shortest cooling time (\(\Delta t_c\)).

- **Powder effect:** maximum difference in \(t_c\) was 9.3 s (4.0 s – 13.3 s) and maximum difference in \(\Delta t_c\) was 2.1 s (0.8 s – 2.9 s)
- **Binder effect:** maximum difference in \(t_c\) was 10.3 s (3.1 s – 13.4 s) and maximum difference in \(\Delta t_c\) was 3.0 s (0.6 s – 3.6 s).

Overall, the binder effect was larger than the powder effect in both cooling time and its dependency to injection temperature.

### 4.2.3. Velocity (flow)-related outputs

#### 4.2.3.1. Maximum shear rate
The shear rate is defined as the rate of change of shear strain with respect to time. Usually the maximum shear rate occurs at the mold wall, which results in high molecular orientation. The maximum shear rate is related to the degree of shear induced particle migration from low shear region to high shear rate region as well as the high flow induced residual stress, to name just a few causes. If the maximum shear rate is higher than a critical value, the binder molecule will be broken.

As seen in Fig. 10, the maximum shear rate exhibits a high sensitivity to the filling time \(t_c\) and gate diameter. Feedstock 7 shows the highest maximum shear rate and Feedstocks 3 and 5 are the lowest and flattest.

To investigate the effects of powder and binder system on maximum shear rate, we used two values; one was the maximum shear rate at the middle point of operating injection temperature range (\(\gamma_{\text{max}}\)) and the other was the difference between the predicted maximum shear strain at the highest and lowest maximum shear rate (\(\Delta\gamma_{\text{max}}\)).

- **Powder effect:** maximum difference in \(\gamma_{\text{max}}\) was 53 s\(^{-1}\) (2261 – 2314 s\(^{-1}\)) and maximum difference in \(\Delta\gamma_{\text{max}}\) was 121 s\(^{-1}\) (0 s\(^{-1}\) – 137 s\(^{-1}\))
- **Binder effect:** maximum difference in \(\gamma_{\text{max}}\) is 108 s\(^{-1}\) (2261 – 2369 s\(^{-1}\)) and maximum difference in \(\Delta\gamma_{\text{max}}\) is 22 s\(^{-1}\) (0 – 22 s\(^{-1}\)).

The maximum shear rate depends more on the binder than the powder. On the other hand, the dependency of maximum shear rate on injection temperature shows an opposite trend which is more sensitive in powder choices.

### 5. Conclusions

The rheological behavior and thermal properties of different combinations of powders and binders system were investigated. By using the injection molding simulation tool, an injection molding parameter study was done with 7 different feedstocks which included 3 feedstocks with the same powder, but different binder system, and three other feedstocks with the same binder system but different powder. The findings are summarized as follows:

- All feedstocks exhibited a shear thinning or pseudoplastic behavior. A non-linear behavior in the variation of viscosity versus shear rate on a log-log scale was observed.
- For rheological properties, the power law index, \(n\) was more sensitive in binder selection than powder selection. We could observe the same trend for the difference in zero shear rate viscosity, \(\eta_0\) but for the reference temperature, \(T_b\), the powder selection gives a relevant control in the temperature sensitivity of feedstock.
- For thermal properties, we found out that both powder and binder selection had the same effect on determining thermal conductivity and heat capacitance of feedstock.
- From the pressure-related outputs, it was determined that the selection of binder system was more critical to minimize injection pressure and clamping force and its dependency on injection temperature. The maximum wall shear stress showed the same trend except that the dependency on injection temperature was found to be almost equal in both cases.
- From the temperature-related outputs, the selection of binder systems was more critical both in controlling the melt front temperature difference and the cooling time.
- From the velocity-related outputs, the selection of both powder and binder systems was critical in controlling the maximum shear rate.

This study demonstrates how new simulation tools can enable rapid convergence to optimized manufacturing conditions. Early investment in these efforts is expected to eliminate later difficulties on project debugging.
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References