Investigation of rheological behaviour of 316L stainless steel–3 wt-%TiC powder injection moulding feedstock

M. Khakbiz, A. Simchi and R. Bagheri

The rheological behaviour of powder injection moulding feedstock comprising of 316L stainless steel and 3 wt-%TiC powders was studied using a capillary rheometer. The flowability and the sensitivity of viscosity to shear rate and temperature of the feedstock were investigated and compared with those of the binder system and the 316L SS PIM feedstock. The general rheological indexes were examined through relevant equations and the influence of TiC addition to the mouldability of the 316L SS feedstock was determined. It was found that all the feedstocks are basically pseudoplastic but the values of flow behaviour index n are influenced by the TiC addition, the solid volume fraction and the temperature. In this context, the results show that TiC addition plays an important role in rheological parameters, i.e. TiC particles decrease the viscosity of PIM feedstock and this effect is more pronounced in the system comprising higher solid volume fraction. Furthermore, the flow activation energy decreases with the introduction of TiC particles, in particular at high shear rates. In other words, the addition of ceramic particles would ease the feedstock flow and suppress the sensitivity of the feedstock to strain rate and temperature variations, if a proper moulding temperature is applied. From the viewpoint of mouldability, the optimum PIM condition for the SS/TiC composite powder containing a wax based binder system was found at 55% solid volume fraction and 70 °C. At this condition, the viscosity of feedstock is low enough to fulfill the requirements of a medium pressure, injection moulding process.

INTRODUCTION

Powder injection moulding (PIM) is an alternative development of the traditional powder metallurgy process for the production of intricate small parts in high quantities. This process, which is a modification of the plastic injection moulding technique where a significant volume fraction of plastic is replaced by a fine powder, circumvents the most common difficulties encountered in powder metallurgy regarding density gradients and geometry limitation. It also results in reasonably tight tolerances and good surface finishes at relatively low cost. Some of its applications are in the automotive industry, medical and dental instruments, orthodontic devices, office machinery, computer peripherals, microelectronic packaging, gun and armament parts, sporting tools, investment casting cores, wristwatch cases, valves, food and beverage processing components.

The PIM process typically consists of four steps. Initially, metal or ceramic powders are mixed with suitable organic binders and granulated to prepare a mouldable feedstock. Binders are usually composed of a main polymer, like polypropylene or polyethylene, to support and maintain the shape of the components during processing. In order to decrease the viscosity of the mixture and to provide a good binder to powder interface, additives such as waxes and polymers with low molecular weight are considered as PIM binders. During moulding, the feedstock flows into and fills a mould under heat and pressure to form a green part with the desired shape. The moulded part then undergoes a debinding step where the powder is extracted out and the powder is sintered to full or near full density.

Recently, as a result of the recognition of the merits of PIM, several materials are being processed by this method, e.g. plain iron, stainless and tool steels, Fe/Ni and Fe/Co alloys, low alloy steels, WC/Co hard metals, titanium and tungsten alloys, alumina, silicon carbide, silicon nitride and ferrites. Among the different materials, the production of stainless steels is the most popular use of the PIM process and it now accounts about 60% of the value of powder sales. Although the mechanical properties of PIM parts can reach or exceed those of cast or forged alloys, there is still a great motivation for producing stronger and tougher materials. For instance, the fabrication of high strength parts from gas atomised and water atomised PH stainless steel powders has recently attracted considerable interest.

A few experiments have also been performed to investigate the rheological behaviour of PIM feedstock containing TiC particles. The influence of TiC addition on the mouldability of the 316L SS feedstock was determined. It was found that all the feedstocks are basically pseudoplastic but the values of flow behaviour index n are influenced by the TiC addition, the solid volume fraction and the temperature. In this context, the results show that TiC addition plays an important role in rheological parameters, i.e. TiC particles decrease the viscosity of PIM feedstock and this effect is more pronounced in the system comprising higher solid volume fraction. Furthermore, the flow activation energy decreases with the introduction of TiC particles, in particular at high shear rates. In other words, the addition of ceramic particles would ease the feedstock flow and suppress the sensitivity of the feedstock to strain rate and temperature variations, if a proper moulding temperature is applied. From the viewpoint of mouldability, the optimum PIM condition for the SS/TiC composite powder containing a wax based binder system was found at 55% solid volume fraction and 70 °C. At this condition, the viscosity of feedstock is low enough to fulfill the requirements of a medium pressure, injection moulding process.

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Keywords: 316L Stainless Steel, TiC Powders, Powder Injection Moulding

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LIST OF SYMBOLS

\[ x_{\text{STV}} \] mouldability index (equations (5) and (6))
\[ n \] shear rate
\[ \eta \] viscosity of PIM feedstock
\[ \eta_0 \] viscosity at a reference temperature \( T_0 \)
\[ \eta_b \] viscosity of binder
\[ n_t \] relative viscosity (\( \eta/\eta_b \))
\[ \Phi \] solid loading
\[ \Phi_c \] critical solid loading (equation (3))
\[ \Phi_r \] relative solid loading (\( \Phi/\Phi_c \))

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Recently, as a result of the recognition of the merits of PIM, several materials are being processed by this method, e.g. plain iron, stainless and tool steels, Fe/Ni and Fe/Co alloys, low alloy steels, WC/Co hard metals, titanium and tungsten alloys, alumina, silicon carbide, silicon nitride and ferrites. Among the different materials, the production of stainless steels is the most popular use of the PIM process and it now accounts about 60% of the value of powder sales. Although the mechanical properties of PIM parts can reach or exceed those of cast or forged alloys, there is still a great motivation for producing stronger and tougher materials. For instance, the fabrication of high strength parts from gas atomised and water atomised PH stainless steel powders has recently attracted considerable interest.

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LIST OF SYMBOLS

\[ E \] flow activation energy (equation (2))
\[ K \] constant (equation (1))
\[ n \] flow behaviour index (equation (1))
\[ R \] gas constant
\[ T \] temperature
performed on the production of composite parts by reinforcing a metal or intermetallic matrix with ceramic particles.\(^3,20\) However, the application of PIM in the production of metal matrix composites has not been reported widely.

The primary goal of this work was to assess the rheological behaviour of 316L stainless steel–3 wt-%TiC powder injection moulding feedstock. This feedstock can be used for the production of intricate parts with high wear and corrosion resistance using the PIM process. It is known that in PIM the moulding process is a critical step for the fabrication of sound parts without cracks and distortion.\(^4,5\) This step requires specific rheological characteristics, therefore, the study of feedstock melt flow and the mould filling are key features for successful manufacturing. Within this paper, the effects of shear rate \(\gamma\), solid volume fraction \(\Phi\) and temperature \(T\) on the flowability and viscosity of the SS and SS/TiC feedstocks were examined using a capillary rheometer. The capillary test, which gives the fundamental rheological data of a viscous fluid, is currently realised as the best approach to predict the flow behaviour during injection moulding.\(^10\) Based on the results of this test, the influence of TiC addition on the rheological behaviour and mouldability of the stainless steel feedstock is presented and discussed. The optimum condition of moulding is also addressed.

### EXPERIMENTAL PROCEDURE

#### Powders

Gas atomised 316L stainless steel powder with a mean diameter \(d_{50}\) of 12.6 \(\mu\)m from Osprey Ltd, UK and TiC powder with \(d_{50}\) of 4 \(\mu\)m from Aldrich were used. The characteristics of these powders are given in Tables 1 and 2. Figure 1 shows the morphology of the powders recorded by scanning electron microscopy (SEM). The steel powder particles are almost perfectly spherical while the ceramic particles are angular in shape.

#### Binder and feedstock

A multicomponent binder system was used to prepare the feedstock. The characteristics of the binder components are given in Table 3. To prepare the feedstock, initially the steel powder was mixed with 3 wt-%TiC in a tumbler mixer for 20 min. The binder components were then blended at 100 \(^\circ\)C in a Haake rheocord 90 torque rheometer for 60 min to ensure adequate time for the binder to melt and homogenise. After that, the powders were added in several stages to achieve a homogenous mixture. The mixing was continued for a further 60 min. Figure 2 shows a light microscopic micrograph of rheometer noodles. The granulation was carried out by a manual chopper. Powders with the solid volume content of 55 and 60% were prepared in this study. Feedstocks are referenced here by their powder constitution and solid loading. For example, SS–3TiC–55 is

#### Table 1 Chemical composition (wt-%) of 316L stainless steel powder used in present study

<table>
<thead>
<tr>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Mn</th>
<th>Si</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>17.2</td>
<td>10.7</td>
<td>2.8</td>
<td>1.4</td>
<td>0.62</td>
<td>0.01</td>
</tr>
</tbody>
</table>

#### Table 2 Characteristics of powder materials

<table>
<thead>
<tr>
<th>Powder</th>
<th>Shape</th>
<th>(D_{10}) (\mu)m</th>
<th>(D_{50}) (\mu)m</th>
<th>(D_{90}) (\mu)m</th>
<th>Apparent density, (\times 10^3) (\text{kg m}^{-3})</th>
<th>Tap density, (\times 10^3) (\text{kg m}^{-3})</th>
<th>Width of particle size distribution*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>Spherical</td>
<td>4.4</td>
<td>12.6</td>
<td>27.6</td>
<td>2.53</td>
<td>4.24</td>
<td>3.84</td>
</tr>
<tr>
<td>TiC</td>
<td>Irregular</td>
<td>1</td>
<td>4</td>
<td>9</td>
<td>–</td>
<td>2.24</td>
<td>2.68</td>
</tr>
</tbody>
</table>

*Sw=2.56/log \((d_{90}/d_{10})\)
the feedstock containing 3 wt-%TiC and has a solid loading of 55%. The following four feedstocks were prepared for research: SS–55, SS–60, SS–3TiC–55, SS–3TiC–60.

Rheological measurement
An Instron 3211 capillary rheometer with temperature control of ±1 K was used to measure the viscosity of the SS and SS/TiC PIM feedstocks. A period of 10 min was allowed to reach thermal equilibrium after charging the barrel. A die 0.08 mm in diameter \( D \) and 2.56 mm in length \( L \), giving a ratio \( (L/D) \) of 35, was used to give the mix a smooth and lamellar flow and minimum entrance corrections²¹ (Bagley entrance correction for stress due to funneling effect at the entrance). The measured shear rates were corrected using the Rabinowitsch equation,²² as PIM feedstocks are considered to be non-Newtonian fluid. As \( L/D \) is >20 the entry and exit effects can be ignored.²³ The testing temperatures were 60, 70, 80 and 90 °C.

RESULTS AND DISCUSSION
The results of viscosity measurement for the feedstocks at different shear rates and temperatures are given in Table 4. These data indicate the flowability of the PIM feedstock, i.e. the lower the value of viscosity the easier it is for a feedstock to flow. It can be seen that the rheological behaviour of the examined feedstocks depends on shear rate \( \gamma \), temperature \( T \) and solid volume fraction \( \Phi \) as presented and discussed below.

Effect of shear rate
Figure 3 shows the viscosity to shear rate relationship for the investigated PIM feedstocks at different temperatures in a log-log scale. This relation for the multicomponent binder system is also shown in the graph for comparison purpose. From this figure, one can notice that the viscosity generally decreases with an increase in shear rate (shear thinning). German and Bose⁴ suggested that particle or binder molecule orientation and ordering with flow causes this phenomenon. This effect is desirable in PIM because it suppresses the possibility of powder–binder separation during moulding. Nevertheless, from these figures one may notice a trend of the viscosity reaching a lower plateau at relatively high shear rates. This can be a result of a disproportionate increase in particle–particle contacts that hinder flow. Here, it is pertinent to point out that shear rates of \( 10^2 \) to \( 10^5 \) s⁻¹ fall in the normal range of shear rates

### Table 3  Characteristics of binder system used for PIM

<table>
<thead>
<tr>
<th>Component</th>
<th>Chemical structure</th>
<th>Melting point, °C</th>
<th>Density, ( \times 10^3 ) kg m⁻³</th>
<th>Content, vol-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraffin wax</td>
<td>( C_{n}H_{2n+2} )</td>
<td>58</td>
<td>0.92</td>
<td>53</td>
</tr>
<tr>
<td>Ethylene vinyl acetate</td>
<td>([C (CH_2CO_2) CH_2] )</td>
<td>92</td>
<td>0.96</td>
<td>30</td>
</tr>
<tr>
<td>Carnauba wax</td>
<td>([C_{25}H_{51}COOC_{30}H_{61}] )</td>
<td>82</td>
<td>0.99</td>
<td>15</td>
</tr>
<tr>
<td>Stearic acid</td>
<td>( CH_3(CH_2)_{16}COOH )</td>
<td>67</td>
<td>0.94</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table 4  Viscosity (Pa s) of examined PIM feedstocks at different temperatures and shear rates

<table>
<thead>
<tr>
<th>Solid loading, %</th>
<th>Feedstock</th>
<th>Temperature, °C</th>
<th>Shear rate, s⁻¹</th>
<th>1181</th>
<th>3543</th>
<th>1181</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1181</td>
<td>3543</td>
<td>1181</td>
<td>3000</td>
</tr>
<tr>
<td>55</td>
<td>SS</td>
<td>60</td>
<td>448.1</td>
<td>181.6</td>
<td>67.5</td>
<td>31.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>70</td>
<td>40.4</td>
<td>26.5</td>
<td>16.7</td>
<td>11.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>42.2</td>
<td>24.8</td>
<td>13.4</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>SS–3 wt-%TiC</td>
<td>60</td>
<td>405.4</td>
<td>160.2</td>
<td>58.0</td>
<td>26.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>70</td>
<td>53.8</td>
<td>31.9</td>
<td>18.0</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>37.6</td>
<td>24.2</td>
<td>14.9</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>SS</td>
<td>60</td>
<td>939.2</td>
<td>442.8</td>
<td>194.2</td>
<td>102.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>70</td>
<td>93.6</td>
<td>30.8</td>
<td>23.4</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>62.7</td>
<td>35.3</td>
<td>18.8</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>SS–3 wt-%TiC</td>
<td>60</td>
<td>340.9</td>
<td>174.0</td>
<td>83.3</td>
<td>47.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>70</td>
<td>107.0</td>
<td>53.8</td>
<td>25.3</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>60.0</td>
<td>33.4</td>
<td>17.6</td>
<td>10.7</td>
<td></td>
</tr>
</tbody>
</table>
Effect of TiC addition on viscosity of 316L stainless steel feedstock as function of shear rate at two solid volume contents of 55 and 60% and two temperatures of a 60°C and b 70°C

4 Nevertheless, tests for shear rate sensitivity are normally conducted up to rates of 1000 s⁻¹ (Ref. 4). The viscosity of the mixture at the moulding temperature should be less than 1000 Pa s, although the upper limit for the low pressure injection moulding is about 40 Pa s. Based on the viscosity data of Table 4, one can notice that the shear rates of 1000 s⁻¹ satisfactorily fulfill this requirement. Therefore, the behaviour of the investigated feedstocks can be regarded as pseudoplastic (shear thinning) in the practical range of shear rates of PIM. It was found that the influence of the addition of TiC particles to the stainless steel powder on the viscosity strongly depends on the temperature and shear rate (Fig. 4). Generally at shear rates >1000 s⁻¹ and at temperatures >70°C, the influence of TiC addition for the examined solid loadings (55 and 60%) is not conspicuous. Nevertheless, at a temperature of 60°C and at low shear rates, a slight decrease in the value of viscosity was determined on the introduction of TiC particles. This effect is more pronounced for the feedstock comprising a higher solid volume content. In other words, the addition of ceramic particles facilitates the feedstock to flow, in particular at higher solid loadings. As shown in Fig. 1, the TiC particles are considerably finer than the stainless steel particles, i.e. the ratio of mean diameters is about 1:3. This means that there is enough space available between SS particles to be occupied by the fine TiC particles. Hence, at a low weight fraction (3 wt-%), the ceramic particles should not significantly influence the viscosity of feedstock even though the shape of particles is irregular. At a constant solid volume fraction, adding TiC particles means less stainless steel powder in the system and thus less particle to particle friction. Here, it should be noted that small particles fill interstitial spaces and release the binder to lubricate particle flow. Anyway, it is evident that the lower interparticle friction reduces the viscosity of feedstock. This effect would be more pronounced if a higher solid content is incorporated. However, at a high shear rate this influence is diminished since PIM feedstocks behave like pseudoplastic substances, i.e. decreasing viscosity with increasing shear rate (shear thinning).

The results show that at an intermediate temperature (70°C) the viscosity of the feedstock is increased when TiC particles are introduced into the mixture. If the temperature of the feedstock is high enough to suppress the influence of interparticle friction in the SS/binder mixture, then it would be expected that the addition of TiC powder increases the viscosity slightly, owing to the angular shape of TiC particles. It is known that the viscosity of PIM feedstocks depends on the powder particle shapes, in which, spherical particles possess lower viscosity while irregular particles yield higher viscosity.²₅⁻²⁶

It was shown above that the examined PIM feedstocks show pseudoplastic flow characteristics in the normal range of injection moulding. For such fluid, shear rate dependence of viscosity could be described by following equation²³

\[
\eta = K \gamma^{n-1}
\]

where η is the feedstock viscosity, γ is shear rate, K is a constant and n is the flow behaviour index <1. The value of n, which indicates the degree of shear sensitivity, gives an important insight about the rheological characteristics of PIM feedstock. A lower value of the flow behaviour index means more viscosity dependency on the shear rate, which is desirable for the producing complex and delicate parts.²⁶

Figure 5 shows the values of n for the examined feedstocks at different temperatures deduced from the slope of the log η—log γ graphs (Fig. 4). It is pertinent to point out that the values of n are calculated at 1181 s⁻¹ shear rate, which falls in the normal range of shear rates of injection moulding of PIM feedstocks. It can be noticed that n varies from 0.15 to 0.75 depending on the feedstock composition and the test temperature. Taking 70°C as a reference temperature, it can be seen that the addition of TiC powder reduces the n value. This means that the SS-3 wt-%TiC feedstock has a greater strain rate sensitivity and pseudoplastic dependency than the SS feedstock. Figure 5 also shows that in the composite feedstock, the n
value decreases with increasing solid loading. This behaviour highlights the influence of shear rate on the breakage of agglomerates in the composite feedstock.

**Influence of temperature**

Another important characteristic of PIM feedstock is the temperature dependence of viscosity. If the viscosity is very sensitive to the temperature variation, any small fluctuation of temperature during moulding will result in a sudden viscosity change. This could cause undue stress concentration in the moulded part, resulting in cracking and distortion. In addition, a strong temperature dependence of viscosity dictates smaller pressure transmission to the cavity, thereby promoting the possibility of the formation of shrinkage related defects. Therefore, it is important to assess the viscosity-temperature relationship.

Normally, the viscosity varies exponentially with absolute temperature $T$ as follows

$$
\eta = \eta_0 \exp \left( \frac{E}{RT} \right)
$$

where $\eta_0$ is the viscosity at a reference temperature of $T_0$, $E$ is a material specific constant which is termed the flow activation energy and $R$ is the gas constant. The smaller values of $E$ show a low sensitivity of viscosity to temperature, thereby minimising stress concentration, cracks and distortion in the moulded parts. By plotting the viscosity of PIM feedstock in logarithmic scale against the reciprocal of temperature, the flow activation energies can be determined at a certain shear rate. As shown in Fig. 6, for the examined feedstocks the points on the graph tend to fit into straight lines in which the slopes are proportional to the values of $E$. The influence of shear rate on the flow activation energy $E$ is shown in Fig. 7. One can notice that with an increase in shear rate the value of $E$ decreases. The data show that the addition of TiC powder reduces the activation energy for the feedstock with 55% solid loading, in particular at high shear rates. For instance, the values of $E$ decrease from 19 to 16 kcal mol$^{-1}$ at a shear rate of 1181 s$^{-1}$. Meanwhile with the increase in the solid volume content, i.e. 60%, higher activation energy was measured for the SS feedstock. Again, the addition of TiC particles reduces the flow activation energy of the SS feedstock although the influence of shear rate is less pronounced (Fig. 7).

It is known that the flow activation energy of PIM feedstock depends on the thermal expansion coefficient of the system, i.e. a higher volume expansion results in a lower viscosity and thereby lower activation energy. Hence, the sensitivity of viscosity to temperature would be lower if less solid loading is incorporated. In other words, since the filler provides very little free volume change with temperature in relation to the binder, the activation energy increases with increasing filler content. Also, when TiC particles are introduced to the system at a constant solid loading, the higher packing of the bimodal mixture allows more binder to act as lubricant, i.e. the small particles fill interstitial spaces and release the binder to lubricate particle flow. In addition, the ceramic particles have lower thermal conductivity than those of the stainless steel powder. The result is lower viscosity of the mixture and less sensitivity to the temperature.

**Effect of powder loading**

It is known that the ratio of powder to binder largely determines the success or failure of PIM. Since the optimum volume fraction of binder and hence the viscosity of PIM feedstock depends on powder characteristics such as the particle size distribution and particle shape, it is important to determine the optimum solid loading for the examined powders. The appropriate model for the solid loading dependence on viscosity of PIM feedstock, which accords well with practice, is as follows

$$
\eta = \eta_0 \left( \frac{A}{1 - \Phi \Theta} \right)^z
$$

where $\eta$ and $\eta_0$ are the viscosity of feedstock and binder, respectively. The critical solid loading $\Phi_0$ is the composition where the particles are packed as tightly as possible without external pressure and all the space between the particles is filled with binder. This parameter can be taken to be 64% for monosized spherical powders. The coefficient $A$ depends on particle size and is typically close to 1. Figure 8 shows the relative viscosity ($\eta/\eta_0$) of the examined feedstocks as a function of shear rate at 60°C for two different solid loadings, i.e. $\Phi = 55$ and 60%. It can be seen that the relative viscosity depends on the shear rate and this dependency varies with the solid loading. Furthermore, the addition of TiC particles decreases the relative viscosity, owing to the ceramic particles impact on the feedstock viscosity as cited above. In order to have better evaluation, equation (3) was modified to incorporate the influence of shear rate on the viscosity as cited in Ref. 23

$$
\eta = A(1 - \Phi)^{-2}\eta_0
$$
where $\eta_r$ and $\Phi_c$ are relative viscosity ($\eta/\eta_b$) and relative solid loading ($W/W_C$), respectively. In this work, the critical solid loading was determined using the Reddy’s model\textsuperscript{21}

$$\eta(1-\Phi) = \eta_b \Phi_c + \eta(1-\Phi_c)$$ \hspace{1cm} (5)

If the viscosity of the PIM feedstock is plotted against the binder viscosity at varying shear rates, the critical solid loading can be easily evaluated from the model using the viscosity data. As shown in Fig. 9, for the examined feedstocks the graphs tend to fit into straight lines in which the slopes give the values of $\Phi_c$. It was found that when $\Phi_c=64\%$ satisfactory fits the experimental results for the SS and SS–3TiC feedstocks at 55$\%$ solid loading and for the SS feedstock at 60$\%$ solid loading. The values of constants $A$ and $m$ were then determined using the best fit methods with a correlation better than 0.97. The results are given in Table 5 for the feedstocks examined at 60°C. It is of interest to note that the values of $A$ decrease with the addition of TiC particles, while the value of $m$ increases. It is known that the value of $A$ approaches unity if the shear rate is high enough to disperse all aggregates without turbulence in the flow.\textsuperscript{4} Therefore, the values of $A$ and $m$ show the importance of shear rate on the homogeneity of the powder/binder distribution. This influence is more pronounced for the higher solid loading, i.e. 60$\%$.

General rheological behaviour

The success of the injection moulding process depends on several factors. From the viewpoint of mouldability, the viscosity of the PIM feedstock and its relationship with temperature, shear rate and solid volume fraction are of special concern. As discussed above, a feedstock with low viscosity, low flow behaviour index and low flow activation energy provides better rheological behaviour during moulding. Nevertheless, there is usually a contradiction among these properties. Therefore, it is regarded as necessary to take into account the above properties together. For this purpose, it has been shown elsewhere\textsuperscript{26} that the mouldability index ($STV$) can be used to assess the general rheological properties of PIM feedstock

$$STV = \frac{1}{E} \left( \frac{n}{\eta_0} \right)^{a-1}$$ \hspace{1cm} (6)

Simplifying the above equation gives the following

$$STV = \frac{1}{E} \left( \frac{n}{\eta_0} \right)^{a-1}$$ \hspace{1cm} (7)

It is clear that the higher the value of this index (lower $n$ and $E$) the better the rheological properties of the feedstock. Figure 10 shows the mouldability index of examined feedstocks as a function of temperature at a reference shear rate of 1181 s$^{-1}$. It is of interest to note that $STV$ increases with the addition of TiC particles. In other words, the composite feedstock exhibits better mouldability than the base SS feedstock. As stated above, the fine ceramic particles fill the interstitial spaces between the SS particles and release binder to lubricate particle flow. However, it was found that the mouldability of the feedstocks with $\Phi=60\%$ is generally inferior in comparison to that of $\Phi=55\%$. Anyway, the mouldability index is fairly low at 60°C, which is not desirable for injection moulding. Based on the results obtained it seems that from the viewpoint of

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Solid volume fraction, %</th>
<th>$A$</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>316L SS</td>
<td>55</td>
<td>0.11</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.11</td>
<td>0.02</td>
</tr>
<tr>
<td>316L SS–3 wt-% TiC</td>
<td>55</td>
<td>0.02</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.01</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 5 Values of $A$ and $m$ in equation (4) for the feedstocks examined at 60°C
mouldability, it is preferable to mould the SS–3TiC composite feedstock at 70°C with 55% solid volume fraction. However, it should be noted that for the debinding and sintering processes, a higher solid loading is more suitable owing to the influence of Φ on the possibility of slumping and the extent of dimensional shrinkage. Therefore, these important attributes must also be taken into account in the selection of proper solid loading, which is not considered in this paper but needs further investigation.

CONCLUSIONS
The influence of 3 wt-% TiC addition on the rheological behaviour of 316L stainless steel feedstock was studied using a capillary rheometer. It was found that the SS and composite feedstocks show basically pseudoplastic behaviour, i.e. the viscosity decreases with increasing shear rate by a power law relationship. However, the viscosity, the flow behaviour index and the flow activation energy decrease with the addition of TiC particles, which in fact is desirable for injection moulding. In other words, the composite feedstock comprising of 316L SS and TiC powders has better mouldability than the base SS powder, i.e. the addition of TiC powder facilitates the melt feedstock flow. Nevertheless, the best moulding level was found for the feedstock with 55% solid volume fraction. The proper moulding temperature was also found to be 70°C for the used multicomponent binder system. Metal matrix composites can be produced by PIM process if proper debinding and sintering cycles are tackled.

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