Original Article

Metal flow behavior of P/M connecting rod preform in flashless forging based on isothermal compression and numerical simulation

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\section*{Abstract}

The intrinsic properties and the damage behavior of powder metallurgy (P/M) connecting rod preform have significant effects on its metal flow behavior during flashless forging into its final complex shape with substantial densification. The P/M material constitutive equation were established using isothermal compression tests, and then used to study the metal flow behavior of a P/M connecting rod preform during flashless forging based on finite element modelling (FEM). Moreover, the preform geometry was designed based on these metal flow mechanisms. Experiments and flashless forging of P/M connecting rod preforms were performed in order to verify the accuracy of the simulations. The simulated results are well consistent with the experimental results. Results showed that the shank is much more prone to cracking due to the higher deformation rate and the faster cooling rate. The optimal dimensions of the P/M preform were obtained. When the preform geometry are optimized, the average density of the connecting rod increases homogeneously, and becomes superior to that of the original shape. This work suggests that the geometry of the preform can be designed efficiently based on our models. This work can help to derive a P/M connecting rod preform optimization methodology, which can offer the possibility of improving the quality of the connecting rods efficiently.

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\section{Introduction}

Powder forging connecting rod technology integrates the advantages of precision flashless forging and powder metallurgy (P/M) in a single operation. This technology allows to directly obtain near-net or net shape connecting rods with...
homogeneous density distribution and excellent mechanical properties from the porous P/M preform. This kind of technology can help to reduce the materials wasted to the flash, which accounts for 20–40% of the original preform, and offers the possibility of producing connecting rods at competitive costs [1–3].

During the flashless forging process, a porous preform perpetrated by the P/M process was flashless forged into its final shape [4]. Since P/M preform is porous, and connecting rods have a non-uniform cross-section and a complex geometrical shape, as shown in Fig. 1, some problems, i.e., poor controllability of the metal flow behavior and substantial densification of the P/M materials during the forming process are inevitable. These problems should be solved and accurately controlled to obtain connecting rods with high and homogeneous density, especially to avoid the preform overload the dies and to fully fill the cavity [5]. Fortunately, further investigating the metal flow mechanisms of a porous P/M connecting rod preform during the flashless forging process and properly designing the geometry of the preform before hot forging can offer the possibility to control the forming process such as to fabricate connecting rods with excellent mechanical properties.

The available literature demonstrates that hot compressive tests used for thermo-physical simulation is a critical task in the design analysis process [6–9]. For example, materials constitutive equations of spray formed LSHR alloy and GH4169 super alloy were successfully established using a Gleebe-3500 thermal simulator [6] or thermo-physical simulation, respectively [7]. Qiu et al. [8] established a constitutive equation for P/M titanium alloys. It can be noted that constitutive equation can provide valuable information about the physical properties of materials [9]. However, since the presence of substantial amount of porosity content in P/M materials, the P/M material constitutive model are still needed to be further accurately interpreted. By reviewing the available reports about the optimization of the shape of a connecting rod preform, it can be noted that most of the investigations focusing on topology and geometry optimization. They only divided the product into different parts with simple geometries and then designed the process condition for each region independently [10–12].

For P/M connecting rod preforms with non-uniform density distribution and complex geometrical shape deformed during flashless forging processing, different parts have different metal flow behaviors. Therefore, it is more appropriate to treat the preform as a whole geometry for studying the metal flow behavior. Only in this way it may be possible to accurately control the mass distribution of the connecting rod.

Finite element modelling (FEM) is a promising approach to design the entire process leading to materials savings as well as to cost and time reduction [13–16]. Abdullin et al. [17] utilized a FEM software to simulate the metal-forming process. Rajeshkannan et al. [18] simulated the powder preform forging process. These examples underline that the computer modeling and simulation offers a great help to iteratively modify the processing parameters and mold design to find the most suitable manufacturing conditions for a connecting rod. However, the simulation of the metal flow behavior of porous P/M connecting rod preforms during flashless forging presents a significant challenge for the development of meaningful models. First, lots of the available studies have defined the porous P/M material as a fully dense material, and/or only considered porosity elimination of sintered compacts with simple geometry. Second, some studies considered boundary constraints of the stress and friction behavior of connecting rods, but neglected the damage behavior of porous P/M materials during the forming process. Cao [19,20] simulated crack nucleation and growth in cold bulk metal forming processes. Khaoulani et al. [21] studied a cup-cone fracture in a tensile test and predicted the fracture limit in metal forming. Li et al. [22] predicted shear-induced fracture in sheet metal forming. Based on these results, it can be concluded that the damage behavior of porous P/M connecting rod preform during flashless forging has a considerable effect on the accuracy of the simulation results, and should be involved. However, in many cases, it still has not been fully understood how to accurately control the metal flow behavior and efficiently design the porous P/M connecting rod preform geometry.

In our previous work, the processing parameters for the hot forging process of the porous P/M material were optimized [23]. In this work, the P/M material constitutive models are further accurately interpreted. And the quality of connecting rod will be further improved from the aspect of porous P/M preform geometric design. First, the P/M material constitutive equation is established, an appropriate criterion satisfying for complex stress state applications is selected, the boundary conditions among the preform, the ambient environment and cavities changing with time are considered, as well as the damage behavior of the porous P/M material during the flashness forging process. Second, the metal flow behavior of a porous P/M preform during flashless forging will be investigated using FEM. Finally, based on these models, the optimal dimensions of the preform are obtained by using an orthogonal design method. This work contributes to a better understanding of the metal flow mechanism of a porous P/M connecting rod preform during the flashless forging process of an Fe-Cu-C alloy as model system. These results can help to derive a P/M connecting rod preform optimization methodology, which can offer the possibility of improving the quality of the connecting rods efficiently.
2. Materials, experimental methods and calculation

2.1. Materials

A Fe-3Cu-0.5C (wt.%) alloy with a relative density of 0.8 manufactured by powder metallurgy route (P/M Fe-Cu-C) was selected as the model material.

2.2. Experimental methods

The isothermal compression test can be used to study the flow stress of the P/M Fe-Cu-C alloy. First, samples with diameter of 8 mm and height of 12 mm were prepared, and then heated by induction coils at a heating rate of 5 K/s and soaked for 10 s by the thermocouple feedback control system. Then, samples were hot compressed using a Gleebe-3500 thermal simulator to a final strain of 0.7 at temperatures of 1333, 1363, 1393 and 1423 K and strain rates of 5, 11.5 and 19.2 s⁻¹, respectively. The true strain–stress curves were obtained automatically.

In the flashless forging operations, the punch velocity was determined as 250 mm/s⁻¹, while the preheating temperature of the preform and the moulds were 1403 and 573 K, respectively. In order to verify the accuracy of the above established models, two connecting rod preforms with the initial geometry were flashless forged under the same processing parameters. One of the preforms was forged to its final shape, another one was stopped after 0.038 s when the preform was partially deformed. Samples with dimension of 8 × 12 mm were cut at different axial locations. The density of the samples was measured using a buoyancy weighing machine. In order to verify the validity of the models, a flashless forging experiment under the same processing conditions was carried out on the optimized preform.

2.3. Numerical calculation

The initial size and geometry of the porous P/M preform are presented in Figs. 2 (a) and (b): the thickness of the small end section (A), the large end section (B) and the connecting section or the shank (E) were 42.4 mm, 23.4 mm and 26.4 mm, respectively. The outer radius of the large end section (C) and the length of the shank (D) were 27.4 and 74.6 mm, respectively, and the degree of the chamfering (F) was 3°.

The thermo-mechanically coupled simulation of the flashless forging of the porous P/M connecting rod preform was performed with the finite-element software, DEFORM-3D. The tooling models were defined as rigid material. For a detailed description of the finite element theory, the readers are referred to [24]. In this work, the initial preform density affected by the P/M process was fixed as a constant for simplicity. The corresponding analysis FEM models of the preform, tool, punch and cavity are established in Fig. 3(a). Isoparametric four-node elements were utilized to define the element mesh, as shown in Fig. 3(b).

The mesh density was changed according to the strain distributions. Namely, the mesh density in a large deformation zones was higher than that in other areas. For example, the element numbers and nodes of the connecting rod preform were 72,341 and 17645, respectively. More details can be seen in Table 1. An adaptive remeshing parameters and an updated Lagrange procedure were chosen for large elastic-plastic deformation. This procedure can also help to reduce the total calculating time. In this work, H13 was utilized for the moulds. The physical property data of the preform and H13 are listed in Table 2 [25,26]. According to the forging conditions, the friction factor for the porous P/M preform was determined as 0.3 for the porous P/M preform [27].

Compared with other damage criteria, the Cockcroft-Latham criterion, which can give accurate results in three dimensional high stress state applications, was utilized [28]:

\[ \int \frac{\sigma_{\text{max}}}{\sigma} \, \text{d}\varepsilon = C_d. \]  

(1)

Where \( \sigma_{\text{max}} \) is the principal stress and \( \text{d}\varepsilon \) is the effective strain increment. The damage factor \( C_d \) can be utilized to describe the crack probability of materials in the DEFORM-3D software. Once \( C_d \) reaches a critical value \( C_d \), fracture occurs.

The heat transfer among the tooling, the billet and the ambient environment is an important factor for the material flow behavior of the preform. Since the flashless forging of a P/M preform is a thermo-mechanical process, the heat balance equation can be described as: [29]

\[ Q_l + A \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - \rho C \frac{\partial T}{\partial t} = 0, \]

(2)

where \( Q_l \) is the heat generated due to plastic deformation or the heat converted from plastic work \( Q_l \); \( A \) is the thermal conductivity.

The heat loss at internal preform during cooling is calculated as:

\[ Q_s = \frac{h_s}{\sqrt{2\pi k}} \left( T - T_s \right) + \frac{\epsilon}{\sqrt{2\pi k}} \left( \frac{\varepsilon^4}{T_s} - \frac{\varepsilon^4}{T_s^4} \right), \]

(3)

where \( T_s \) is the environment temperature, and \( \varepsilon \) and \( \xi \) are the emissivity constant and the Stefan-Boltzmann’s constant, respectively.

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### Table 1 – Element numbers and nodes of different simulation models.

<table>
<thead>
<tr>
<th></th>
<th>Preform</th>
<th>Bottom die</th>
<th>Cavity block</th>
<th>Top die</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements</td>
<td>72,341</td>
<td>14521</td>
<td>64899</td>
<td>76682</td>
</tr>
<tr>
<td>Nodes</td>
<td>17645</td>
<td>61235</td>
<td>15468</td>
<td>17812</td>
</tr>
</tbody>
</table>

### Table 2 – Physical property data of the preform and the mould [25,26].

<table>
<thead>
<tr>
<th></th>
<th>P/M Fe-Cu-C alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>155</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>460</td>
</tr>
<tr>
<td>Heat capacities per unit mass (Jkg⁻¹K⁻¹)</td>
<td>C_p = 317.202 + 0.433 × T</td>
</tr>
<tr>
<td></td>
<td>2.10 (293 K) 1.91 (293 K) 1.75 (293 K)</td>
</tr>
<tr>
<td>Thermal conductivity (Wm⁻¹K⁻¹)</td>
<td>36.6 (293 K) 32.1 (293 K) 29.7 (293 K)</td>
</tr>
<tr>
<td>Heat capacities (Jkg⁻¹K⁻¹)</td>
<td>445.6 (293 K) 553 (293 K) 641 (293 K)</td>
</tr>
</tbody>
</table>
The heat lose at the preform/model interface model can be evaluated as:

$$Q_2 = h_2 (T - T_a),$$  \hspace{3cm} (4)$$

Compared with the hot forming process, the convection coefficients $h_1$ is determined as 28 Wm$^{-2}$K$^{-1}$ and $h_2$ is taken as $4.8 \times 10^4$ Wm$^{-2}$ K$^{-1}$ in this work [30,31].

The heat $Q_3$ generated due to the friction between the preform and the model is given as:

$$Q_3 = C \cdot |\tau \cdot \rho_c|,$$  \hspace{3cm} (5)$$

where $\tau$ is the friction force $a$ and $C$ refers to the distribution coefficient.

3. Results and discussion

3.1. P/M material constitutive equation

The flow stress $\sigma$ of the porous P/M preform in isothermal compression depends heavily on the temperature $T$ and strain rate $\dot{\varepsilon}$, as shown in Fig. 4. It can be seen that flow stress of P/M Fe-Cu-C alloy is greatly sensitive to strain rate and deformation temperature. With increasing of temperature, the flow stress decreases, as shown in Fig. 4 (a). The flow stress increases greatly with an increase in strain rate, as shown in Figs. 4 (b), (c) and (d).

In order to establish the P/M material constitutive equation, the relationship among $\sigma$, $T$ and $\dot{\varepsilon}$ should be described precisely. In this work, a kinetic rate equation given by Zener, Hollomon and Shi et al., were utilized [32,33]

$$\dot{\varepsilon} = A \{\sinh(\alpha \sigma)\}^n \exp \left[ -Q/(RT) \right]$$  \hspace{3cm} (6)$$

The activation energy of hot deformation $Q$ can be determined by $Q = R \left\{ \frac{\alpha}{\sinh(\alpha \sigma)} \right\} \left\{ \frac{\ln(\sinh(\alpha \sigma))}{(T/7)} \right\}$, where $\alpha$ is independent of the deformation temperature and can be determined as 0.011 based on experimental results (Fig. 4). The universal gas constant $R$ is 8.314 J/mol. The average slope value of line ln $\dot{\varepsilon}$ is $\frac{\alpha}{n}$, which is 5.95. Since $Q = RnK$, $Q$ is 188.56 kJ/mol. Therefore, the constitutive equation of P/M preform are obtained as following:

$$\dot{\varepsilon} = 5 \times 10^7 \{\sinh(0.011\sigma)\}^{5.95} \exp \left[ -188560/(8.314T) \right]$$  \hspace{3cm} (7)$$

This established constitutive equations, Eq. (7), and the other above models were used to simulate the metal flow behaviors of materials during forging process in FEM.

3.2. Comparison of calculated and experimental results

The calculated relative density distribution and damage distribution profiles of the connecting rod at different locations are shown in Fig. 5 (a), i.e., one original connecting rod preforms were flashless forged and stopped after 0.38 s, when the preform had been partially deformed. Another was flashless forged to its final shape under the same processing parameters. By comparing the calculated relative densities ($\rho_{\text{calc}}$) of the connecting rod preform partially deformed (at 0.38 s) and the fully deformed (at the end) at various axial locations with the measured relative densities ($\rho_{\text{meas}}$), as shown in Fig. 5 (a) and Table 3, it can be observed that the calculated values of $\rho_{\text{end}}$ at $P \ominus$ (the large end section) and at $P \oplus$ (at the small end section) of the fully deformed connecting rod are 0.998 and 0.952, respectively. These values are well consistent with the measured values $\rho_{\text{end}}$ of 0.986 and 0.957. Furthermore, it can also be seen for the partially deformed connecting rod that the measured $\rho_{\text{end}}$ values at different locations agree well.
Fig. 4 – The flow stress of the porous P/M preform at different temperatures and various stain rates: (a) 5 s⁻¹; (b) 11.5 s⁻¹; (c) 19.2 s⁻¹.

Table 3 – Comparison of calculated and experimental relative densities at different locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>P 1</th>
<th>P 2</th>
<th>P 3</th>
<th>P 4</th>
<th>P 5</th>
<th>P 6</th>
<th>P 7</th>
<th>P 8</th>
<th>P 9</th>
<th>P 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated Pₑ-md</td>
<td>0.998</td>
<td>1.000</td>
<td>0.995</td>
<td>0.992</td>
<td>0.991</td>
<td>0.995</td>
<td>0.994</td>
<td>0.952</td>
<td>0.946</td>
<td></td>
</tr>
<tr>
<td>Experimental Pₑ-md</td>
<td>0.986</td>
<td>0.991</td>
<td>0.988</td>
<td>0.989</td>
<td>0.986</td>
<td>0.963</td>
<td>0.973</td>
<td>0.957</td>
<td>0.955</td>
<td></td>
</tr>
<tr>
<td>Calculated Pₑ=0.038</td>
<td>0.854</td>
<td>0.894</td>
<td>0.884</td>
<td>0.893</td>
<td>0.884</td>
<td>0.885</td>
<td>0.884</td>
<td>0.846</td>
<td>0.861</td>
<td></td>
</tr>
<tr>
<td>Experimental Pₑ=0.038</td>
<td>0.834</td>
<td>0.861</td>
<td>0.862</td>
<td>0.853</td>
<td>0.892</td>
<td>0.873</td>
<td>0.881</td>
<td>0.825</td>
<td>0.834</td>
<td></td>
</tr>
</tbody>
</table>

with the calculated results. For example, the calculated value of $Pₑ=0.038 = 0.846$ at P 2 (at the small end section) of the connecting rod deformed for 0.038 s corresponds well with the measured value of $Pₑ=0.038 = 0.825$. The deviations between the experimental and simulated results are small. Obviously, the simulated density variation of the connecting rod compared with that measured by experiments at zero, 0.38 and 0.48 s can well verify the accuracy of the above established models.

However, it should be noted that during the forging process, at about 0.02 s, the relative density at P 2 decreases initially and then increases again. This is different from the findings at P 2, as shown in Fig.5 (b). This phenomenon can be well explained by the damage distribution profiles of the connecting rod during flashless forging. In Fig. 5 (b), the damage distribution profiles after nearly 0.02 s of deformation and for the fully deformed state are displayed in the colour maps. It can be seen that after nearly 0.02 s of deformation, the damage factor value $C_d$ at the shank is large compared with that of the fully deformed connecting rod. This means that the shanks are prone to crack at 0.02 s, which may lead to a decrease of the relative density. However, the fracture does not occur at the end. Both the experiment and the simulated results reveal that $C_d$ does not reach its critical value of $C_d = 0.45$. This means that the crack probability decreases when this zone is completely filled and $Pₑ$ increases at the end of the deformation. The finding that cracks occur easily at the shank is also underlined by the variations of the metal flow behavior of the partially deformed (at 0 s, 0.38 s and 0.48 s) and fully deformed
(the end) porous P/M preform at various locations, as shown in Fig. 5 (b).

3.3. Metal flow behavior

Figs. 6 (a) and (d) show that the connecting rod preform gets initially in contact with the punch from a vertical view and a side view, respectively. Some representative points, i.e., A, B, C, D, E, and F, were selected for further analysis. While A is a point on the surface of the connecting section, B and C are points at the small end section and D, E, and F are points at the large end section, respectively. From a vertical view, as shown in Fig. 6 (b), as well as from a side view in Fig. 6 (e), it can also be observed that point A at the shank gets in contact with the mold initially. This can lead to a long time and a large deformation. It can be safely speculated that the heat loss will be quite pronounced. Moreover, the shank is prone to cracking due to the high deformation rate and fast cooling. If this zone is not fully densified, due to the inappropriate design of the preform geometry or unsuitable processing parameters, cracking will be unavoidable. Once the shank is completely filled, the deformation processed into the other areas, i.e., points C, D, E, and F at the large end section and point B at the small end section, as shown in Figs. 6 (c) and (f).

The metal flow behavior of the preform during the forging process was determined by the load history supplied by the top die, as shown in Fig. 7. The density increases with increasing load supplied by the tool. When the forging time increase from 0.020 to 0.054 s, the load values exerted by the top die increase from 52 to 733 K N. As the P/M preform contains internal pores, the density increases effectively with increasing load. Then, a higher forging force is needed with increasing metal flow resistance. It can be noticed that the deformation and densification of the porous P/M materials occur simultaneously during flashless forging.

3.4. Optimization of the preform geometry

The orthogonal design method was used to optimize the preform geometry. Through this method, it is possible to optimize
Fig. 6 – Metal flow behavior of a P/M preform during flashless forging: (a) 0 s, (b) 0.38 s and (c) 0.48 s are from a vertical view, while (d) 0 s, (e) 0.38 s, (f) 0.48 s and (g) the end are from a side view.

<table>
<thead>
<tr>
<th>Factors</th>
<th>A (mm)</th>
<th>B (mm)</th>
<th>C (mm)</th>
<th>D (mm)</th>
<th>E (mm)</th>
<th>F (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value 1</td>
<td>48.4</td>
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<td>25.4</td>
<td>78.6</td>
<td>27.4</td>
<td>6</td>
</tr>
<tr>
<td>Value 2</td>
<td>46.4</td>
<td>26.4</td>
<td>27.4</td>
<td>74.6</td>
<td>26.4</td>
<td>5</td>
</tr>
<tr>
<td>Value 3</td>
<td>44.4</td>
<td>25.4</td>
<td>29.4</td>
<td>70.6</td>
<td>24.4</td>
<td>3</td>
</tr>
<tr>
<td>Value 4</td>
<td>42.4</td>
<td>24.4</td>
<td>31.4</td>
<td>66.6</td>
<td>22.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Value 5</td>
<td>40.4</td>
<td>23.4</td>
<td>33.4</td>
<td>62.6</td>
<td>20.4</td>
<td>0</td>
</tr>
<tr>
<td>Average value 1</td>
<td>97.112</td>
<td>97.812</td>
<td>97.433</td>
<td>97.433</td>
<td>96.162</td>
<td>97.740</td>
</tr>
<tr>
<td>Average value 2</td>
<td>97.992</td>
<td>97.880</td>
<td>97.170</td>
<td>97.418</td>
<td>97.378</td>
<td>97.627</td>
</tr>
<tr>
<td>Average value 3</td>
<td>98.054</td>
<td>97.396</td>
<td>98.346</td>
<td>97.976</td>
<td>97.870</td>
<td>97.261</td>
</tr>
<tr>
<td>Average value 4</td>
<td>96.992</td>
<td>97.712</td>
<td>97.730</td>
<td>97.712</td>
<td>97.820</td>
<td>97.950</td>
</tr>
<tr>
<td>Average value 5</td>
<td>96.980</td>
<td>96.330</td>
<td>96.451</td>
<td>96.592</td>
<td>94.900</td>
<td>96.712</td>
</tr>
<tr>
<td>F value</td>
<td>1.075</td>
<td>1.550</td>
<td>1.904</td>
<td>1.383</td>
<td>3.487</td>
<td>1.031</td>
</tr>
<tr>
<td>Significant</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 4 – The uniform designs L25(5)^6 and the orthogonal table of the maximum relative density $\rho_c$. The sizes of the preform, A, B, C, D, E and F are described in Fig. 3(a).

The dimensions of the preform quickly, easily and accurately. In this work, some representative sizes with different levels were considered. The typical ranges of sizes of the porous P/M preform were determined as follows: A ranges from 40.4 to 48.4 mm, B ranges from 23.4 to 27.4 mm, C ranges from 25.4 to 33.4 mm, D ranges from 62.6 to 78.6 mm, E ranges from 20.4 to 27.4 mm and F ranges from 0 to 6°, respectively. These representative sizes of the preform, i.e., A, B, C, D, E and F, are illustrated in Fig. 3(a). Table 4 shows the simulation results obtained by using the uniform design L25(5)^6. It can be seen that $\rho_c$ is sensitive to the size and geometry of the P/M preform. Obviously, the thickness of the shank E plays a more significant role for $\rho_c$ as compared with the other size ranges. Moreover, the effects of the outer radius of the big end C and the thickness of the big end B on the relative density are more remarkable compared with that of the thickness of the small end A and the degree of the chamfering F. Based on our above-described numerical models and the FEM simulation results, the following optimized dimensions of the preform are

![Graph](image-url)

**Fig. 7** – Load curve of top die along the Z axis.
obtained: \( A = 44.4 \text{ mm}, B = 26.4 \text{ mm}, C = 29.4 \text{ mm}, D = 70.6 \text{ mm}, \)
\( E = 24.4 \text{ mm}, \) and \( F = 1.5^\circ, \) as shown in Fig. 8.

Compared with the initial geometric size of the P/M preform, Fig. 3 (b), the optimal values of \( D, \ E \) and \( F \) are small, and the optimal \( A, \ B \) and \( C \) values are large. In order to verify the validity of the optimized preform geometry, experiments were done under the same processing conditions. As shown in Table 5, the values \( \rho_p \) at different positions of the preform are compared with the values \( \rho_{ex} \). It can be seen that \( \rho_{p} \) agrees well with \( \rho_{ex} \). For example, the value \( \rho_{p} = 1.000 \) at P (a4) in the shank closely matches the experimentally measured value \( \rho_{ex} = 0.997 \). Moreover, when the preform geometry is optimized, the value \( \rho_{p} \) at P (a6) of the connecting rod is increased and the density distribution of the connecting rod is uniform.

Table 5 – Comparison of the \( \rho_p \) and \( \rho_{ex} \).  

<table>
<thead>
<tr>
<th>( \rho_p )</th>
<th>( \rho_{ex} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (a)</td>
<td>0.995</td>
</tr>
<tr>
<td>P (a4)</td>
<td>0.997</td>
</tr>
<tr>
<td>P (b)</td>
<td>1.000</td>
</tr>
<tr>
<td>P (c)</td>
<td>0.998</td>
</tr>
</tbody>
</table>

More details about the density variations of the connecting rod for both the optimized and original geometries can be seen in Fig. 9 (a). Undoubtedly, the value \( \rho_{p} \) of the connecting rods at different locations increases significantly when the geometry is optimized. This result is reasonable since a larger deformation generates larger metal flow stresses in P/M materials, and these stresses improve the densification of the materials. Accordingly, the density increases strongly. It can be noted that the value \( \rho_{p} \) at P (a4) of the connecting rod forged with optimized preform geometry increases with increasing time, which is different from the results for the connecting rod forged from the original preform (i.e., the \( \rho_{p} \) decreases initially and then increases again).

Specifically, when the forging time increases from 0.018 to 0.054 s, the value \( \rho_{p} \) at P (a4) of the connecting rods forged with optimized geometry design increase from 0.858 to 0.999, while \( \rho_{p} \) of that in the connecting rods forged using the original preform geometries increases from 0.749 to 0.995. This means that the cracks developing in the connecting rod using the original preform can be eliminated effectively through optimizing the geometry design. This phenomenon can also be observed in Fig. 9(b). When the preform size and geometry are optimized, the average density of the connecting rod increases homogeneously, and becomes superior to that of rods forged with the original shape.

During the flashless forging process, the temperature, the effective strain and the effective stress are important factors determining the metal flow behavior of the porous P/M preform. Fig. 10 displays the temperature, the effective stress and the effective strain distributions of the porous P/M preform during the flashless forging process for some representative points (i.e., points (\( \odot \)), (\( \triangle \)), (\( \bigcirc \)), (\( \bigtriangledown \) and (\( \square \)), as shown in Fig. 10 (b). The selected points (\( \odot \)), (\( \triangle \)) and (\( \bigcirc \)) are at the large end section and at the small end section, respectively. It can be seen that the curves of the temperature at different locations decrease dramatically, as shown in Fig. 10 (a). This is attributed to the fact that the heat loss during the forging process is quite pronounced, such as at points (\( \triangle \)) and (\( \square \)). However, the cooling rates at different times and different positions are different. The cooling rate at the shank of the connecting rod, such as at point (\( \bigcirc \)), is lower than that near the large end section (point (\( \odot \))) and the small ends (point (\( \square \))). This was determined by the balance between the heat generated due to the plastic deformation and the heat loss due to conduction, convection, and radiation. Figs. 10 (b) and (c) reveal that the effective stress and the effective strain at the shank increase dramatically. It can be safely speculated that the deformation rates at different locations do not change significantly. This means that the deformation of the porous P/M preform occurs homogeneously during the flashless forging process. Hence, altogether, this work presents a method and an analysis to manipulate the size and geometry of the preform, thus ensuring a uniform density distribution that helps to improve the quality of connecting rods.

4. Conclusions

The properties and the damage behavior of P/M connecting rod preform has a significant influence on its metal flow behavior during flashless forging. The metal flow behavior of a P/M connecting rod preform during flashless forging were studied based on isothermal compression tests and FEM. First, the P/M material constitutive equation was established. Then, an appropriate criterion satisfied for complex stress state applications was selected, the boundaries conditions among the preform, the ambient environment and cavities changed with time were considered, as well as the damage behavior of the porous P/M material during the flashless forging process. Second, the metal flow behavior of a porous P/M preform during flashless forging was investigated using FEM. The simulated results are consistently well with the experimental results. Results showed that the shank is much more prone to cracking due to the higher deformation rate and the faster cooling rate. The optimal dimensions of the P/M preform obtained by using an orthogonal design method were: \( A = 44.4 \text{ mm}, B = 26.4 \text{ mm}, \)
\( C = 29.4 \text{ mm}, D = 70.6 \text{ mm}, \) and \( E = 24.4 \text{ mm}, \) and \( F = 1.5^\circ. \) When the preform geometry are optimized, the average density of the
connecting rod increases homogeneously, and becomes superior to that of the original shape. This work suggests that the geometry of the preform can be designed efficiently based on our models. This work can help to derive a P/M connecting rod preform optimization methodology, which can offer the possibility of efficiently improving the quality of the connecting rods.

**Conflict of interest**

The authors declare no conflict of interest

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**REFERENCES**


