Original Article

Effect of powder shape on effective thermal conductivity of Cu–Ni porous coatings

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A B S T R A C T

Porous coat is a kind of increasing heat transfer coatings based on increasing surface area and bubble nucleation. Several properties of the porous coat, including effective thermal conductivity (ETC) and porosity are influential design factors in determining the high heat flux performance. There are many factors which affect the mentioned properties and powder shape is the most important parameter. The aim of this study is to investigate the effect of powder shape and its surface roughness on thermal conductivity of Cu–Ni sintered porous coatings with three porosity levels (20, 30 and 40%). The porous samples were prepared by powder metallurgy technique in reduction atmosphere. It was found that at constant porosity, spherical powder with smooth surface and narrow range pore size distribution has higher ETC, on the other hand, irregular-jagged powder with wide range pore size distribution has lower ETC. The experimental results show that ETC values increased from 7 to 14% by increasing porosity level from 20 to 40%. Surface roughness affected ETC more than powder shape.

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1. Introduction

High flux sintered porous coatings have been widely used to resolve thermal management problems [1–4]. Sintered porous surfaces are the best in terms of the capacity for heat transfer in comparison to other roughened surfaces [5,6]. The volume shrinkage, porosity and effective thermal conductivity of sintered metallic powders affect the overall performance of porous coatings [4,5,7,8]. The porosity of coating by powder shape, sintering condition such as time and sintering temperature. The effective thermal conductivity is determined considering the thermal conductivity of the constituent phases of the material, i.e. the solid phase and fluid phase [9]. Porosity percent define the portion of each phase. Previous investigations on effective thermal conductivity frequently considered and modeled sintered porous media as sphere particles connected by neck in simple cubic unit cell and

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evaluated effective thermal conductivity by porosity percent. Alexander, Maxwell, EMT and Parallel theory are some of important theories on thermal conductivity of porous media [10–15]. Bauer in 1993 introduced the effect of pore distribution on effective thermal conductivity in heterogeneous medium [16]. The number, size, distribution and shape of pores, in the coating are closely related to powder particle shape, size, distribution and surface [12].

In this paper, experimental result for effective thermal conductivity of coatings with various powder shapes and surface roughness are reported. Three different kinds of porous tablets with a spherical-smooth, irregular smooth and irregular-jagged at three porosity level (20, 30 and 40%) were created. The porous tablets were prepared by powder metallurgy technique in the programmable tube furnace. The effects of powder morphology and powder surface roughness on pore structure, pore size distribution and their influence on effective thermal conductivity of samples were examined.

2. Experimental procedure

As received gas atomized (GA) and water atomized (WA) Cu–10% Ni powder with spherical-smooth and irregular-smooth morphology, respectively, were used in this study. The WA powder was milled for 60 min in a high energy
planetary ball mill (PM 200 Retch) under an argon atmosphere (99.99%). Stainless steel hardened vial and balls (65 HRC hardness), (10 mm diameter) were used with ball to powder weight ratio of 10:1. In addition, about 0.1 wt.% of load, stearate was added to prevent the agglomeration and cold welding of powders. Milling process was done in ambient temperature. Fig. 1 shows the morphology of powders. Ball milled powder (BM) morphology is irregular with jagged surface. The powders characteristics are summarized in Table 1. Powder size distribution illustrate in Fig. 2. All powder type was selected in same size and distribution range (~100 µm) by using mechanical sieving according to ASTM B214-07.

In this research porous coating assumed as porous media. In this regard three types of porous media (porous tablet) with 20, 30 and 40% porosity volume were made from each kind of powders (GA, WA and BM). All tablets sintered at 900 °C for 60 min in reduction atmosphere (N2–5%H2). Density method was used for evaluating the porosity of the samples. The uncertainty of measurement was estimated at ±1.0%.

The pore size distribution (PSD) and porosity of the sintered tablets were determined by mercury intrusion porosimetry. “Image J 1.48” software was used for evaluating the SEM pictures obtained from surface of tablets. Schematic view of the effective thermal conductivity test section (P.A. Hilton Company) and the locations of thermocouples were shown in Fig. 3. Nine K-type thermocouple were placed with equal-distance. The effective thermal conductivity of porous samples could be determined by:

$$ K = \frac{K_{Cu} \Delta T_{Cu}}{\Delta T_{tablet}} $$

where $\Delta T_{Cu}$ is the temperature difference of measuring point on the copper bar, $\Delta T_{tablet}$ is the temperature difference of measuring point on the porous tablet and $K_{Cu}$ is the thermal conductivity of copper bar, 372 W/(mK) [10].

3. Results and discussion

Fig. 4 presents experimental values of effective thermal conductivity for three types of porous tablet and five theoretical models that predict effective thermal conductivity by porosity [13,15]. Experimental results for three types of samples are very close, but in all porosity level, GA powder present maximum and BM powder show minimum effective thermal conductivity. These consequence predicted by other researchers [12,17–19]. Table 2 shows the $R^2$ values that indicate coefficient of correlation between experimental data and theoretical values. $R^2$ changes from 0 to 1 and

<table>
<thead>
<tr>
<th>Experimental $R^2$ value</th>
<th>Theory ETC model</th>
<th>Parallel</th>
<th>Peterson</th>
<th>Maxwell</th>
<th>EMT</th>
<th>Alexander</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>Not match</td>
<td>Not match</td>
<td>0.62</td>
<td>0.40</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>WA</td>
<td>Not match</td>
<td>Not match</td>
<td>0.83</td>
<td>0.59</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>Not match</td>
<td>0.51</td>
<td>0.90</td>
<td>0.65</td>
<td>0.26</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3 – Set-up for investigation of ETC of samples.
in cases which $R^2$ reaches to 1 there is a good correlation between two data series. According to Table 2, experimental values are matched with Maxwell, EMT and Alexander theory. WA and GA powder adopt Maxwell and BM powder adopts with Alexander model more than others. Among experimental data, GA powder results, show best accommodation with theoretical values based on Maxwell model ($R^2 = 0.9$) \[19\].

It can be found from Fig. 4 that by increasing porosity level from 20 to 40%, differences between thermal conductivity of three type of samples increase from 7 to 14%. At the studied porosity range, difference between ETC values of irregular (WA) and spherical (GA) powder with smooth surface was obtained 3.5–5%. The mentioned difference was obtained 3.8–9.4% for irregular-smooth (WA) and irregular-jagged (BM) powder. It seems that surface roughness affect ETC more than powder shape. Since the shape and surface roughness of powder affect the porosity and pore distribution, further investigation focused on effect of pore distribution on ETC.

Fig. 5 shows pore network for three types of tablets and interconnected pores are clearly visible. It can be seen that BM powder made wide range of pores and irregular pore network. At constant porosity level, powder surface roughness affects pore size distribution (PSD).

For more investigation, PSD of tablets were examined by mercury intrusion test. Fig. 6 shows the results of PSD of tablets with 40% porosity level. BM powder with irregular-jagged presents wide range pore size distribution, from 1 to 30 $\mu$m. Mentioned range for spherical and irregular powder with jagged surface changes from 3–13 $\mu$m and 20–30 $\mu$m, respectively. Difference between upper limit and lower limit of pore size is the same for spherical and irregular powder with smooth surface (10 $\mu$m) and it represents that mention
powders made same pore networking according to ordering aspect. It is concluded that BM powder (irregular-jagged) with wide range of PSD made irregular pore network in comparison to GA (spherical-smooth) and WA (irregular smooth) powder. Roughened surface powders causes wide range PSD and irregularity in pore network, so ETC value will be decreased in comparison to smooth surface powders with narrow range PSD. Powder shape has low effect on ETC value and powder surface roughness is more effective than powder shape.

Fig. 5 – Top surface view and porosity networking of samples obtained by SEM picture and image processing software (ImageJ): (a) GA, (b) WA, (c) BM.
4. Conclusion

Three different kinds of sintered tablets were produced from spherical-smooth (GA), irregular-smooth (WA) and irregular-jagged (BM) powder and the effect of powder shape and surface roughness on ETC value was studied. The conclusion can be summarized as follows:

- Experimental ETC values for GA and WA powder adopt Maxwell model. GA powder present better matching with theoretical model in comparison to BM and WA powder.
- In all porosity level, GA powder presents maximum and BM powder shows minimum ETC. by increasing porosity level from 20 to 40% differences between ETC values rises from 7 to 14%.
- At constant porosity, difference between ETC values of GA and WA powder with different shapes and same surface roughness (3.8–9.4%). Therefore, surface roughness affects ETC more than powder shape.
- Wide range of PSD and irregularity in pore network, which is caused by surface roughness, decrease ETC of porous tablets in comparison to smooth surface powder with narrow range PSD and regular pore networking.

**Conflicts of interest**

The authors declare no conflicts of interest.

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