BISMUTH BASED POROUS MATERIAL MANUFACTURING AND PROCESSING FOR THERMOELECTRIC ENERGY CONVERSION

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ABSTRACT

Porous metal, or metal foam, is the material that consists of solid metal and a large volume of pores. These pores can be sealed or left open depending on material needed but the defining characteristic of this material is its very high porosity. Because of the open porous structure of the material, it has a low mass density compared to a solid piece of material (5-25% of the solid piece's density), large surface area, high permeability, low thermal conductivities, and absorption of mechanical shock and sound. Porous materials has found many applications such as for energy absorption, thermal energy storage, and lightweight components. Examples of porous material products include orthopedic-prosthetics, heat exchangers, sound dampening units, and weight reduction structures. The objective of this work is to develop a casting manufacturing process for a bismuth-based porous material. The thermoelectric property of the material has been studied to explore the application of this material for energy conversion. The experimental results show that the Seebeck coefficient of the porous bismuth material is independent of porosity. The porosity of the material can be controlled through manufacturing parameters.

INTRODUCTION

Many important industry applications require the use of porous materials. Such materials are desired for insulation applications, impact protection, heat exchangers to mention a few. This can be advantageous and desirable when low thermal conductivity or permeability properties are required. There are different methods to manufacture a porous material. For manufacturing foam, there are four major manufacturing techniques. They are casting, deposition, gas-eutectic transformation, and powder metallurgy. In view of the potential for large scale production, casting and powder metallurgy are employed as the commercial manufacturing methods to produce porous metals. Powder metallurgy is a processing route by which metal powders are pressed and sintered into dense, monolithic components [1]. The powder metallurgical processing can produce materials with extremely fine and uniform microstructure and enables the formulation of materials composed from different constituents yielding unique property combinations [2]. But the cost is usually high due to the high price of the powder materials. On the contrary, casting is a relatively simple and inexpensive production method. In this paper, our focus is on using the casting manufacturing processing approach to make a bismuth based alloy with porous structure. Thermoelectric property in view of the Seebeck coefficient is investigated.

MATERIAL PROCESSING AND MANUFACTURING

A vacuum induction melting followed by casting experimental method was developed to create porous Bi-Sn material. For the experimental setup, a quartz tube was filled half way with NaCl. The pieces of the Bi-Sn alloy were placed on top of the salt. A tee was used to connect the quartz tube, compressor and vacuum pump. Figure 1 shows the equipment setup for the experiment.

Figure 1 Experimental setup prior to melting the aluminum alloy

The first step was to create vacuum in the salt. The compressor valve was closed and the vacuum valve was opened prior to using the heat inductor. The quartz tube was then placed in between the heating rings and also ensuring that the metal and rings were at the same height level. The electromagnetic field is present in order for induction heating to work. After the alloy being melted, the compressor valve was open to place pressure on the molten metal and cast the metal into the loosely compacted salt. After letting the metal alloy solidify, the tube was cut in order to extract the porous metal. Water was used to dissolve the salt from the cast. The metallic sample was then dried as the final step of the manufacturing experiment.

CHARACTERIZATION

After the manufacturing, the material was once weighed again, before the ends of the sample were wrapped in aluminum as electrodes to be analyzed by the electrochemical analyzing instrument (Figure 2). The top and bottom ends of the sample were connected through banana clips (as shown in Figure 3) and that were connected to the machine which outputs its results onto a computer. Once ready, sample was set on a steel block that was set on a plate heater as the steel block allows for slower temperature changes and easier adjustments for the testing. The sample was then heated to 26 degrees Celsius and held there while the machine held the 5 second test. Once that was completed, it was raised to 28 degrees and 29 degrees and redid the test at each temperature interval. At this point, other samples were tested as well as comparisons to the sample that was created in the characterization experiment.

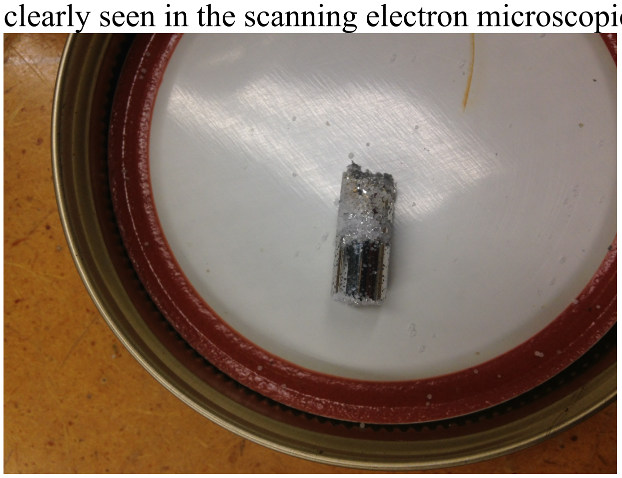
Figure 2 Electrochemical analyzer

Figure 3 Porous metal on heat plate being analyzed

RESULTS AND DISCUSSION

Structure of the Bi-Sn porous material

Both macro- and microstructure of the Bi-Sn porous material were observed. Figure 4 shows the optical image of the material. It is found that the part of material cast into the salt is highly porous, while the rest of the part is with shinny feature, which represents the part with low content of pores. Under electron microscopic observation, the pores and the grain boundaries are clearly seen in the scanning electron microscopic (SEM) image (Figure 5).



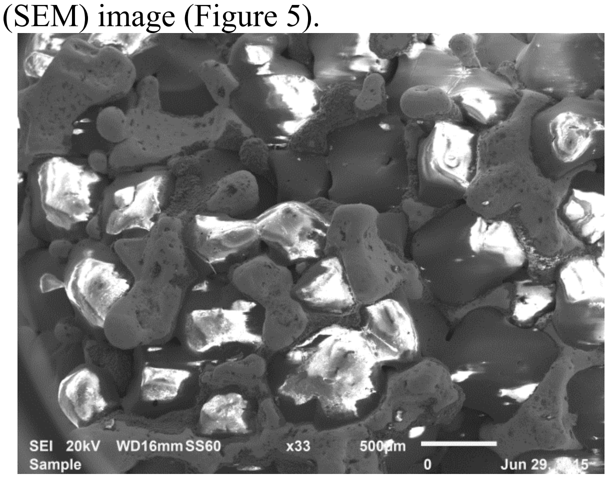


Figure 4 Optical image of the porous material

Figure 5 SEM image of the porous material

Apparent and true porosity of the Bi-Sn

The amount of porosity in a material can be calculated using the following equations:

$$\text{Apparent porosity} = \frac{W_W - W_D}{W_w - W_S} * 100\% \qquad (1)$$

where W_W is the weight of the sample after removal from water; W_D is the dry weight of the sample; W_S is the suspended weight of the sample in water.

Apparent porosity is a measure of open pore content. True porosity, on the other hand, measures both pores which are interconnected and closed as given by:

$$\text{True porosity} = \frac{\rho - B}{\rho} * 100\% \qquad (2)$$

where ρ is the density of the sample; B is the bulk density defined as

$$B = \frac{W_d}{W_W - W_S} \qquad (3)$$

Measurements to calculate the porosity of the sample were found to be: W_D= 1.55 g, W_S= 1.24 g, and W_W= 1.70 g. Therefore, the Apparent porosity $= \frac{1.70-1.55}{01.70-1.24} * 100\%$, i.e. Apparent porosity = 32.6 %. But ρ = 8.16 g/cm^3, and B = $\frac{1.55}{1.70-1.24}$, or B = 3.369 g/cm^3. Therefore, the True porosity = $\frac{8.16-3.369}{8.16}$*100%; i.e. True porosity = 58.7 %.

Seebeck coefficient

The thermoelectric property of the Bi-Sn porous material was measured using the electrochemical analyzer. The test conditions are given in Table 1. The data received from the analyzer was used to find the Seebeck coefficient values as listed in Table 2.

Table 1 Conditions for Seebeck coefficient measurement

Sample 1	Bottom Temp (^oC)	Top Temp (^oC)
Test 1	26	23
Test 2	29	24
Test 3	28	24
Sample 2		
Test 1	29	25
Test 2	29	24
Test 3	29	24
Sample 3		
Test 1	29	24
Test 2	27	24
Test 3	30	23

Table 2 Seebeck coefficient

Sample 1	Potential Change (V)	Temperature (K)	Seebeck Coefficient (mV/K)
Test 1	2.00E-03	276	7.24E-03
Test 2	2.00E-04	278	7.19E-04
Test 3	2.00E-04	277	7.22E-04
		Average	2.89E-03
Sample 2	Potential Change (V)	Temperature (K)	Seebeck Coefficient (mV/K)
Test 1	3.50E-04	277	1.26E-03
Test 2	1.00E-03	278	3.50E-03
Test 3	2.00E-04	278	7.19E-04
		Average	1.83E-03
Sample 3	Potential Change (V)	Temperature (K)	Seebeck Coefficient (mV/K)
Test 1	2.00E-04	278	7.19E-04
Test 2	5.00E-05	276	1.81E-04
Test 3	3.00E-04	280	1.07E-03
		Average	6.57E-04

As seen from the results, the Seebeck coefficient is independent of porosity. However because of the phonon-drag effect, it can indirectly influence the porosity through manufacturing means. The phonon-drag is increased by reducing the defects in the grains inside the porous material, which in turn creates a "cleaner" interior structure which can indirectly increase the porosity. As the phonon-drag is increased so is the Seebeck coefficient which means the thermal conductivity becomes lower [3]. To the effect of which how porosity increases with the Seebeck coefficient still remains to be further studied. However because of the direct correlation between the Seebeck coefficient and the thermal conductivity, it can be seen that sample #1 which has the highest coefficient is the best one out of the three. This porous Bi-Sn (sample #1) may be used as the best thermoelectric energy conversion candidate among the three samples as its thermal conductivity is the lowest.

CONCLUSIONS

As a result of experimenting with the casting approach to produce a porous Bi-Sn metal, a new manufacturing process was developed using the induction heating in vacuum followed by gas compression. This method is successful in view of providing a controllable way of making the porous material. NaCl is proved to be a good material to create porosity. Although there is always a possibility that other materials could be also suitable to create porosity, salt serves the purpose in a simple way of removing easily by dissolving into water in this work.

This experiment and research showed that while the Seebeck coefficient is independent of porosity, the phonon-drag effect caused by the Seebeck coefficient can indirectly affect the porosity through manufacturing means. By wanting a lower thermal conductivity material, the manufacturing can be altered in which the lattices and grains are less flawed which can in turn increase porosity. Some changes in this research that should be made would be to use in actual pressure release valve in the air compressor and vacuum pump line as that would increase consistency in making various additional materials. Using argon gas instead of pressurized air would be more ideal as well because of the smaller particle sizes created with argon versus air. In terms of the analyzing, using a much more temperature controlled unit to heat the samples and using something more fine such as platinum as the electrodes would produce cleaner data. The Seebeck coefficients differ as visually the 3rd sample looked like the most porous material yet is calculated as the "least" porous by the results. Further testing should be done to fully analyze how electrical conductivity is affected by the processing parameters. The Seebeck coefficient data in this work correlate well with the porosity. This research provides some initial results, from the energy conversion point of view, to validate how useful porous material is. Because porous material has various properties such as lightweight capabilities, thermal exchanging, and energy conversion and mechanical shock absorption, it has the potential of widely applications in engineering components or structures.

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