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Processing and Seebeck Effect Measurement of a Bismuth Based Alloy

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Authors' contributions

This work was carried out in collaboration between all authors. Authors JVB, CT, ME and CDNNN managed the literature searches, experimental process and wrote the first draft of the manuscript. Author RNG did the data collection. Author YXG designed the study. All authors read and approved the final manuscript.

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ABSTRACT

The objective of this work is to develop a casting manufacturing process to produce a bismuth-based porous material. Induction heating was applied to melt Bi-Sn alloy in a quartz tube and the molten alloy was cast into loosely compacted sodium chloride powder. After the sodium chloride powder was dissolved by water, pores were generated in the Bi-Sn alloy. The true porosity of the alloy can be controlled as high as 58.7% in volume. 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. The higher the porosity is, the slower the heat conduction in the material.

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1. INTRODUCTION

Porous metal, or metal foam, is the material that consists of solid metal and a large volume of pores [1-3]. These pores can be sealed or left open depending on material needed but the defining characteristic of this material is its very high porosity. In addition, because of the open porous structure of the material [4-8], 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. However, due to the larger exposed surface area, metal foam's long term resistance to corrosion, erosion, and fouling may be increased.

There are different methods to manufacture a porous material or foam [9,10]. 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 [11]. 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 [12]. 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. The thermoelectric property in view of the Seebeck coefficient is tested.

2. MATERIALS PROCESSING AND MANUFACTURING METHODS

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 valve tee connection was used to connect the quartz tube, compressor and vacuum equipment. Fig. 1 shows the equipment setup for the experiment.

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 was melted, the compressor valve was open to place pressure on the molten metal and cast the metal into the loosely compacted salt.

After the molten alloy solidified, 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.

Fig. 1. Experimental setup prior to melting the aluminum alloy

3. MATERIAL 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 a CH Instrument electrochemical analyzing instrument. The top and bottom ends of the sample were connected through banana clips (as shown in Fig. 2) 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℃ and held for 5 second to collect data. Once that was completed, it was raised to 28℃, and 29℃ etc. The test was repeated at each degree level three times. After that, other samples were tested as well as comparisons to the sample that was created in the characterization experiment.

Fig. 2. Porous metal on heat plate

4. RESULTS AND DISCUSSION

4.1 Structure of the Porous Material

Both macro- and microstructure of the Bi-Sn porous material were observed. Fig. 3 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 (Fig. 4).

4.2 Porosity

The amount of porosity in a material can be calculated using the following equations (1-3). First, the apparent porosity, p_a, is given by

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

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 the permeability of the material which is the ease a fluid or gas can have to seep through the material. True porosity, p_t, on the other hand, measures both pores which are interconnected and closed. It is given by:

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

where,

ρ is the density of the sample
B is the bulk density defined which in turn can be 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.
W_W= 1.70 g.

$$\text{Apparent porosity} = \frac{1.70 - 1.55}{01.70 - 1.24} * 100\%$$

Apparent porosity = 32.6%

ρ = 8.16 g/cm^3

B = $\frac{1.55}{1.70-1.24}$

B = 3.369 g/cm^3

True porosity = $\frac{8.16-3.369}{8.16}$*100%

True porosity = 58.7%

4.3 Seebeck Coefficient

The thermoelectric property of the B-Sn porous material was measured using the electrochemical analyzer. The test conditions are given as Table 1. The data received from the analyzer was then input into a graph of Potential versus Time with a trend line in all the tests. Finding the potential change over the tested time and the temperature gradient between the samples at each of the tests, the Seebeck coefficient was calculated and averaged over the 3 tests for each of the samples. The Seebeck coefficient measurement results are listed in Table 2.

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 [13,14]. 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.

Table 1. Test conditions summary

Sample #1	**Bottom Temp (°C)**	**Top Temp (°C)**
Test 1	26	23
Test 2	29	24
Test 3	28	24
Sample #2	Bottom Temp (°C)	Top Temp (°C)
Test 1	29	25
Test 2	29	24
Test 3	29	24
Sample #3	Bottom Temp (°C)	Top Temp (°C)
Test 1	29	24
Test 2	27	24
Test 3	30	23

Fig. 3. Optical image of the porous material

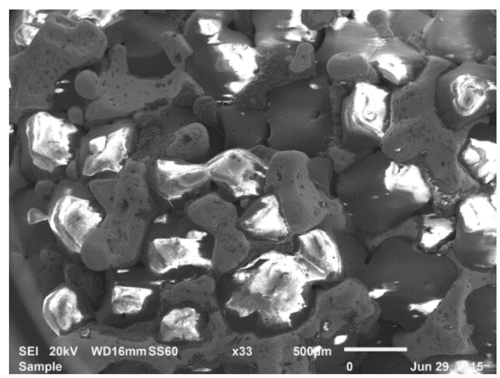

Fig. 4. SEM image of the porous material

Table 2. Seebeck coefficient results

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

5. 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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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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