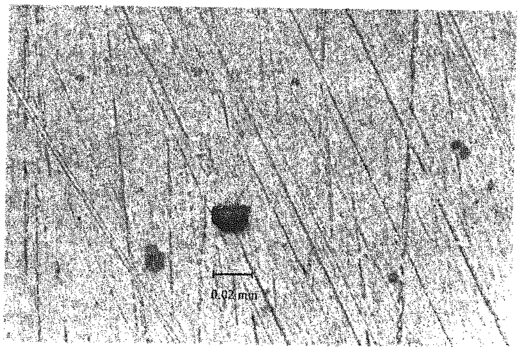

Figure (5) Microscopic picture of the thermocouple.

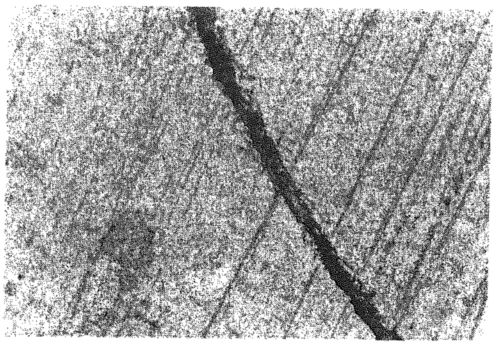

Figure (6) Picture showing a gap at the junction interface.

References

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complete deposition of copper layers on the entire outer surface of the constantan wire.

Applications

The chemical electroplating method brings some advantages to the manufacturing process of TC for special purposes. The method can easily be adjusted to produce TC with various complex geometries. The lower cost is another advantage especially when compared with other techniques such as sputtering and CMOS technology. Hundreds of thermocouples can be manufactured simultaneously in a medium size-electroplating container, therefore making the process inexpensive.

The significance of the method is highlighted in its use in manufacturing thermopiles for thermal radiation or local heat flow sensing purposes. Combinations of series and parallel TCs are constructed at once to satisfy the voltage and current needs of the thermopile and thus its desired thermoelectric power. The base metal of the TC (constantan in this study) can have various forms such as plate, foil, rod or wire.

Conclusions

The open-circuit voltage and thermoelectric power of some electroplated copper-constantan thermocouples were reported in the range $80<T<270^{\circ}C$ Vc was approximately 35% lower than that of a standard T-type thermocouple. It was discussed that the difference is due to the existence of structural inhomogenities in the copper layer. Some possible metallurgical defects were detected and shown. The size and the number of defects can be reduced by taking special precautions. The chemical electroplating method is therefore suggested as a reliable and economic method for manufacturing large number of TC or thermopiles for special purposes.

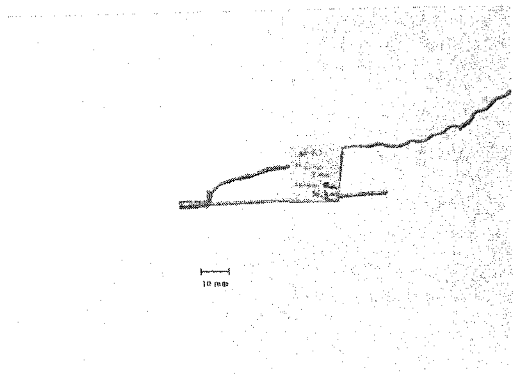

Figure (1) Photo of an electroplated thermocouple.

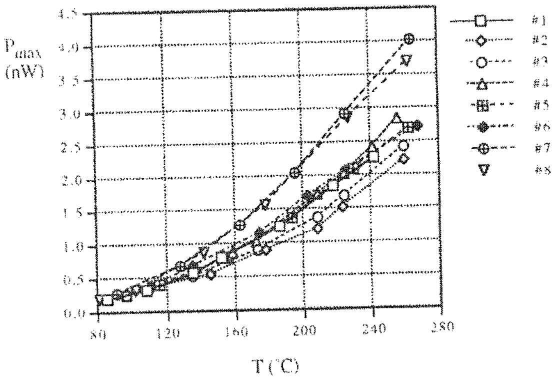

Figure (3) Thermoelectric power of the electroplated thermocouples.

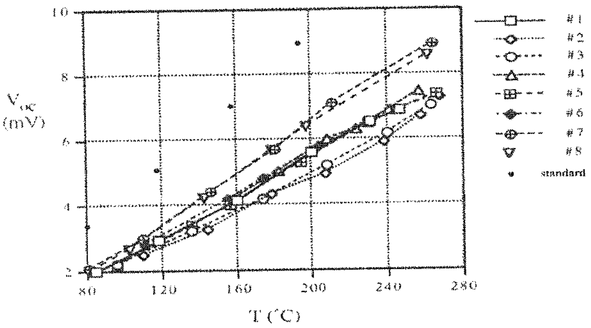

Figure (2) Thermocouple output voltage.

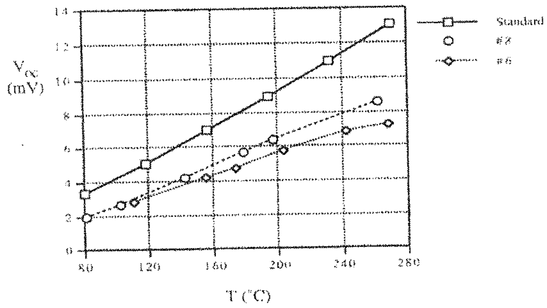

Figure (4) Comparison between electroplated and standard thermocouples.

Results

Figure 2 shows the open circuit voltage of the thermocouples. Variation of the junction voltage of the couple (V_{OC}) is linear with temperature in the entire range. For this temperature range V_{OC} varies from 2 to 9 mV. Theoretically one should expect that the size of the thermocouple junction does not affect its thermoelectric voltage. However, it is shown in figure 2 that at 240°C, V_{OC} of thermocouple #8, having a junction volume of 667 mm^3 is 32.2% higher than that of thermocouple #2 which its junction volume is 35 mm^3. It is also evident that there is no significant difference in the voltage for thermocouple #1, #4 and #5 which their junction sizes are almost equal. It was observed that variations of the thermocouple current were also linear in the entire range of the temperature difference.

The thermoelectric power of the electroplated thermocouples is presented in figure 3. In the range $80°C < T < 270°C$ the power output of the thermocouples was varied between 0.2 to 4.0 nW. As the temperature is increased the thermoelectric power is increased at a rate which is proportional to the square of the temperature difference between the heat source and sink. The power output data of a standard type-T thermocouple was not available for comparison.

Equation (1) defines the power produced as a function of temperature for thermocouple #6. At lower temperatures ($T < 120°C$) the difference among the thermoelectric power of the thermocouples is not significant. As the temperature rises above 120°C the difference becomes more and more significant.

$$P = -1.115 + 0.0128\Delta T + 4.785\times10^{-6}(\Delta T)^2 \quad \text{(nW)} \tag{1}$$

Figure 4 shows a comparison between Electroplated thermocouples and a standard T-type (copper-constantan) thermocouple. The thermoelectric voltage data of the standard T-type thermocouple is taken from [6]. As it is evident from figure 4, the standard thermocouple offers higher thermoelectric voltage. The relative difference is about 39% at 90°C and 32% at 260°C. By definition, the slope of the graphs can be considered as an indication of the seebeck coefficient, α of the thermocouples. Seebeck coefficients calculated by this method for the electroplated thermocouples number 6 and 8 were 33 and 37 μV/°C respectively. The Seebeck coefficient of a standard T-type thermocouple is reported in reference [6] to be 49 μV/°C.

As can be seen, the Seebeck coefficients of the electroplated thermocouples are 33% and 25% lower than that of a standard T-type thermocouple. The reason for a lower value of α in electroplated thermocouples may lie in the fact that metallic structure of copper when made in form of wire (as in the standard thermocouple), is much denser than the case where the TC is made by electroplating. The mechanical work done during the wire drawing process is the reason for its dense structure. A dense structure is equivalent of more current carrier concentration and possibly better electron mobility, which in turn leads to a higher Seebeck coefficient. In addition to that, during chemical electroplating, some inhomogenities may occur in the formation of the metallic structure of the copper layer. The inhomogenities are usually in form of tiny pores (less than 4 μm in diameter). In special cases the size of the pores might become large in the order of 20 μm. Larger pores will contribute to decrease the junction volume and therefore will decrease the power output of the TC. Figure 5 is a microscopic picture (500X magnification) of the structure of the copper layer showing a relatively large pore together with a number of normal size pores of the order of less than 4 μm. The area on the right side of the picture is the constantan area.

There is possibility for other type of defects to occur. The worst case is when the defect occurs at the interface of the constantan and the copper layers. Figure 6 shows a poor contact between the two metals. In this case no contact has been made along a 0.5 mm length of the interface. From this picture, the depth of the gap can not be determined. Defects of this kind will be a source of considerable reduction of the power output of the TC. Therefore care must be taken in preparation of the outer surface of the constantan wire in order to ensure a wire a regular copper wire was wrapped around the surface of the constantan wire . The wax covered part of the constantan wire would act as its other lead wire. The wire assembly was immersed in a container containing a solution of copper sulfate in distilled water and the temperature of the solution was kept at 35°C by using an electric heater sealed in a glass tube. Copper metal strips 20 mm wide and 5 mm thick was used as anode of the electroplating assembly and the cathode was connected to the constantan wire.

The power supply was equipped with a polarity inversion device. The distance between the electrodes was carefully determined and fixed in order to produce a homogeneous structure of the deposited copper metal. The electric current required was approximately 80-90 mA. High deposition rates resulted in copper layers with high porosity. To decrease porosity, two adjustments were made to the manufacturing process. A low speed mechanical agitator was used in the container, which provided an environment having homogeneous concentration of the electrolytic solution.

The agitator also produced uniform temperature in the solution. Another function provided by the agitator was to prevent the accumulation of copper particles at the tip of the constantan wire. The second adjustment to the process was the inversion of polarity. The polarity of the power supply was reversed for one minute for every three-minute period of copper deposition. This caused the copper particles to be removed from the recently deposited layer. As a result the copper deposit on the final product had less porosity and a smoother surface. Several thermocouples were manufactured having different copper layer thicknesses. Figure 1 shows one of the thermocouples manufactured by the above method.

Experiments

The experimental setup was consisted of a 1500 W hot plate as the heat source (hot junction), a mixture of ice and water (cold junction), a commercial type K thermocouple probe and its digital indicator as the temperature measuring device and the electroplated thermocouples. The thermocouple hot junction was inserted in the cavity of a small aluminum block. In order to eliminate possible damage to the measuring instruments, the hot junction was electrically isolated from the aluminum block by inserting a thin layer of insulating material. The temperature of the block was varied from 80 to 270°C using the hot plate and was measured by the type K thermocouple with ±0.5°C accuracy. A Hioki 3200 multimeter measured the open-circuit voltage of the thermocouples with ±0.1mV accuracy.

The aluminum block was insulated on the outside surface. A 10 KΩ electrical resistor was used as the electrical load for the circuit. The current was measured and the thermoelectric power of the thermocouple was calculated.

The measurements were taken during heating up and cooling down (heater off) processes and the average value of measurements was recorded. The maximum measured voltage difference observed between heating up and cooling down stages at the same temperature was 0.32 mV. A total of 20 thermocouples were tested. The specifications of some of the thermocouples are shown in Table 1.

Table (1) Thermocouple specifications.

number	copper layer outer diameter (mm)	copper layer length (mm)	constantan wire length (mm)	junction volume (mm^3)
1	3.0	10.3	150	73
2	2.0	11.0	150	35
3	2.2	11.8	150	45
4	3.3	9.0	150	77
5	3.3	9.3	90	75
6	2.6	40.0	120	212
7	2.8	59.4	140	366
8	3.3	78.0	160	667

Electroplating Technique as a Method for Manufacturing Copper-Constantan Thermocouples

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Abstract

Proof of concept experiments on the use of the chemical electroplating technique in manufacturing copper-constantan thermocouples are conducted. The thermoelectric voltage of the thermocouples are measured and power produced are calculated. The Seebeck coefficient of the electroplated thermocouples was found to be lower than the standard T-type thermocouple. Microscopic pictures of the junction revealed some possible causes of inferior performance and remedies are proposed to improve performance. The technique is suggested for mass production of thermocouples for various applications.

Keywords

Thermocouple, Electroplating

Introduction

Thermoelectric converters can be used in several applications. Among those are: power generation, refrigeration, heat flux sensors, radiation detectors and infrared thermography [1], [2], [3]. Since 1820s when Seebeck and later Peltier reported two principal thermoelectric phenomena, this branch of science has drawn the attention of many scientists. Several theoretical and experimental works have been done on this subject [4].

Low conversion efficiencies have restricted their use as power generators. Thermoelectric refrigerators also receive little attention regarding commercial utilization and mass production. However thermoelectric sensors are being developed and used more widely in today's industry.

Thin film thermocouples (less than 15μm thick) have been developed for heat transfer and temperature measurements on turbine blade and vane surfaces [5].

The problems involved in production of thin film thermocouple include: need for vacuum chambers and precision equipment, difficulties in connecting lead wires to the thermocouple junction.

The above problems will increase their price. By using chemical electroplating method, thermocouples can be manufactured without the need of vacuum chambers and clean rooms, the lead wires can be easily connected to the junction and the price of such thermocouples will be much lower. In this paper the performance of copper-constantan thermocouples manufactured by chemical electroplating method is studied and reported.

Manufacturing method

Several copper-constantan thermocouples were manufactured by chemical electroplating of copper layers on constantan wires. The manufacturing process started with a 1.25 mm thick constantan wire having grease-free surface.

The entire length of the wire was then covered with wax to protect the surface from deposition of copper . The wax from a portion of the wire at the tip was removed. As the lead