

Magnetization Measurements of PdNi, PdCo and ZCuNi Ferromagnetic Thermosteds

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Abstract

High quality heating device made of ferromagnetic alloy (thermal seed) was developed for hyperthermia treatment of cancer. Ferromagnetic seeds of PdNi, PdCo and CuNi are prepared by induction furnace and subsequent heat treatment. Magnetic induction and hysteresis loops are measured as functions of temperature. The power dissipated from each seed was calculated from the area enclosed by the hysteresis loop. The device was found to generate sufficient heat at room temperature and stop heating at the Curie temperature T_c .

Keywords: Ferromagnetic thermosteds, hyperthermia.

Introduction

Hyperthermia is raising the tissue temperature between 41.5-46°C to kill cancerous cells while preserving normal cells. Initial attempts to make advantage of anti cancer activity of hyperthermia involved the use of pyrogens for the induction of high fevers in patients with malignancies. Perhaps the best known of these studies was that of Coley in 1893 [1], who used bacterial toxins to raise the temperature in patients. In hyperthermia, the temperature of the tissue is elevated artificially with the aim of receiving therapeutic benefits. It is considered as an adjunct to other treatments [2, 3, 4]. One of the common methods for heating small tissue volumes was suggested firstly by Burton et al. in 1971 [5] using self-regulating implants. These implants are usually needle-shaped ferromagnetic thermosteds.

The physical process of seed heating is based on eddy current induced by an oscillating magnetic field or by magnetic hysteresis loss [6]. Then, the temperature of the cancer tissue is raised until the Curie temperature of the implants is reached. Thermal seed of binary alloys or ferrites [6,7,8,9] are used by various investigators for interstitial hyperthermia. On the other hand, the power absorption of ferromagnetic

seeds have been measured experimentally using a calorimetric method [9] and static magnetic hysteresis loop [6]. Moreover, a theoretical calculation of heating power based in linear theory rather than the calorimetric measurements was investigated by many authors [10,11].

Computations performed by Atkinson et al. (1984) [11] indicated that a heat production rate of 200 mW/cm is adequate for most clinical application.

In the present study, we have measured the inductance, and the hysteresis loops for the PdNi, PdCo and CuNi seeds as a function of temperature. The power dissipated from ferromagnetic thermoseeds is estimated from the area of the hysteresis loop. Results are compared with the previous work for possible applications.

Experimental

Thermal rods were prepared from a mixture of magnetic and nonmagnetic elements. Nominal composition of palladium nickel ($\text{Pd}_x\text{Ni}_{100-x}$), palladium cobalt ($\text{Pd}_x\text{Co}_{100-x}$) and copper nickel ($\text{Cu}_x\text{Ni}_{100-x}$) alloys are used.

In CuNi, the composition of 29.6% atomic percent for copper and 70.4% for nickel is prepared.

Two samples of PdCo were prepared, the first of the composition of 10% atomic percent cobalt and 90% atomic percent palladium and the second is of composition 10.8% atomic percent for cobalt and 89.2% atomic percent for palladium.

In PdNi three samples were prepared, the first is of the composition of 25% atomic percent Nickel and 75% atomic percent palladium, the second is of the composition 26% atomic percent Nickel and 74% atomic percent palladium and the third compositions is of 27% atomic percent for Nickel and 73% for palladium

Constituent elements of at least 99.85 % purity were alloyed into ingots in an induction furnace. They were cold worked into approximately 0.9 mm diameter wire and cut to 5.5 cm length seeds. As significant cold work destroys the normal lattice structure, inhibits formation of magnetic domains and impedes Bloch wall movement. A recrystallization heat treatment at 1000°C was necessary to improve bulk magnetic properties and homogeneity of the alloys. A second annealing at 1000°C, 1000°C, 800°C for PdNi, PdCo and Cu Ni alloys respectively in an inert atmosphere was performed to relieve any mechanical stresses resulting from the cold working, and also to provide magnetic uniformity to the alloys.

Since the value of the inductance L is directly proportional to a.c susceptibility ($\chi_{a.c}$), an experiment is constructed for fast detecting T_c by measuring L instead of a.c susceptibility ($\chi_{a.c}$). A copper wire was wound around the rod shape sample and the coil was connected to an inductance bridge (model *Hioki3520 tester*). The inductance L of the samples was measured in the temperature range from 20 to 100°C at 100 kHz.

To calculate the heating power generated from the ferromagnetic thermoseeds, the magnetic hysteresis loops of each sample were measured at different temperatures below the T_c in fields up to 0.8T using Oxford Faraday magnetometer [12].

According to Shimizu et al [6], the heating power can be deduced from the area of the recorded hysteresis loop using ;

$$P = f \oint M dH \quad (1)$$

where, P is the measured heating power per unit length under applied magnetic field, f is the assumed frequency of the applied a.c magnetic field and $\oint M dH$ is the area of the hysteresis loop.

Results and Discussion

Figure 1 shows measurements of the inductance L as a function of temperature T for the annealed seeds PdNi_{27.0}, PdCo_{10.8} and CuNi_{70.4}. Sharp transitions at Curie temperature T_c for PdNi_{27.0}, PdCo_{10.8} and CuNi_{70.4} are observed at 52°C, 57°C and 49°C respectively.

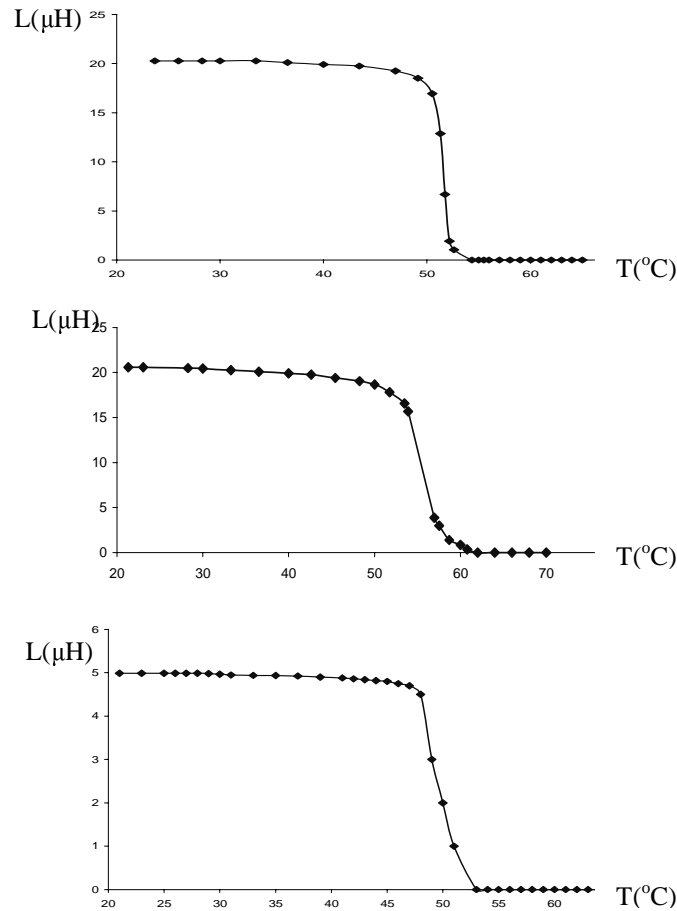


Figure 1: Temperature dependent of the inductance for ferromagnetic seeds at 100 kHz, (a) PdNi_{27.0B}, (b) PdCo_{10.8B} and (c) CuNi_{29.0}.

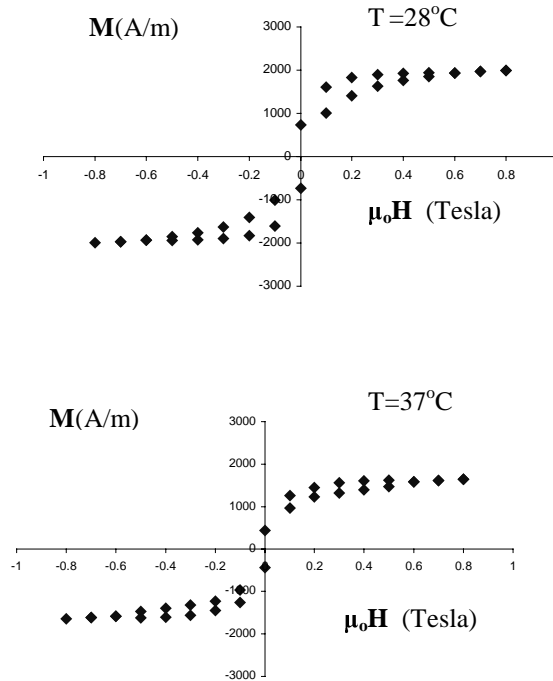
The magnetization of the samples is temperature and magnetic field dependent. From hysteresis loop, the total magnetization M can be represented by $M = \pm\sigma + \chi H$, where, σ is the spontaneous magnetization and χ is termed the susceptibility of the material of the sample. The negative sign represents the value of the magnetization when the field is swept from the negative value back towards zero fields.

Figure 2 shows the hysteresis loops of PdNi_{127.0} at temperatures below the Curie point. It can be seen from the figure that the σ , the saturation magnetization M_s and the area of hysteresis loop decreases with increasing temperature. This can be understood as a decrease in the value of the power loss with increasing temperature. Similar behavior was found for the other prepared seeds. The power heating loss decreases with decreasing the area of the hysteresis loop and stopped automatically when the Curie temperature is reached.

The area under the hysteresis loop was evaluated using a numerical analysis method [14,15,16] by the following relation;

$$\int_0^H M(H)dH = h \int_0^n f_q dq = h \left[f_o + q \nabla f_o + \frac{q(q+1)}{2!} \nabla^2 f_o + \frac{q(q+1)(q+2)}{3!} \nabla^3 f_o + \dots \right]_0^n \quad (2)$$

where, h is the step of integration between each two points of H (here $h=0.1$), f_q is the magnetization function of H , n is the integral terminator and q is constant near values of n .



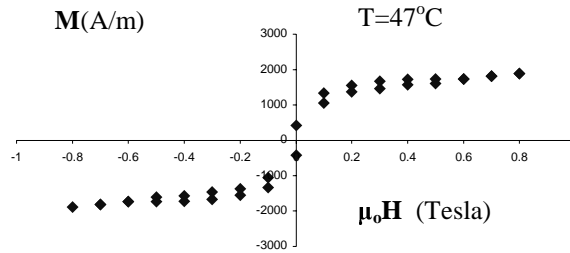


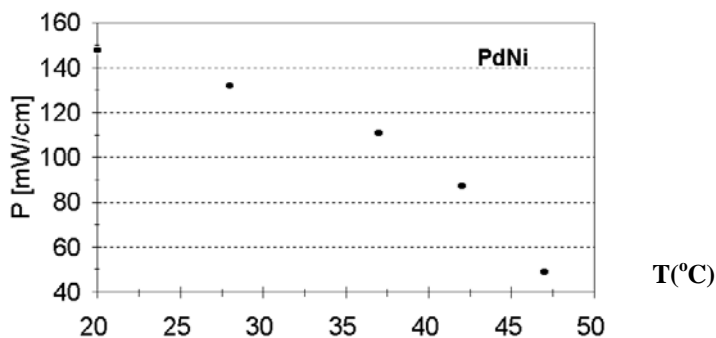
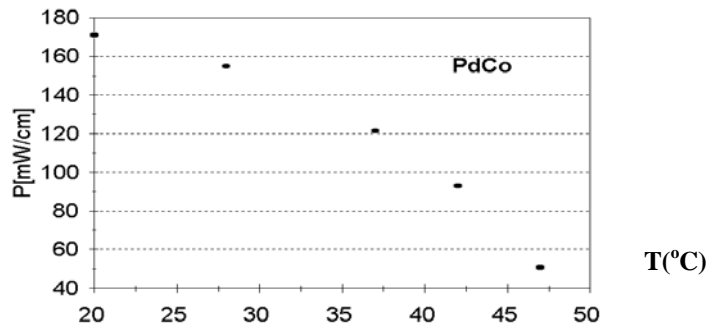
Figure 2: The magnetic hysteresis loops for PdNiB_{27.0B} alloy at different temperature below T_{BcB}.

The heating power evaluated using eq.1 for PdNi_{27.0}, PdCo_{10.8} and CuNi_{70.4} seeds as a function of temperature are shown in figure (3). It is clear from the figure that, the heating power of samples decreases with increasing temperature and a disappearance of power produced from these seeds is observed near the Curie temperature. For this reason, the ferromagnetic thermoseeds are considered as localized self-regulated temperature control systems.

The experimental points of the temperature dependent of power, which are shown in figure 3, are fitted using a proposed empirical formula,

$$P = (a - bT^2)^{1/2} \tag{3}$$

where, a and b are constants which depend some how on the magnetic characteristics of the seeds. Solid lines in figure (3) are the fit result.



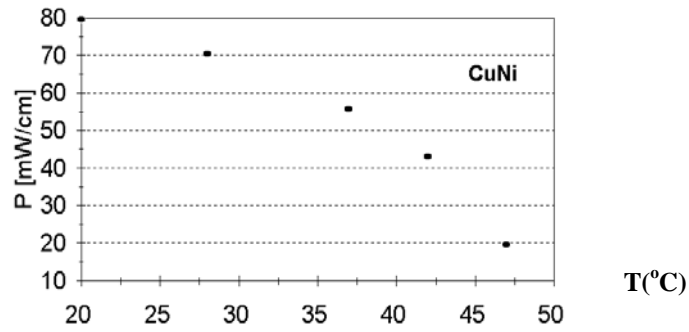


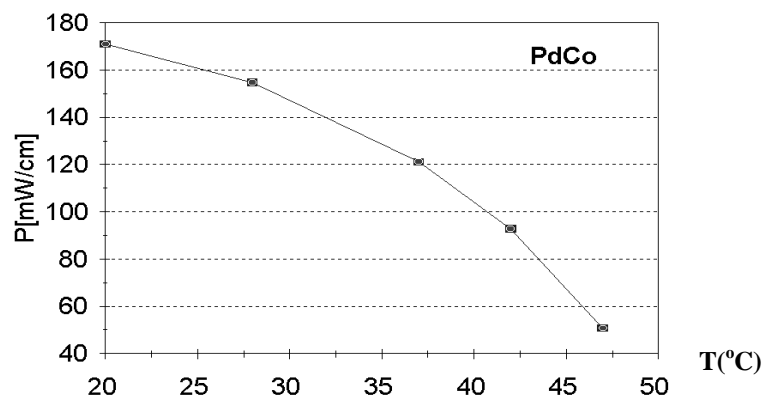
Figure 3: The power heating loss as a function of temperature for PdCo_{10.8}, PdNi_{27.0}, and CuNi_{29.0}, calculated from the area under the hysteresis loop using the numerical analysis methods.

Conclusion

PdNi_{27.0}, PdCo_{10.8} and CuNi_{70.4} ferromagnetic thermoseeds have been prepared for interstitial hyperthermia in cancer treatment. The PdNi_{27.0}, PdCo_{10.8} and CuNi_{70.4} seeds show sharp ferromagnetic to paramagnetic transition temperatures at 52°C, 57°C and 49°C respectively. Eddy current loss and hysteresis loss are the most important losses in ferromagnetic substances.

The heating power at 20°C is about 171mW/cm for PdCo_{10.8} and 150 mW/cm for PdNi_{27.0}, which are sufficient for some clinical applications. On the other hand, CuNi_{70.4} seed shows a heating power of about 80 mW/cm much smaller than other materials.

Therefore, the above mentioned seeds are clinically useful in treating localized tumors due to their sufficient power and self regulation of temperature.



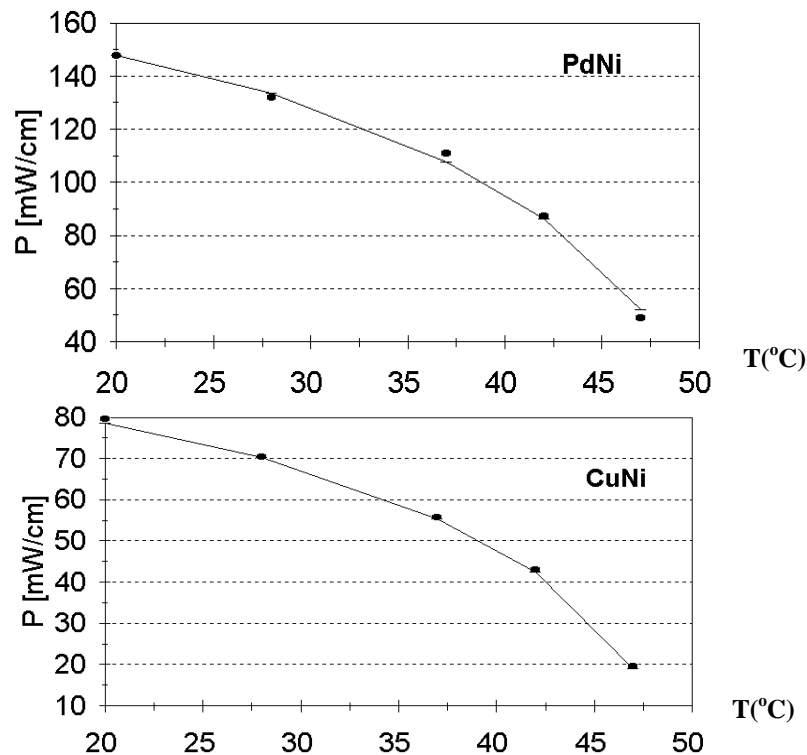


Figure 4: Temperature dependent of the heating power for PdCoB_{10.8}, PdNiB_{27.0B}, and CuNiB_{70.4}. The solid line represents a fitting curve to the experimental points using an empirical formula $P=(a-bT^2)^{1/2}$. See text for details.

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