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Design of a Substrate Heater for Calcium Hydroxyapatite Coating by Pulsed Laser Deposition

Abstract

Calcium hydroxyapatite (HA) is the main chemical constituent of bone. When replacement hip joints are coated with this chemical, the body may be more likely to accept the artificial joint, forming new bone that bonds the joint to the original leg bone. HA deposited by laser ablation in vacuum adheres to the substrate better at high temperatures of up to 700°C. This heater should be capable of uniformly heating to 700°C a silicon disk 150 mm in diameter.

The heater consists of two wire heating coils brazed into a disk of stainless steel, with tantalum shields on top and at the sides of the heater to minimize radiation loss. Three spring-rotation clamps at the bottom of the heater hold the substrate disk in place.

This report describes the heater and how it was developed, including design evolution and thermal modeling. Also, detailed information about parts is discussed.

1.0 Introduction

Calcium hydroxyapatite (HA) is the main chemical constituent of bone[1]. When replacement hip joints are coated with this chemical, the body is more likely to accept the artificial joint, forming new bone that bonds the joint to the original leg bone. HA deposited by laser ablation adheres to the substrate better at high temperatures of up to 700°C. This heater should be capable of uniformly heating to 700°C a silicon disk 150 mm in diameter.

This heater will be used in a vacuum system with pressures less than 1×10^{-7} torr. The copper vapor laser used for ablation operates with 200 kW, at 4.4 kHz, and at wavelengths of 578 and 514 nm.

The heater consists of two wire heating coils brazed into a disk of stainless steel, with tantalum shields on top and at the sides of the heater to minimize radiation loss. Three spring-rotation clamps at the bottom of the heater hold the substrate disk in place.

This report describes the heater and how it was developed, including design evolution and thermal modeling. Also, detailed information about parts is discussed.

2.0 Design Specifications

- Heat 150 mm diameter disk
- Heat to maximum temp 700°C, $\pm 10^\circ\text{C}$ variation allowable
- Easy to use clamps for holding substrate
- Maximum width allowable 8" to fit in vacuum chamber
- Voltage input under 120 V
- Heater must attach to feedthrough shaft
- Works in vacuum better than 1×10^{-7} torr.

3.0 Thermal Modeling

Thermal modeling was done in three steps, with control volumes decreasing in size, and increasing in complexity and physical effects modeled.

3.1 Radiation Heat Transfer Only

In the first step, the disk was analyzed as a single control volume to find the power input required to maintain the disk at 700°C. Thus, the energy required is the sum of the radiation from the top of the heater and the radiation from the bottom of the heater, as shown by Figure 3.1.1.

Figure 3.1.1 Whole disk as control volume.

$$q_{in} = q_{r,top} + q_{r,bottom}$$

This yielded an estimate of 320 W, the power input required to maintain the disk at 700°C.

3.2 1-D Radiation and Conduction

In the next step, thermal transfer was modeled as one dimensional thermal conduction and radiation. The desired temperature of the bottom of the heater was set at 700°C, with the temperature of the top of the heater and the power input adjusted until the conduction heat transfer equaled the radiation loss from the bottom of the heater.

Figure 3.2.1 Entire disk as control volume.

Figure 3.2.2 Bottom layer of disk as control volume.

$$q_{in} = q_{r,top} + q_{r,bottom}$$

$$q_k = q_{r,bottom}$$

$$q_k = kA(T_{top} - T_{bottom})$$

This analysis provided a more exact estimate, 324.47 W, of the power required to achieve 700°C on the bottom of the heater. Also, this gave us an estimate for how hot the top of the heater should be, 705°C.

3.3 2-D Convection and Conduction

A coil-shaped wire heater would best suit the goal to heat a circular substrate. Thus, the focus of the 2-D modeling was to determine a reasonable spacing between coils.

In this step, thermal transfer was modeled in two dimensions. The situation was set up as a block with a line heater on the upper left edge and convection on the top face. There was no heat transfer on the bottom and right faces because of planes of symmetry. Convection was used to approximate the radiation loss.

Figure 3.3.1 Diagram of 2-D analysis.

The temperature distribution of this situation was found in Conduction of Heat in Solids[2].

$$T = \sum_{n=1}^{\infty} \frac{2(h^2 + \alpha_n^2) \cos(\alpha_n x) \cosh(\alpha_n(b-y))}{[(h^2 + \alpha_n^2)a + h] \cosh(\alpha_n b)} \int_0^a f(x) \cos(\alpha_n x) dx$$

where

$$h = \frac{\text{convection coefficient}}{\text{conduction coefficient}}$$

$$\alpha \tan(\alpha a) = h$$

The eigenvalues α_n of the last equation were computed iteratively.

For the temperature distribution $f(x)$, we chose

$$f(x) = (T_{top} - T_{bottom})e^{-Kx} + T_{bottom}$$

which gives a sharp temperature peak at $x=0$, with a drop-off to the temperature at the bottom of the heater. With $K=8000$, the temperature drops quickly, as shown in the following graph:

Figure 3.3.2 Heater temperature $f(x)$ vs. x .

The temperature distribution T varied greatly depending on the equation used for the line heat source $f(x)$ at the top left of the block. However, for reasonable estimates of $f(x)$, this model showed that temperature gradients were low on the bottom of the heater surface ($.44^{\circ}\text{C}$), and that a heater coil spacing of 1 cm was reasonable. The graph below, giving the change in temperature across the top of the heater, shows the small temperature gradient.

Figure 3.3.3 Temperature T vs. y , $x=0$.

4.0 Final Design

4.1 Heater

Heater Body

In the final design, most parts, including the heater body, are stainless steel. Stainless steel has a fairly high conduction coefficient, $38 \text{ W/m}^{\circ}\text{K}$ at 500°C , and welds easily. Using a common material cuts down on cost, and makes obtaining parts easier. Also, because most of the parts are stainless steel, there is less likelihood of electrochemical reactions between the parts. The heater body is a 6" diameter disk, 1/2" inch thick, with an 1/8" deep spiral groove cut for the heaters.

Shields

Shields are positioned on the sides and top of the heater to minimize radiation heat loss. Tantalum was chosen for the shields because of its low vapor pressure and ability to withstand high temperatures. 1/4" outer diameter ceramic tubing is used around the screws to serve as spacers for the shields and to minimize conduction heat transfer.

Heating Coil

Originally, we wanted one continuous coil heater to fit in a groove in the heater body. However, this specification was too rigorous for the heaters on the market. Instead, we chose to have two separate coil heaters, both from Watlow, 1/8" wire diameter, 47" long, able to take up to 120 V and 235 W. One heats the region from diameter 1" to 3.25", and the second coil heats from diameter 3.5" to 5.75".

Figure 4.1 Picture of heater assembly.

4.2 Spring-Rotation Clamp

The spring-rotation clamp was chosen for its versatility. The clamp can be removed from the substrate by pulling down on the lower large nut, then rotating. The height of the clamps can be adjusted by turning the nut on the 4-40 stud. Because it is "powered" by a compression spring (3/16" outer diameter, 1/2" long, .184" wire diameter), this clamp is secure. The clamp contacts the substrate with the 1/8" stainless steel ball, ensuring that the substrate will not be damaged when the clamp is being moved, in case the operator fails to pull down on the clamp before rotating it.

Figure 4.2 Picture of clamp assembly.

4.3 Detail Drawings

Figure 4.3.1 Assembly drawing.

INCHES, SCALE 1.0

1 STAINLESS ST.

Figure 4.3.2 Heater body.

INCHES, SCALE 1.0

Figure 4.3.3 Heater groove.

INCHES, SCALE 1.0

(3) $\frac{1}{8}$ " SST

Figure 4.3.4 Clamp - part I.

INCHES, SCALE 1.0

(3) $\frac{1}{8}$ " SST

Figure 4.3.5 Clamp - part II.

INCHES
DRAWING NOT TO SCALE

GUST PROVIDED

HOLES 4-40 CLEARANCE

Figure 4.3.6 Side shields.

INCHES, SCALE 1.0

STAINLESS STEEL
QUANTITY: 1

.253 ϕ ON
5.625 ϕ BC

.253 ϕ ON
3.375 ϕ BC

3x4-40 -
CLEARANCE
3.125 BC
8 O'SINK
~~BACK~~
SIDE

3x4-40
DRILL & TAP
5 ϕ BC

0.125

CS

CS

CS

Figure 4.3.7 Lower shields.

INCHES, SCALE 1.0

STAINLESS STEEL
QUANTITY: 1

.253 ϕ
ON 5.025 ϕ BC

.253 ϕ
ON 3.375 ϕ BC

3x4-40
CLEARANCE
5 ϕ BC

Figure 4.3.8 Lower plate.

INCHES, SCALE 1.0

Figure 4.3.9 Upper shields.

INCHES, SCALE 1.0

STAINLESS STEEL
QUANTITY: 1

.253 ϕ
ON 5.625 ϕ BC

.253 ϕ
ON 3.375 ϕ BC

3x4-40
CLEARANCE
5 ϕ BC

Figure 4.3.10 Upper plate.

INCHES, SCALE 1.0

1 STAINLESS STEEL

Figure 4.3.11 Coupler.

5.0 Design Evolution

Drawings for the assembly and clamps are shown in chronological order to show the development of the design.

5.1 Assembly Evolution

Changes in the assembly were rather gradual, a result of wanting to minimize heat loss.

Figure 5.1.1 13 June 1995

Figure 5.1.2 16 June 1995

Figure 5.1.3 19 June 1995

Figure 5.1.4 26 June 1995

5.2 Clamp Evolution

The designing of the clamps was a major challenge. The clamps had to be easy to use, and had to be able to move "out of the way" of the heater. Also, preferably, they would not interfere with the side shields. The following is a sampling of proposed designs, to give an idea of other options for clamps.

Figure 5.2.1 C clamp.

Figure 5.2.2 Spring flange.

Figure 5.2.3 Swirl clamp.

Figure 5.2.4 Fork rotation clamp.

Figure 5.2.5 Smooth surface clamp.

Figure 5.2.6 Rotation clamp.

Figure 5.2.7 X-spring clamp.

Figure 5.2.8 Counterweight clamp.

Figure 5.2.9 Spring-rotation clamp.

6.0 Parts List

Part	Material	Quantity	Supplier	Mat'l Cost *	Labor Hours
Heater body	Stainless steel	1	MSC	50.08	18.5
Heater coils	Stainless steel	2	Watlow	180.00	—
Lower shields	Tantalum	3	Surplus	—	1.5
Lower plate	Stainless steel	1	Shop	—	1.0
Upper shields	Tantalum	3	Surplus	—	1.5
Upper plate	Stainless steel	1	Shop	—	1.0
Side shields	Tantalum	2	Surplus	—	3.0
Spacers	Ceramic	36	Surplus	—	—
4-40 screws	Stainless steel	12	Surplus	4.50	—
Coupler	Stainless steel	1	MSC	1.62	3.0
1/8" balls	Stainless steel	3	SPI	0.10	—
Compr. springs	Stainless steel	3	Surplus (PIC)	0.70	—
Welding	—	N/A	ME Shop	—	1.0
Brazing	Nickel Gold	N/A	Braze Shop	—	—

* Costs given per piece.

References

1. Cotell, Catherine M., Chrisey, Douglas B., Grabowski, Kenneth S., Sprague, James A., and Gossett, Charles R.: Pulsed Laser Deposition of Hydroxylapatite Thin Films on Ti-6Al-4V. Patent Application.
2. Carslaw, H. S. and Jaeger, J.C.: Conduction of Heat in Solids. Clarendon Press, Oxford, 1959. Page 167.

MAH:dlb
ST 95-115

Milestones

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
	May 22-26	May June 30-2	June 5-9	June 12-16	June 19-23	June 26-30	July 5-11
Thermal Modeling	X	X	X				
Preliminary sketches			X	X			
Final design					X		
Detail drawings					X	X	
Part Ordering					X	X	
Manufacturing						X	X
Design Report						X	X