Phonon Modulation By Polarized Lasers For Material Modification

Sen-Yong Chen
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PHONON MODULATION BY POLARIZED LASERS
FOR MATERIAL MODIFICATION

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
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Major Professor: Aravinda Kar
Raj Vaidyanathan
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ABSTRACT

Magnetic resonance imaging (MRI) has become one of the premier non-invasive diagnostic tools, with around 60 million MRI scans applied each year. However, there is a risk of thermal injury due to radiofrequency (RF) induction heating of the tissue and implanted metallic device for the patients with the implanted metallic devices. Especially, MRI of the patients with implanted elongated devices such as pacemakers and deep brain stimulation systems is considered contraindicated. Many efforts, such as determining preferred MRI parameters, modifying magnetic field distribution, designing new structure and exploring new materials, have been made to reduce the induction heating. Improving the MRI-compatibility of implanted metallic devices by modifying the properties of the existing materials would be valuable.

To evaluate the temperature rise due to RF induction heating on a metallic implant during MRI procedure, an electromagnetic model and thermal model are studied. The models consider the shape of RF magnetic pulses, interaction of RF pulses with metal plate, thermal conduction inside the metal and the convection at the interface between the metal and the surroundings. Transient temperature variation and effects of heat transfer coefficient, reflectivity and MRI settings on the temperature change are studied.

Laser diffusion is applied to some titanium sheets for a preliminary study. An electromagnetic and thermal model is developed to choose the proper diffusant. Pt is the diffusant in this study. An electromagnetic model is also developed based on the principles of inverse problems to calculate the electromagnetic properties of the metals from the measured magnetic transmittance.
This model is used to determine the reflectivity, dielectric constant and conductivity of treated and as-received Ti sheets. The treated Ti sheets show higher conductivity than the as-received Ti sheets, resulting higher reflectivity.

A beam shaping lens system which is designed based on vector diffraction theory is used in laser diffusion. Designing beam shaping lens based on the vector diffraction theory offers improved irradiance profile and new applications such as polarized beam shaping because the polarization nature of laser beams is considered. Laser Pt diffusion are applied on the titanium and tantalum substrates using different laser beam polarizations. The concentration of Pt and oxygen in those substrates are measured using Energy Dispersive X-Ray Spectroscopy (EDS). The magnetic transmittance and conductivity of those substrates are measured as well. The effects of laser beam polarizations on Pt diffusion and the magnetic transmittance and conductivity of those substrates are studied. Treated Ti sheets show lower magnetic transmittance due to the increased conductivity from diffused Pt atoms. On the other hand, treated Ta sheets show higher magnetic transmittance due to reduced conductivity from oxidation. Linearly polarized light can enhance the Pt diffusion because of the excitation of local vibration mode of atoms.

Laser Pt diffusion and thermo-treatment were applied on the Ta and MP35N wires. The Pt concentration in laser platinized Ta and MP35N wires was determined using EDS. The ultimate tensile strength, fatigue lives and lead tip heating in real MRI environment of those wires were measured. The lead tip hating of the platinized Ta wires is 42 % less than the as-received Ta wire. The diffused Pt increases the conductivity of Ta wires, resulting in more reflection of magnetic field. In the case of the platinized MP35N wire, the reduction in lead tip heating was only 1 °C.
due to low concentration of Pt. The weaker ultimate tensile strength and shorter fatigue lives of laser-treated Ta and MP35N wires may attribute to the oxidation and heating treatment.
ACKNOWLEDGEMENTS

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LIST OF SYMBOLS

\begin{itemize}
  \item \(A\) \hspace{1cm} \text{Cross-sectional area of metal (m}^2\text{)}
  \item \(\alpha\) \hspace{1cm} \text{Absorption coefficient (m}^{-1}\text{)}
  \item \(B_{rms}\) \hspace{1cm} \text{Root mean square of magnetic flux density (T)}
  \item \(B_s\) \hspace{1cm} \text{Flux density of static magnetic field in MRI (T)}
  \item \(B_I\) \hspace{1cm} \text{Magnetic flux density in metal (\(\mu\)T)}
  \item \(B_I\) \hspace{1cm} \text{Biot number}
  \item \(B_{RF}\) \hspace{1cm} \text{Flux density of applied RF magnetic field in MRI (\(\mu\)T)}
  \item \(\bar{B}\) \hspace{1cm} \text{Magnetic flux density in media (T)}
  \item \(\bar{B}_m\) \hspace{1cm} \text{Incident magnetic flux density (T)}
  \item \(B_{in0}\) \hspace{1cm} \text{Amplitude of incident magnetic flux density (T)}
  \item \(B_{inc}\) \hspace{1cm} \text{Amplitude of incident magnetic flux density (T)}
  \item \(\bar{B}_m\) \hspace{1cm} \text{Magnetic flux density in metal (T)}
  \item \(B_{m0}\) \hspace{1cm} \text{Amplitude of magnetic flux density in metal (T)}
  \item \(\beta\) \hspace{1cm} \text{Complex wave number (m}^{-1}\text{)}
  \item \(c\) \hspace{1cm} \text{Speed of light (m/s)}
  \item \(C_p\) \hspace{1cm} \text{Specific heat (J/kg·K)}
  \item \(d\) \hspace{1cm} \text{Thickness of metals (\(\mu\)m)}
  \item \(d_c\) \hspace{1cm} \text{Thickness of the crystal (mm)}
  \item \(d_j\) \hspace{1cm} \text{Distance of \(j\)-th interface from the magnetic field source (\(\mu\)m)}
  \item \(D\) \hspace{1cm} \text{Distance between lens and target plane (mm)}
\end{itemize}
\( D_j \) Electric displacement in media \( j \) (A)

\( D_l \) Diameter of lens (mm)

\( \delta \) Skin depth (\( \mu \)m)

\( \delta_i \) Zero field depth in metal (\( \mu \)m)

\( \delta_l \) Lateral displacement (mm)

\( \delta_l \) Skin depth (\( \mu \)m)

\( e \) Charge of the electron (C)

\( E_{in} \) Incident electric field strength (V/m)

\( E_{j+} \) Forward electric field strength in media \( j \) (V/m)

\( E_{j-} \) Backward electric field strength in media \( j \) (V/m)

\( E_j \) Electric field strength in metal (V/m)

\( \bar{E} \) Electric field strength in media (V/m)

\( \bar{E}_m \) Electric field strength in metal (V/m)

\( \Delta E_p \) Energy gap between aligned state and anti-aligned state (eV)

\( \varepsilon \) Permittivity of media (F/m)

\( \varepsilon_j \) Permittivity of media \( j \) (F/m)

\( \varepsilon_m \) Permittivity of metal (F/m)

\( \varepsilon_{ij} \) Relative permittivity of media \( j \)

\( \varepsilon_0 \) Permittivity of air (F/m)

\( f_L \) Larmor frequency (Hz)

\( \gamma \) Deviation angle of extra-ordinary beam (degree)

\( \gamma_f \) Gyromagnetic ratio of the proton (Hz/T)
\( \gamma_p \)  
Gyromagnetic ratio of the proton (eV/T)

\( h \)  
Heat transfer coefficient (W/ m\(^2\)·K)

\( h_b \)  
Free convection coefficient (W/ m\(^2\)·K)

\( h_s \)  
Heat transfer coefficient in the metal sheet (W/ m\(^2\)·K)

\( H_I \)  
Magnetic field strength in metal (A/m)

\( H_{ln} \)  
Incident magnetic field strength (A/m)

\( \bar{H}_{ln} \)  
Experimental values of incident magnetic field strength (A/m)

\( H_{inc} \)  
Amplitude of incident magnetic field strength (A/m)

\( H_r \)  
Reflected magnetic field strength (A/m)

\( H_I \)  
Magnetic field strength in metal (A/m)

\( H_{j+} \)  
Forward magnetic field strength in media \( j \) (A/m)

\( H_{j-} \)  
Backward magnetic field strength in media \( j \) (A/m)

\( \bar{H}_{j+} \)  
Experimental values of forward magnetic field strength in media \( j \) (A/m)

\( \bar{H}_t \)  
Experimental values of transmitted magnetic field (A/m)

\( I_c \)  
Current flow through metal sheet (A)

\( I_{in} \)  
Incident irradiance (W/m\(^2\))

\( I_m \)  
Irradiance in metal (W/m\(^2\))

\( I_r \)  
Reflected irradiance (W/m\(^2\))

\( J_{cI} \)  
Induced current density in metal (A/m\(^2\))

\( J_c \)  
Induced current density in media (A/m\(^2\))

\( \bar{J}_s \)  
Source current density in media (A/m\(^2\))

\( k_B \)  
Boltzmann constant (eV/K)
\( \kappa_j \)  
Absorption index of \( j \)-th medium

\( k_{th} \)  
Thermal conductivity (W/m·K)

\( \vec{k}_d \)  
Difference of unit wave vector

\( \hat{k}_j \)  
Complex wave vector in media \( j \) (m\(^{-1}\))

\( \hat{k}_m \)  
Unit vector along the direction of laser beam propagation

\( K \)  
Correction factor

\( L_g \)  
Grain size (nm)

\( L_c \)  
Coherence length of surface height (\( \mu \)m)

\( \lambda_a \)  
Wavelength of magnetic field (m)

\( \lambda_L \)  
Wavelength of the laser (nm)

\( M_{xy} \)  
Transverse magnetization (A/m)

\( M_z \)  
Longitudinal magnetization (A/m)

\( m_A \)  
Atomic mass

\( m_e \)  
Electron mass (kg)

\( \mu \)  
Permeability of media (H/m)

\( \mu_j \)  
Permeability of media \( j \) (H/m)

\( \mu_m \)  
Permeability of metal (H/m)

\( \mu_{ij} \)  
Relative permeability of media \( j \)

\( \mu_0 \)  
Permeability of air (H/m)

\( n \)  
Refractive index

\( n_e \)  
Refractive index for extra-ordinary beam

\( n_o \)  
Refractive index for ordinary beam
\( n_j \) Refraction index of \( j \)-th medium

\( N \) Number of pulses during the MRI procedure

\( N_H \) Number of protons at aligned state \((\text{m}^3)\)

\( N_L \) Number of protons at anti-aligned state \((\text{m}^3)\)

\( N_0 \) Free electron density \((\text{m}^3)\)

\( P_L \) Laser power \((\text{W})\)

\( p_f \) Pulse repetition rate \((\text{Hz})\)

\( \hat{p}_m \) Unit vector along \( p \)-polarization

\( q \) Energy deposited in the metal per second \((\text{W})\)

\( \Theta \) Angle between optical axis and laser propagation direction \((\text{degree})\)

\( \theta_i \) Incident angle of laser beam \((\text{degree})\)

\( \theta_r \) Reflected angle of laser beam \((\text{degree})\)

\( \theta_{rs} \) Specular reflection angle \((\text{degree})\)

\( \theta_t \) Transmitted angle of laser beam \((\text{degree})\)

\( \Delta\theta_a \) Acceptance angle of photodetector \((\text{degree})\)

\( r_{lm} \) Reflection coefficients from medium \( l \) to medium \( m \)

\( R \) Reflectivity

\( R \) Reflectance

\( \bar{R}_b \) Bidirectional reflectance distribution function

\( \bar{R}_{bd} \) Diffuse bidirectional reflectance distribution function

\( \bar{R}_{bs} \) Specular bidirectional reflectance distribution function

\( R_F \) Fresnel reflectivity
\( R_{fp} \)  Fresnel reflectivity for \( p \)-polarization

\( R_{fs} \)  Fresnel reflectivity for \( s \)-polarization

\( \bar{R}_{gr} \)  Total bidirectional reflectance for rough surface

\( \bar{R}_{gs} \)  Total bidirectional reflectance for perfectly smooth surface

\( R_{th} \)  Reflectivity of rough surface

\( r_r \)  Reflection coefficient of metal

\( r_s \)  Radius of free electron sphere (nm)

\( \rho_c \)  Charge density in media (C/m\(^3\))

\( \rho_{eff} \)  Effective surface roughness (nm)

\( \rho_m \)  Mass density of metal (kg/m\(^3\))

\( \rho_{rms} \)  surface roughness (nm)

\( \hat{s}_m \)  Unit vector along \( s \)-polarization

\( s_p \)  Separation between the two inner voltage probes (mm)

\( \bar{S} \)  Instantaneous Poynting vector (W/m\(^2\))

\( S_{avg} \)  Average Poynting vector (W/m\(^2\))

\( S \)  Target plane

\( S' \)  Aperture plane

\( \sigma \)  Conductivity of media (\( \Omega \cdot m^{-1} \))

\( \sigma_0 \)  DC conductivity (\( \Omega \cdot m^{-1} \))

\( \sigma_j \)  Conductivity of media \( j \) (\( \Omega \cdot m^{-1} \))

\( t_c \)  Center thickness (mm)

\( t \)  Overall transmission coefficient of metal sheet
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{lm}$</td>
<td>Transmission coefficients from medium $l$ to medium $m$</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$T$</td>
<td>Transmittance</td>
</tr>
<tr>
<td>$T_B$</td>
<td>Oscillation period of the magnetic field (s)</td>
</tr>
<tr>
<td>$T_{err}$</td>
<td>Error between the calculated and experimental transmittances</td>
</tr>
<tr>
<td>$T_1$</td>
<td>Temperature of metal ($^\circ$C)</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Initial temperature of the metal ($^\circ$C)</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Surface temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$T_\infty$</td>
<td>Temperature far from the metal ($^\circ$C)</td>
</tr>
<tr>
<td>$\tilde{T}$</td>
<td>Experimental values of transmittance</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature change ($^\circ$C)</td>
</tr>
<tr>
<td>$\Delta t_d$</td>
<td>Time duration (s)</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Surface sag (mm)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Interaction time (s)</td>
</tr>
<tr>
<td>$\tau_e$</td>
<td>Electron relaxation time (ps)</td>
</tr>
<tr>
<td>$u$</td>
<td>Laser scanning speed (mm/s)</td>
</tr>
<tr>
<td>$\vec{U}$</td>
<td>Diffracted field</td>
</tr>
<tr>
<td>$\vec{U}'$</td>
<td>Incident field on aperture plane</td>
</tr>
<tr>
<td>$\nu_0$</td>
<td>Scattering frequency (Hz)</td>
</tr>
<tr>
<td>$\nu_0'$</td>
<td>Scattering frequency at the edge of grain (Hz)</td>
</tr>
<tr>
<td>$\Delta \nu_1$</td>
<td>Bandwidth of RF magnetic pulse (Hz)</td>
</tr>
<tr>
<td>$V_m$</td>
<td>Voltage drop between two probes (V)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<td>--------</td>
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<tr>
<td>$w$</td>
<td>Radius of flat-top beam (mm)</td>
</tr>
<tr>
<td>$w'$</td>
<td>Radios of Gaussian beam (mm)</td>
</tr>
<tr>
<td>$w_g$</td>
<td>Grain boundary width (nm)</td>
</tr>
<tr>
<td>$w_p$</td>
<td>Width of the current probe (mm)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency (rad)</td>
</tr>
<tr>
<td>$\omega_l$</td>
<td>Carrier frequency of RF pulse (rad)</td>
</tr>
<tr>
<td>$d\omega_i$</td>
<td>Solid angle of incident beam (sr)</td>
</tr>
<tr>
<td>$Z_e$</td>
<td>Number of free electrons per atom</td>
</tr>
<tr>
<td>$Z_j$</td>
<td>Impedance of $j$-th medium ($\Omega$)</td>
</tr>
<tr>
<td>$Z_m$</td>
<td>Impedance of metal ($\Omega$)</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>Impedance of free space ($\Omega$)</td>
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CHAPTER 1: INTRODUCTION

1.1 Introduction to Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is an imaging technique widely used, to show structure of tissues in human bodies. The magnetization of hydrogen nuclei (protons) in the body will be parallel to the applied static magnetic field (from 1.5 T to 3 T). Radio frequency (RF) magnetic fields are applied to disturb the magnetization. Different tissues can be identified because the disturbed protons return to their equilibrium states at various rates depending on the tissues after the RF magnetic field are turned off.

The nuclei of hydrogen (¹H) consist of a single particle, the proton, which carries a positive charge and possesses a spin, a basic property of elementary particles. We can think that the proton rotates like a spinning top. Because the proton is a rotating charge with a mass, it has an angular momentum and magnetic moment which is influenced by magnetic fields and electromagnetic waves. The spin of a proton can be represented by a sphere spinning around its own axis as shown in Fig 1.1. The magnetic field associated with the spinning proton can be considered as a bar magnet and is usually referred to as the nuclear magnetic dipole moment and denoted by a vector indicating the direction of the field. The direction of the dipole moment is along the axis of rotation.
During the MRI procedure, a static external magnetic field $B_s$ is applied to align the spins along the field direction. Based on quantum mechanics, the proton has only two possible alignment states (either with or against). These two states have a small energy difference ($\Delta E_p$) which is proportional to the strength of the applied magnetic flux density $B_s$ [Smith et al. (1998)]:

$$\Delta E_p = \gamma_p B_s \quad (1.1)$$

where $\gamma_p$ is the gyromagnetic ratio of the proton which is $1.7 \times 10^{-7}$ eV/T. The state of aligned with the field is the lower energy state. Eq. (1.1) corresponds to the Larmor equation:

$$f_L = \gamma_f B_s \quad (1.2)$$

where $f_L$ is the Larmor frequency (MHz) and $\gamma_f$ is the gyromagnetic ratio of the proton which is 42.58 MHz/T. For an external magnetic field of 1.5 T, the energy difference is $2.6 \times 10^{-7}$ eV, which corresponds to the Larmor frequency of 63.86 MHz. Since the energy difference is smaller than the thermal energy, the protons continuously flip back and forth between two states. The distribution of protons between the two states follows the Boltzmann distribution, which is

$$\frac{N_H}{N_L} = \exp \left( -\frac{\Delta E_p}{k_B T} \right) \quad (1.3)$$
where \( N_H \) and \( N_L \) are the number of protons in a higher energy state and lower energy state, \( k_B \) is the Boltzmann constant (which is \( 8.62 \times 10^{-5} \) eV/K) and \( T \) is the temperature in Kelvin. At 37 °C and an external flux density of 1.5 T, a sample of two million protons will have around 10 more protons in the lower energy state when they reach equilibrium. When protons are exposed to an external magnetic field, the small excess of protons aligned with the field will produce a net magnetization along the external field direction as shown in Fig. 1.2 [Weishaupt et al. (2003)]. By convention, the magnetization along the direction of the applied field is referred to as longitudinal magnetization \( M_z \) and the magnetization in the plane perpendicular to the external field is called transverse magnetization \( M_{xy} \). At equilibrium, the net magnetization is aligned along the direction of the external field and therefore does not precess. If something disturbs the alignment of the net magnetization, it will precess around the axis the external field as shown in Fig. 1.2.

Assuming that the static magnetic flux density is applied along the positive z axis and a second weak external magnetic field which has a flux density of \( B_{RF} \ll B_z \) is applied to disturb the equilibrium, the net magnetization will precess around the z axis at a frequency referred to as the
resonance frequency. If $B_{RF}$ is applied for a short period of time, its effect will be to slowly rotate the net magnetization toward the transverse plane. The degree of converting longitudinal magnetization $M_z$ into transverse magnetization $M_{xy}$ depends on the strength and duration of the $B_{RF}$ field. In MRI, the $B_{RF}$ rotates around the $z$ axis at the Larmor frequency and it is applied for a short period of time (3.2 ms on the GE Signa 1.5-T system). Therefore, it is referred as an RF pulse. The most commonly used RF pulse is a $90^\circ$ pulse which completely converts longitudinal magnetization into transverse magnetization as shown in Fig 1.3. The net transverse magnetization will itself rotate in the $xy$ plane at a resonance frequency of 63.86 MHz. This rotating magnetic field induces voltage changes within the receiver coil of the MR scanner and generate the MR signal.

![Diagram](image)

Figure 1.3 Illustration of a net magnetization which is on the transverse plane

After $B_{RF}$ is turned off, two independent processes are now reducing the magnitude of transverse magnetization, causing a return to the equilibrium situation before $B_{RF}$ was applied: spin-lattice interaction and spin-spin interaction. Both processes are also named $T1$- and $T2$- relaxation, respectively.
After $B_{RF}$ is turned off, the magnitude of transverse magnetization (the projection of net magnetization on the xy plane) decreases slowly and the magnitude of the longitudinal magnetization will slowly be restored. It is coupled with emission of energy into the surroundings (the lattice, and thus it is called spin-lattice interaction). The time constant of this process is termed $T_1$, and it is independent of the flux density of $B_s$ and of the internal movement of the molecules. $T_1$ varies with tissue types. For tissues at 1.5 T, $T_1$ is of the order of magnitude of one half to several seconds.

After $B_I$ is applied, each individual proton precesses synchronously on the xy plane so all of them are in phase. Once $B_{RF}$ is turned off, this phase coherence will vanish, and then the transverse component of the magnetic moment of each individual proton will cancel out each other. This process is named T2-relaxation which is made up of two components: mutual energy exchange between the spins and time independent inhomogeneities within the external magnetic field $B_s$.

$T_1$- and T2-relaxations are totally independent of each other and proceed simultaneously. However, magnetic resonant (MR) signal has already decayed within the first 100-300 ms due to T2-relaxation. This happens long before the longitudinal magnetization has been fully restored by T1-relaxation (one half to several seconds). Different tissues have different $T_1$- and T2-relaxation time, enabling the construction of MR images.
1.2 Biomedical Effects of Electrically Conductive Implants in MRI Procedure

Most MR systems operate with static magnetic field flux density ranging from 0.2 to 3 T. Higher magnetic flux density is used in the research setting. Such a strong static magnetic field will apply a force and torque on conductive implants. The magnetic forces applied on the conductive implants which are less than the gravity force or the magnetic torque less than the torque due to device weight do not increase the risk to the patients [Nyenhuis et al. (2005)]. Larger force and torque might be acceptable, which depends on the counter-forces [Shellock et al. (2004)].

The RF magnetic pulses in MRI induce currents in the body, whose principle effect is induction heating. MRI procedure will increase the body and skin temperature of the patients less than 0.6 °C, which results in no serious physiologic consequence [Shellock et al. (1989)]. Heating of implanted devices during MRI procedure might be a problem for devices made of conductive materials, especially for the metallic implants with very elongated structure such as guidewires, electrodes, lead and catheters due to the magnified heating at the end of wires [Smith et al. (2000)]. The specific absorption rate (SAR) near the lead tip can be 7000 times of the ground level, which may result in excessive temperature rise at the tissues contact with the lead [Yeung et al. (2002)].

Smith et al. (2000) measured a temperature rise of 16.8 °C above base line for a 40-cm wire with insulation. Liu et al. (2000) measured a temperature increase of 17 °C for a guidewire at 1.5. The temperature rises near the guidewires depend on the length of guidewires and exceed 30 °C in some cases [Nitz et al. (2001); Konings et al. (2000)]. Ladd et al. (1998) reported a maximum
temperature rise of 18 °C for catheters and guidewires which are used for intravascular interventions and connected to a coaxial cable in air.

It is considered contraindicated to give MRI procedure to the patients with cardioverter defibrillators and pacemakers due to the induction heating at the lead electrodes. An in vivo temperature increase of 24 °C near the tips of lead of cardiac pacemakers was measured at 0.5 T [Sommer et al. (2000)]. Achenback et al. (1997) measured a temperature rise of 63 °C at the electrode of a lead at a static magnetic flux density of 1.5 T. The leads are placed inside the phantoms for the above three cases. Luechinger (2002) measured a temperature rise of 13 °C at the electrodes of a unipolar lead. The leads are placed inside the phantoms for the above three cases. Luechinger (2002) also measured a temperature rise a temperature of 30 °C for a screw-in lead and an increase of 15 °C for a passive fixation lead in vivo in a pig. In a clinical investigation [Martin et al. (2004)], 54 patients underwent various whole-body MRI procedures at 1.5 T. There was no unfavorable event observed although 10 leads needed to be replaced. However, there was no direct measurement for the effects of MRI related heating in this study.

Some clinical reports show that a sufficiently strong RF magnetic field will cause thermal injury to the patient with a deep brain stimulation (DBS) system. A patient with a DBS system became comatose after a jaw diathermy [Nyenhuis et al. (2005)]. A patient had a thermocoagulation lesion by the electrode of a DBS system after receiving a MRI whole-body procedure at 1 T [Ruggera et al. (2003)]. Schueler et al. (1999) reported that there is no heating of several implants, including DBS systems, in a phantom filled with saline. Rezai et al. (2002) used a phantom filled with gelled materials to prevent thermal convection and measured a temperature
rise of 25 °C at the lead without loops and 6 °C for a lead positioned with two small loops. The distinct results between Schueler et al. (1999) and Rezai et al. (2002) attributed to the materials in the phantoms. Park et al. (2003) showed that the phantom with viscous materials yielded a temperature rise five times more than the saline-only phantom. Therefore, it was suggested that MRI procedures which using high levels of RF powers be avoided until safe parameters are establish based on more specific experiments.

On the other hand, metallic implants with smooth edges have less induction heating because the self-inductance and smooth edges will decrease induced currents and heating [Nyenhuis et al. (2005)].

1.3 Current Approaches to Reduce Induction Heating

There is a need to perform MRI on patients with metallic implants. Among the metallic implants, the pacemaker and DBS system have the most severe induction heating issues due to their leads. Efforts have been made to solve the induction heating issues of pacemaker and SDB during MRI procedures. There are three main approaches to reduce the induction heating: (i) changing the MRI parameters such as magnetic field strength, scanner type, type of sequence and position and posture of patients in the scanner bore [Roguin et al. (2004); Sommer et al. (2006)], (ii) modifying the field distribution to have zero field strength at the position of metallic implants [Eryaman et al. (2010) and (2011)] and (iii) design new structures for metallic implants.
Ladd et al. (2000) inserted one or two coaxial chokes with a length of quarter wavelength of RF magnetic field into the lead. The temperature rise at the lead tip with one and two coaxial chokes are 3.4 and 3.7 °C, respectively, while the temperature rise at the lead tip without coaxial chokes is 55 °C. The coaxial choke can disrupt the standing wave patterns of induced currents on leads, resulting in less induction heating on the lead tip. Vernickel et al. (2005) placed transformers along the wire, splitting the long wire into short sections. The transformers are designed to avoid the induced current and signal attenuation. Based on the simulation, the half-wavelength long wire with transformers has 85% less SAR than the half-wavelength long wire without transformers. Stevenson et al. (2007) proposed an electronic bandstop filter chip which reduces the heating due to the high impedance at the RF frequency used in MRI machines. Another design [Umathum et al. (2006)] is that the long wire is divided into several short sections by PIN diodes, reducing the temperature rise from 58 °C to 7.2 °C.

Baker et al. (2005) designed a lead management device with a DBS lead which is coiled into concentric loops of 18 mm to 23 mm in diameter. The temperature rise of the lead with concentric structure decreases by 41% to 74% due to two possible mechanisms. First, the loops themselves may form an inductor which increases the impedance of the lead, reducing the induced current in the wire and induction heating at the tip. Second, the induced voltage from the loop section of the lead may cancel parts of the induced voltage from the straight section of the lead, resulting less induced current in the lead and induction heating at the tip. Gary et al. (2005) tested two different form of coiled wire: multi-filar coiled wire (unmodified) and multi-filar coiled wire with spacing between adjacent five-filar coil loops (modified). The coiled wires acts as inductors and shift the resonance frequency of leads to Larmor frequency, resulting in high
impedance of the leads and less induction currents. The temperature rise for modified coiled wire is 26.4 °C lower (66% less) than the case for the unmodified coiled wire at the same MRI conditions.

Greatbatch et al. (2002) replaced the metallic wire of a lead with a fiber optic cable which is made of glass. The temperature rise at the tip of the fiber-optics pacing lead is 0.8 °C using a whole-body coil at an SAR of 1.5 W/kg.

1.4 Proposed Approaches to Reduce Induction Heating

Selecting proper MRI conditions to minimize induction heating is the easiest way to avoid injury. This solution may sacrifice the image quality and limit the portion of body where undergoes MIR scanning. Modifying the magnetic field distribution to reduce the induction heating can be applied to the patients with the implants which are not compatible to MRI. Modifying the magnetic field by new design of coils might not be feasible due to the image quality, scanning the vicinity of the implants and the costs to replace the existing MRI scanners. Developing MR-compatible implants that inherently minimize heating is preferred. Adding lump elements to the lead section, design the new structures for the lead and adding insulation cladding are used. The first pacemaker system which is safe for MRI is commercially available and has been examined [Sutton et al. (2008); Wilkoff et al. (2011)]. However, the patients with this pacemaker system still undergo the MRI procedure under limiting conditions: non-thoracic MRI at 1.5 T with an SAR < 2 W/kg and excluding orphan leads due to induction heating concerns.
In this study, an approach of reducing induction heating by modifying thermal properties and response to magnetic fields of materials is proposed. Diffusing species can alter the properties of materials. Increasing the magnetic reflectivity of materials can reduce the amount of magnetic field penetrating into the materials, resulting less induction current and heating. Increasing heat capacity of materials can lower temperatures of materials at a given amount of deposited energy. Improving materials properties combined with the existing design for implant devices is expected to make implant devices more MR-compatible.

1.5 Introduction to Laser Beam Shaping

Beam shaping is a technique to manipulate the dimension, shape of cross-section, irradiance and/or phase distribution of the laser beams. Uniform intensity across laser beams is desirable in many laser applications such as holography, material processing, lithography etc. where uniform irradiation is crucial. There are three common approaches to obtain a uniform intensity profile [Dickey et al. (2000)]. The first one is using an aperture to select a suitably flat portion of an expanded laser beam. The disadvantage of this technique is loss of energy so it is not suitable for the application demanding high power lasers. The second approach is beam integrating, also known as beam homogenizing. Beam integrators break the incident beam into beamlets and make the overlap on the target plane. The common integrators are fly eye lens [Dickey et al. (1988); Ozaki et al. (1989)], light pipe [Chen et al. (2007)] and diffractive integrators [Zheng et al. (2005)]. Integrator approach is suitable for laser beams with highly irregular irradiance profiles and low coherence. The third technique is field mapping. Field mappers redirect each portion of the laser beam onto the target plane. The field mappers can be diffractive optical
elements [Lee et al. (1981); Veldkamp et al. (1982); Hahn et al. (2006)], diffusers [Borek et al. (1999); Bokor et al. (2001)], refractive optical elements [Rhodes et al. (1980); Hoffnagle et al. (2003)] and reflective optical elements [McDermit et al. (1974); Malyak et al. (1992)]. If the intensity profile and phase of the laser beam is known, the field mappers are the more suitable candidates for beam shaping. Beam integrators and field mappers can be implemented with refractive/reflective optical elements based on geometrical optics or diffractive optical elements based on wave theory which considers the interference and diffraction.

A beam shaping system composed of lenses with specific surface profiles can transfer the Gaussian beam into a flat-top beam which has a uniform intensity within a certain cross-section area. Most beam shaping lenses are designed based on geometric optics or scalar diffraction theory [Dickey et al. (2000); Zhang et al. (2008); Zhang et al. (2009)]. The geometric optics approach is only valid at certain conditions while the scalar diffraction approach can be applied to most cases. One of the assumptions made in scalar diffraction theory is that all components of electric and magnetic fields obey the same scalar wave equation. The spatial gradient term is simplified to the partial derivative to one coordinate axis only such as either x or y axis in the Cartesian coordinates. Thus, the x component of the incident field contributes the x component of the field on the target plane and there is no longitudinal component i.e. z-component. In order to determine the intensity profile more accurately on the target plane, the longitudinal component should be considered and calculated based on the vector diffraction theory. In this paper, the beam shaping lenses are designed based on the vector diffraction equations in order to transform the Gaussian beam into a flat-top beam.
1.6 Motivation and Objectives

There is a need to provide MRI-safe metallic implants for patients because MRI is powerful diagnosed tools. While the magnetic properties of materials are modified to reduce induction heating, the other properties of materials should be kept the same in order to satisfy the FDA requirements for mechanical properties of implants. Laser diffusion can alter the properties of materials with minimum changes in mechanical properties of materials due to the highly localized heating and short irradiation time.

The lead wires of pacemakers and DBS system are made of MP35N alloys which chemical composition are complicated. In this research, Ti and Ta substrates are studied because they are the potential candidates for metallic implants. The experiences obtained from Ti and Ta may be the foundation for studying MP35N alloys.

In this research, the magnetic response of treated and untreated materials such as reflectivity and transmittance will be studied. The effects of laser polarizations on the diffusion of species and materials properties such as magnetic transmittance and conductivity will be examined. Electromagnetic and thermal models will be developed to calculate the temperature rise of metallic implants due to induction heating during MRI procedure. Another model will be developed based on the principles of inverse problems to determine the materials properties such as reflectivity and dielectric constant from the measured magnetic transmittance data. In order to have better control of laser diffusion, a beam shaping lens system will be designed to transform a Gaussian laser beam into a flat-top laser beam. Vector diffraction theory is used to design the
beam shaping system in order to consider the laser beam polarizations and obtain improved irradiance profile of the output flat-top beam.

In sum, an approach to reduce the induction heating of metallic implants by modifying the materials properties will be proposed. The effects of laser polarizations on the laser diffusion and material properties modification will be studied. A beam shaping lens system will be designed to improve the laser diffusion process. The magnetic transmittance of materials will be measured directly. An electromagnetic model will be developed to determine the properties of materials which cannot be measured directly using commercial readily equipment. Electromagnetic and thermal models will be developed to calculate the temperature rise due to induction heating during MRI procedure.
CHAPTER 2: ELECTROMAGNETIC AND THERMAL MODELS

2.1 Magnetic Field in Metals

The calculation of fields inside metals starts from Maxwell equations:

\[ \nabla \cdot \vec{E}(r,t) = \frac{\rho_c(r,t)}{\varepsilon} \quad (2.1) \]

\[ \nabla \times \vec{E}(r,t) = -\frac{\partial \vec{B}(r,t)}{\partial t} \quad (2.2) \]

\[ \nabla \cdot \vec{B}(r,t) = 0 \quad (2.3) \]

\[ \nabla \times \vec{B}(r,t) = \mu \vec{J}_s(r,t) + \mu \vec{J}_i(r,t) + \mu \varepsilon \frac{\partial \vec{E}(r,t)}{\partial t} \quad (2.4) \]

\[ \vec{J}_c(r,t) = \sigma \vec{E}(r,t) \quad (2.5) \]

where \( \varepsilon \) is permittivity, \( \mu \) is permeability, \( \rho_c \) is charge density, \( \vec{J}_s \) is source current density, \( \vec{E} \) is electric field strength, \( \vec{B} \) is magnetic flux density, \( \sigma \) is conductivity and \( \vec{J}_i \) is induced current density in the media. Assuming that there is no source current and charge, \( \rho_c = 0 \) and \( \vec{J}_s = 0 \), one can simplify Maxwell equations as:

\[ \nabla \cdot \vec{E}(r,t) = 0 \quad (2.6) \]

\[ \nabla \times \vec{E}(r,t) = -\frac{\partial \vec{B}(r,t)}{\partial t} \quad (2.7) \]

\[ \nabla \cdot \vec{B}(r,t) = 0 \quad (2.8) \]

\[ \nabla \times \vec{B}(r,t) = \mu \sigma \vec{E}(r,t) + \mu \varepsilon \frac{\partial \vec{E}(r,t)}{\partial t} \quad (2.9) \]

Wave equations can be obtained after the derivations:
\[ \nabla^2 \vec{E}(r,t) - \mu \varepsilon \frac{\partial^2 \vec{E}(r,t)}{\partial t^2} - \mu \sigma \frac{\partial \vec{E}(r,t)}{\partial t} = 0 \] (2.10)

\[ \nabla^2 \vec{B}(r,t) - \mu \varepsilon \frac{\partial^2 \vec{B}(r,t)}{\partial t^2} - \mu \sigma \frac{\partial \vec{B}(r,t)}{\partial t} = 0 \] (2.11)

In a good conductor, \( \mu \sigma \gg \mu \varepsilon \), so the wave equations become

\[ \nabla^2 \vec{E}(r,t) - \mu \sigma \frac{\partial \vec{E}(r,t)}{\partial t} = 0 \] (2.12)

\[ \nabla^2 \vec{B}(r,t) - \mu \sigma \frac{\partial \vec{B}(r,t)}{\partial t} = 0 \] (2.13)

and Eq (2.9) becomes

\[ \nabla \times \vec{B}(r,t) = \mu \sigma \vec{E}(r,t) \] (2.14)

For simplicity, assuming the incident magnetic field has \( z \) component only and propagates in \( x \) direction as shown in Fig. 2.1.

\[ B_{in}(x,t) = B_{00} \sin \left( \omega t - \frac{\omega}{c} x \right) \hat{z} \] (2.15)
where $B_{in0}$ is the amplitude of incident magnetic flux density, $\omega$ is its angular frequency of the magnetic field (equals to $2 \times \pi \times 63.86$ MHz), and $c$ is the speed of light. From Eq. (2.9), we can solve for the magnetic flux density inside the metal:

$$B_m(x,t) = B_{m0} \exp\left(-\frac{x}{\delta}\right) \sin\left(\omega t - \frac{x}{\delta}\right) \hat{z}$$

(2.16)

where $\mu_m$ is the permeability of the metal, and $\delta$ is the skin depth:

$$\delta = \sqrt{\frac{2}{\omega \mu_m \sigma}}$$

(2.17)

Substituting Eq. (2.16) into Eq. (2.14), one can have the electric field inside the metal:

$$E_m(x,t) = \sqrt{\frac{\omega}{\mu_m \sigma}} B_{m0} \exp\left(-\frac{x}{\delta}\right) \sin\left(\omega t - \frac{x}{\delta} + \frac{\pi}{4}\right) \hat{y}$$

(2.18)

One can determine the Drude conductivity $\sigma(\omega)$ based on the Drude model [Fox (2001)]:

$$\sigma(\omega) = \frac{N_0 e^2}{m_e} \frac{1}{\nu_0 + i \cdot \omega}$$

(2.19)

where $N_0$ is the free electron density, $e$ is the charge of the electron, $m_e$ is the electron mass and $\nu_0$ is the scattering frequency. The microstructure of solids affects the scattering of electrons [Palmer et al. (1989)]. The atoms arrange orderly in a grain, resulting less electron scattering. Grain boundary is the region between any two grains. Atoms arrange randomly in grain boundary, resulting more electron scattering. Considering the effect of grain size $L_g$, grain boundary width $w_g$ and the different scattering frequency at the edge and center of grains, Palmer et al. (1989) expressed Drude conductivity as:

$$\sigma(\omega) = \frac{N_0 e^2}{m_e} \frac{1}{\nu_0 + \nu_0 \frac{w_g}{L_g} + i \cdot \omega}$$

(2.20)
where $v_0$ and $v_0'$ the scattering frequency at the center and edge of grains, respectively. One can rewrite Eq. (2.20) in terms of dc conductivity $\sigma_0$:

$$\sigma(\omega) = \frac{\sigma_0}{1 + \frac{v' w_g}{v_0 L_g} + i \frac{\omega}{v_0}}$$  \hspace{1cm} (2.21)$$

where

$$\sigma_0 = \frac{N_0 e^2}{m_e v_0}$$  \hspace{1cm} (2.22)$$

$\omega/v_0$ is around $10^{-6} < 1$, so Eq. (2.22) can be written as:

$$\sigma(\omega) \approx \frac{\sigma_0}{1 + \frac{v' w_g}{v_0 L_g}}$$  \hspace{1cm} (2.23)$$

The instantaneous pointing vector is expressed as:

$$\bar{S}(x, t) = \frac{1}{\mu} \bar{E} \times \bar{B}$$  \hspace{1cm} (2.24)$$

The irradiance is equal to the time average of the instantaneous pointing vector over one period $T_B$:

$$I_m(x) = S_{avg}(x) = \frac{1}{T_B} \int_0^{T_B} \left| \bar{S}(x, t) \right| dt$$  \hspace{1cm} (2.25)$$

We can have the instantaneous transmitted pointing vector inside the metal:

$$\tilde{S}_m(x, t) = \frac{\omega B_{m0}^2}{2\sigma \mu_m^{3/2}} \exp\left( -\frac{2x}{\delta} \right) \left[ \sin^2\left( \omega t - \frac{x}{\delta} \right) + \sin\left( \omega t - \frac{x}{\delta} \right) \cos\left( \omega t - \frac{x}{\delta} \right) \right]$$  \hspace{1cm} (2.26)$$

and the irradiance of the transmitted magnetic field in metals:
\[ I_m(x) = \frac{1}{2\sqrt{2}} \sqrt{\frac{\omega}{\sigma}} \frac{B_{m0}^2}{\mu_m^{3/2}} \exp\left(-\frac{2x}{\delta}\right) \]  

(2.27)

The irradiance of the incident field at the surface of the metal is

\[ I_{in}(0) = Z_0 \left( \frac{B_{rms}}{\mu_0} \right)^2 = \frac{1}{2} \sqrt{\frac{1}{\varepsilon_0}} \frac{B_0^2}{\mu_0^{3/2}} \]  

(2.28)

where \( Z_0 \) is the impedance of free space and \( B_{rms} \) is the root mean square of magnetic flux density.

The irradiance of the transmitted field at the surface is

\[ I_m(0) = \frac{1}{2\sqrt{2}} \sqrt{\frac{\omega}{\sigma}} \frac{B_{m0}^2}{\mu_m^{3/2}} \]  

(2.29)

The irradiance of the reflected field would be

\[ I_r(0) = I_{in}(0) - I_m(0) = \frac{1}{2} \left( \sqrt{\frac{1}{\varepsilon_0}} \frac{B_0^2}{\mu_0^{3/2}} - \frac{1}{\sqrt{2}} \sqrt{\frac{\omega}{\sigma}} \frac{B_{m0}^2}{\mu_m^{3/2}} \right) \]  

(2.30)

Therefore, the reflectivity is

\[ R = \frac{I_r(0)}{I_{in}(0)} = 1 - \frac{1}{\sqrt{2}} \sqrt{\frac{\omega\varepsilon_0}{\sigma}} \left( \frac{\mu_0}{\mu_m} \right)^3 \left( \frac{B_{m0}}{B_0} \right)^2 \]  

(2.31)

2.2 Temperature Distribution in Metals

The material is chosen based on the temperature change \( \Delta T \) which is equal to final temperature, \( T_{final} \), minus initial temperature, \( T_{initial} \),

\[ \Delta T = T_{final} - T_{initial} \]  

(2.32)

Assume all the transmitted energy is absorbed by the metal, so the energy deposited in the metal per second is \( q \):
\[ q = A \cdot I_m(0) \]  
\[ (2.33) \]

where \( A \) is the cross-sectional area of metal. Assuming that all the deposited energy becomes the thermal energy, one can have

\[ q = mC_p \frac{\Delta T}{\Delta t} = A\delta_i \rho_mC_p \frac{\Delta T}{\Delta t} \]  
\[ (2.34) \]

where \( C_p \) is the specific heat of metals, \( \rho_m \) is the mass density of metals and \( \delta_i \) is the depth where the irradiance inside the metal decreases to zero. Therefore, the temperature change of metals after a time of \( \Delta t_d \) can be written as:

\[ \Delta T = \frac{I_m(0)}{\delta_i \rho_mC_p} \Delta t_d \]  
\[ (2.35) \]

Eq. (2.36) is the temperature change due to one pulse. MRI uses RF pulses, so we need to consider the pulse repetition rate \( p_f \). The temperature change would be

\[ \Delta T = \frac{I_m(0)}{\delta_i \rho_mC_p} \Delta t_d \times p_f \]  
\[ (2.36) \]

2.3 Calculated Results and Discussion

In an MRI scanner, the incident RF magnetic field has a flux density of 14 µT. The incident magnetic field flux density is shown as Fig. 2.2 based on Eq. (2.14).
Silver, gold, copper, platinum, titanium and tantalum are selected for preliminary calculation.

Their electronic properties are listed in Table 2.1.
The electronic properties of six selected metals are given in Table 2.1. The table includes the free electron density \(N_0\) (m\(^{-3}\)), scattering frequency \(v_0\) (Hz), DC conductivity \(\sigma_0\) (\(\Omega^{-1}\)m\(^{-1}\)), and permeability \(\mu_m\) (H/m). The transmitted magnetic flux density varies with time and depth. We examine the case of maximum transmitted magnetic flux density which happens at the time equal to one quarter oscillation period of magnetic field. Fig. 2.3 shows the magnetic flux density inside the selected materials.

![Table 2.1 Electronic properties of six selected metals](image)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Free electron density (N_0) (m(^{-3}))</th>
<th>Scattering frequency (v_0) (Hz)</th>
<th>DC conductivity (\sigma_0) ((\Omega^{-1})m(^{-1}))</th>
<th>Permeability (\mu_m) (H/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>2.27(\times)10(^{29})</td>
<td>2.5(\times)10(^{15})</td>
<td>2.56(\times)10(^{6})</td>
<td>1.25686(\times)10(^{-6})</td>
</tr>
<tr>
<td>Ta</td>
<td>2.76(\times)10(^{29})</td>
<td>9.5(\times)10(^{14})</td>
<td>8.20(\times)10(^{6})</td>
<td>1.25686(\times)10(^{-6})</td>
</tr>
<tr>
<td>Cu</td>
<td>8.47(\times)10(^{28})</td>
<td>3.7(\times)10(^{13})</td>
<td>6.49(\times)10(^{7})</td>
<td>1.25663(\times)10(^{-6})</td>
</tr>
<tr>
<td>Au</td>
<td>5.90(\times)10(^{28})</td>
<td>3.3(\times)10(^{13})</td>
<td>4.87(\times)10(^{7})</td>
<td>1.25659(\times)10(^{-6})</td>
</tr>
<tr>
<td>Pt</td>
<td>6.61(\times)10(^{28})</td>
<td>7.1(\times)10(^{14})</td>
<td>5.26(\times)10(^{6})</td>
<td>1.25697(\times)10(^{-6})</td>
</tr>
<tr>
<td>Ag</td>
<td>5.86(\times)10(^{28})</td>
<td>2.5(\times)10(^{13})</td>
<td>6.80(\times)10(^{7})</td>
<td>1.25662(\times)10(^{-6})</td>
</tr>
</tbody>
</table>

The value of \(N_0\) and \(v_0\) are determined by [Ashcroft et al. (1976)]

\[
N_0 = 6.022 \times 10^{23} \frac{Z_e \rho_m}{m_A}
\]  

\[
r_s = \left( \frac{3}{4\pi N_o} \right)^{\frac{1}{3}}
\]

\[
\nu_0 = \left[ 0.22 \sigma_0 \left( \frac{r_s}{a_0} \right)^{3 \gamma -1} \right]^{-1}
\]

where \(Z_e\) is the number of free electrons per atom, \(m_A\) is atomic mass, and \(r_s\) is the radius of free electron sphere.
metals at $t = T_B/4$ where $T_B$ is the oscillation period of the magnetic field. Ag, Au and Cu have higher conductivity, resulting in shorter skin depth.

The reflectivity and irradiance in the metals are plotted in Fig. 2.4 and Fig. 2.5, respectively. Ag, Au and Cu have higher reflectivity and lower irradiance due to their higher conductivity.
Figure 2.4 Reflectivity of selected metals

$\frac{w}{L} = 0.001$

$\nu'/\nu_0 = 5$

Figure 2.5 Transmitted irradiance inside the metals

$\frac{w}{L} = 0.001$

$\nu'/\nu_0 = 5$
Consider the effects of microstructure on the transmitted irradiance on the surface of metals, $I_m(0)$, which is equal to the amount of energy entering the metals. First, there is a need to examine how the grain size $L_g$ and grain boundary width $w_g$ affect $I_m(0)$ as shown in Fig. 2.6. The grain boundary width is assumed around 1 nm. Small $w_g/L_g$ ratio implies large grain size. When grain size is larger than 100nm, $I_m(0)$ remains almost the same as the grain size increases. The case that $w_g/L_g$ is equal to 1 can be seen as amorphous case. Therefore, less energy is deposited into ordinary metals than amorphous metals. The deposited energy in Ti at different scattering frequency is shown in Fig 2.7. Less energy is deposited in Ti when the scattering frequency at the grain edge is smaller. Less scattering in Ti results in higher conductivity and more magnetic field is reflected.

![Figure 2.6](image)

**Figure 2.6** Energy deposited in metals at different ratios of grain boundary width to grain size
The temperature rise due to induction heating from time-varying magnetic fields is calculated using Eq. (2.37). The mass density, thermal properties and zero filed depth of the selected metals are listed in Table 2.2. The pulse repetition rate of RF magnetic fields is assumed to 50 Hz. The temperature of metals at different MRI procedure time is plotted in Fig. 2.8. The temperature increases as the MRI procedure time increases because more energy is deposited. The temperature in metals depends not only the amount of deposited energy but also the product of mass density and specific heat. Copper has lowest temperature due to its second least deposited energy and larger product of mass density and specific heat. Platinum has second lowest temperature due to its larger product of mass density and specific heat even though more energy is deposited in platinum than in gold and silver. Copper is inappropriate for implant devices due
to its toxicity. Platinum is selected as the added element due to its bio-compatibility and lower temperature at the MRI procedure.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Mass density (kg/m³)</th>
<th>Specific heat (J/kg·K)</th>
<th>Thermal conductivity (W/m·K)</th>
<th>Zero irradiance depth (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>4500</td>
<td>522</td>
<td>199.7</td>
<td>21.9</td>
</tr>
<tr>
<td>Ta</td>
<td>16600</td>
<td>140</td>
<td>105.1</td>
<td>57.5</td>
</tr>
<tr>
<td>Cu</td>
<td>8933</td>
<td>385</td>
<td>33.4</td>
<td>401</td>
</tr>
<tr>
<td>Au</td>
<td>19300</td>
<td>129</td>
<td>38.4</td>
<td>317</td>
</tr>
<tr>
<td>Ag</td>
<td>10500</td>
<td>235</td>
<td>33.0</td>
<td>429</td>
</tr>
<tr>
<td>Pt</td>
<td>21450</td>
<td>133</td>
<td>93.24</td>
<td>71.6</td>
</tr>
</tbody>
</table>
2.4 Conclusion

The electromagnetic and thermal models are developed to determine the distribution of magnetic flux density and temperature in metals. Theoretical results for magnetic flux density and temperature in the metals during the MRI procedure are calculated for 6 selected metals based on the models. The more conductive metals such as Ag, Cu and Au reflect more magnetic flux, resulting less deposited energy and shorter zero irradiance depth. The temperature in metals depends on two factors: (i) the amount of deposited energy and (ii) mass density and specific heat. The temperature of Cu and Pt is lower than the other four metals due to the larger values of mass density and specific heat. Pt is chosen as the added element for this study due to its biocompatibility.
CHAPTER 3: ELECTROMAGNETIC AND THERMAL MODEL FOR RF MAGNETIC PULSES

3.1 Responses of Metals to Pulsed Incident Magnetic Field

It is assumed in this study that the metal is a linear, homogeneous and isotropic medium and the permittivity \( \varepsilon_m \) and permeability \( \mu_m \) of the metal are constant. Maxwell’s equations for electromagnetic fields in the source-free, linear, homogeneous and isotropic region are described as follows:

\[
\nabla \cdot E_1 = 0 \quad (3.1)
\]

\[
\nabla \times E_1 = -\frac{\partial B_1}{\partial t_1} \quad (3.2)
\]

\[
\nabla \cdot B_1 = 0 \quad (3.3)
\]

\[
\nabla \times H_1 = J_{c1} + \varepsilon_m \frac{\partial E_1}{\partial t_1} \quad (3.4)
\]

where \( E_1 \) is the electric field strength, \( B_1 \) is the magnetic flux density, \( H_1 \) is the magnetic field strength and \( J_{c1} \) is the conduction current density. The constitutive relation is \( B_1 = \mu_m H_1 \). There is another relation of \( J_{c1} = \sigma E_1 \) between \( J_{c1} \) and \( E_1 \). \( \sigma \) is the conductivity of the metal. For metals, the conduction current density \( J_{c1} \) is much larger than the displacement current density \( \varepsilon_m \frac{\partial E_1}{\partial t_1} \). Therefore, the displacement current term in Eq. (3.4) can be neglected, and Eq. (3.4) can be simplified as

\[
\nabla \times H_1 = J_{c1} \quad (3.5)
\]

Applying the curl operation on both sides of Eq. (3.5) and using Eq. (3.2), a differential equation for \( H_1 \) is obtained.
\[ \nabla^2 H_1 = \mu_m \sigma \frac{\partial H_1}{\partial t_i} \]  \hspace{1cm} (3.6)

This is a partial differential equation similar to a diffusion equation. In this study, the simple situation is considered: the incident magnetic field has the z-component only, the electric field has the y-component only and the magnetic field propagates in the x-direction as shown in Fig. 3.1. Then Eq. (3.6) can be simplified as:

\[ \frac{\partial^2 H_1(x_1, t_1)}{\partial x_1^2} = \mu_m \sigma \frac{\partial H_1(x_1, t_1)}{\partial t_i} \]  \hspace{1cm} (3.7)

Figure 3.1 An illustration of the metal-air interface and the magnetic field considered in the electromagnetic model.

Eq. (3.7) is the governing equation of the magnetic field strength inside the metal. Here, consider the metal with an infinite thickness and define \( \mu_o \) as the permeability of air, \( \varepsilon_o \) as the permittivity of air, \( r_f \) as the reflection coefficient of metal, \( Z_m \) as the impedance of the metal, \( p_f \) as the pulse repetition rate, \( N \) as the total number of pulses during the MRI procedure, \( c \) as speed of light in air, \( 1/\Delta \nu_i \) as the temporal width of the RF pulse, \( \omega_i \) as the carrier frequency of RF pulse and \( H_{inc} \) as the magnitude of incident magnetic field strength. The boundary condition at \( x_1 = 0 \) is determined based on the fact that the tangential component of the magnetic fields at both sides of
the interface should be continuous. At \( x_f = \infty \), the magnetic field should attenuate to zero due to the large absorption from the metal. The boundary conditions for Eq. (3.7) can be described as follows:

\[
H_i(x_1, t_1) = (1 - r_r) H_{inc} \sin(\Delta \omega t_1) \cos(\omega t_1) \text{ at } x_f = 0 \quad (3.8a)
\]

\[
H_i(x_1, t_1) = 0 \text{ at } x_f = \infty \quad (3.8b)
\]

Eq. (3.8a) can be written as:

\[
H_i(x_1, t_1) = (1 - r_r) H_{inc} \frac{\sin(\Delta \omega t_1)}{\Delta \omega t_1} \cos(\omega t_1) \quad (3.9)
\]

The product of the two trigonometric functions can be written as the integral of the cosine function:

\[
H_i(x_1, t_1) = (1 - r_r) H_{inc} \frac{1}{2 \cdot \Delta \omega t_1} \int_{\omega_f - \Delta \omega}^{\omega_f + \Delta \omega} \cos(\omega t_1) d\omega \quad (3.10)
\]

A cosine function is equal to the real part of an exponential function so Eq. (3.10) can be written as:

\[
H_i(x_1, t_1) = \frac{(1 - r_r) H_{inc}}{2 \Delta \omega t_1} \Re \int_{\omega_f - \Delta \omega}^{\omega_f + \Delta \omega} \exp(j \omega t_1) d\omega \text{ at } x_f = 0 \quad (3.11)
\]

Therefore, the boundary conditions can be expressed as:

\[
H_i(x_1, t_1) = \frac{(1 - r_r) H_{inc}}{2 \Delta \omega t_1} \Re \int_{\omega_f - \Delta \omega}^{\omega_f + \Delta \omega} \exp(j \omega t_1) d\omega \quad (3.12a)
\]

\[
H_i(x_1, t_1) = 0 \text{ at } x_f = \infty \quad (3.12b)
\]

The reflection coefficient \( r_r \) can be determined using [Cheng (1996)]

\[
r_r = \frac{Z_m - Z_0}{Z_m + Z_0} \quad (3.13)
\]
\[ Z_m = \sqrt{j \omega \mu \sigma / \omega} \] and \( Z_0 \) is the impedance of the air.

The initial condition is
\[ H_i(x_1, t_1) = 0 \text{ at } t_1 = 0 \] (3.14)

Consider a solution of the form
\[ H_i(x_1, t_1) = H_{inc} \int_{\Delta \omega_1}^{\Delta \omega_1 + \omega_1} \exp\left[j(\omega t_1 - \beta x_1)\right] d\omega \] (3.15)

where \( \beta \) is the complex wave number and determined by:
\[ \beta^2 = -j \omega \mu \sigma \] (3.16)

Then the magnetic field strength inside the metal can be written as:
\[ H_i(x_1, t_1) = (1 - r_i)H_{inc} \exp\left(-\frac{x_1}{\delta_1}\right) \exp\left(-j \frac{x_1}{\delta_1}\right) \sin(\Delta \omega_1 t_1) \cos(\omega_1 t_1) \] (3.17)

where \( \delta_1 \) is the skin depth and defined as \( \delta_1 = \sqrt{2 / \omega_1 \mu \sigma} \).

Rewrite Eq. (3.5) in the simple one dimension case, one can have the following relation between \( E_i \) and \( H_i \)
\[ E_i(x_1, t_1) = -\frac{1}{\sigma} \frac{\partial H_i(x_1, t_1)}{\partial x_1} \] (3.18)

Therefore, the electric field strength inside the metal is expressed as:
\[ E_i(x_1, t_1) = \frac{(1 - r_i)}{\sigma} H_{inc} \sin(\Delta \omega_1 t_1) \cos(\omega_1 t_1) \beta^* \exp\left(-\frac{x_1}{\delta_1}\right) \exp\left(-j \frac{x_1}{\delta_1}\right) \] (3.19)

where \( \beta^* \) is the complex conjugate of \( \beta \). The time-average pointing vector in one cycle, \( T_B = 1 / \omega_1 \), can be described as:
\[ \overline{S}_1(x_1, t_1) = \frac{1}{T_B} \text{Re} \int_0^{T_B} E_i \times H_i^* \, dt \] (3.20)
Therefore, the Poynting vector is described as:

\[
\mathbf{S}_1(x_1, t_1) = \text{Re} \left( \frac{(1 - r_r)^2}{T_b \sigma} H_{inc}^2 \exp \left( -\frac{2x_1}{\delta_1} \right) \beta^* \sin^2(\Delta \omega_1 t_1) \right) \int_0^T \cos^2(\omega_1 t_1) dt_1
\]  

(3.21)

Since \( \Delta \omega_1 \ll \omega_1 \), the \( \sin^2(\Delta \omega_1 t_1) \) term varies slowly and can be seen constant in one cycle, \( T = 1/\omega_1 \), and can be taken out from the integral. Then

\[
\mathbf{S}_1(x_1, t_1) = \frac{1 - |r_r|^2}{2\sigma\delta_1} H_{inc}^2 \exp \left( -\frac{2x_1}{\delta_1} \right) \sin^2(\Delta \omega_1 t_1)
\]

(3.22)

Using the relations \( B_{inc} = \mu_o H_{inc} \) and \( R = |r_r|^2 \), Eq. (3.18) can be written as:

\[
\mathbf{S}_1(x_1, t_1) = \frac{c(1 - R)}{2\sigma\delta_1 \mu_o} B_{inc}^2 \exp \left( -\frac{2x_1}{\delta_1} \right) \sin^2(\Delta \omega_1 t_1)
\]

(3.23)

Eq. (3.23) represents the amount of energy deposited on the metal implants per unit area from RF pulses, and the energy deposited is the source of RF heating in the metal. Both the magnetic field strength and Poynting vector decrease exponentially inside the metal due to the absorption of the metal.

### 3.2 Temperature Rise Due to Pulsed Incident Magnetic Field

To determine the temperature distribution due to the incident RF magnetic pulses, a thermal model which considers the heat conduction and convection is required. The assumption made here is that the optical and thermo-physical properties of the metal are constant and that heat conduction happens in x direction only. Based on energy conservation that the rate of heat entering a control volume \( V \) plus the rate of energy generated in \( V \) is equal to the rate of storage of energy in \( V \), the governing equation can be expressed as:
\[ k_{th} \frac{\partial^2 T_i(x_1, t_1)}{\partial x_1^2} + g(x_1, t_1) = \rho_m \cdot C_p \frac{\partial T_i(x_1, t_1)}{\partial t_1} \]  

(3.24)

where \( \rho_m \), \( k_{th} \) and \( C_p \) are the mass density, thermal conductivity and specific heat of the metal implant respectively. \( T_i(x_1, t_1) \) is the temperature distribution function and \( g(x_1, t_1) \) is the rate of energy generation in \( V \) which is equal to \(-\frac{\partial S_i(x_1, t_1)}{\partial x_1}\), so one can have the relation:

\[ g(x_1, t_1) = -\frac{\partial S_i(x_1, t_1)}{\partial x_1} \]  

(3.25)

Then Eq. (3.24) becomes

\[ k_{th} \frac{\partial^2 T_i(x_1, t_1)}{\partial x_1^2} = -\frac{\partial S_i(x_1, t_1)}{\partial x_1} + \rho_m \cdot C_p \frac{\partial T_i(x_1, t_1)}{\partial t_1} \]  

(3.26)

Consider that heat dissipates by convection from the boundary surface into the surroundings and that this heat transfer is proportion to temperature difference, and then the boundary conditions for both interfaces can be written as:

\[ k_{th} \frac{\partial T_i(x_1, t_1)}{\partial x_1} = h[T_i(x_1, t_1) - T_\infty] \text{ at } x_1 = 0 \]  

(3.27a)

\[ k_{th} \frac{\partial T_i(x_1, t_1)}{\partial x_1} = -h[T_i(x_1, t_1) - T_\infty] \text{ at } x_1 = d \]  

(3.27b)

where \( d \) is the thickness of metals, \( h \) is the heat transfer coefficient at the interface between the metal and its surroundings. In this case, assuming that the initial temperature of the metal \( T_i \) is the same as the temperature far from the metal \( T_\infty \), the initial condition is

\[ T_i(x_1, t_1) = T_i = T_\infty \text{ at } t_1 = 0 \]  

(3.28)
Define the following dimensionless variables: \( x = x_i / d \), \( t = \alpha \cdot t_i / d^2 \), \( \Delta \omega = d^2 \Delta \omega_i / \alpha \), \( p_f = d^2 p_{f_i} / \alpha \), and \( \delta = \delta_i / d \), where \( \alpha = k_n / (\rho_n \cdot C_n) \) is the thermal diffusivity. Then, the temperature distribution and heat source term can be written as:

\[
T(x,t) = \frac{T_i(x_i,t_i) - T_{\infty}}{T_{\infty}}
\]

(3.29)

\[
\frac{\partial \vec{S}(x,t)}{\partial x} = \frac{d^2}{k_n T_{\infty}} \frac{\partial \vec{S}_i(x_i,t_i)}{\partial x_i}
\]

(3.30)

Therefore, the original governing equation, boundary conditions and initial condition become

\[
\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{\partial \vec{S}(x,t)}{\partial x} + \frac{\partial T(x,t)}{\partial t}
\]

(3.31)

\[
\frac{\partial T(x,t)}{\partial x} = B_i \cdot T(x,t) \text{ at } x = 0
\]

(3.32a)

\[
\frac{\partial T(x,t)}{\partial x} = -B_i \cdot T(x,t) \text{ at } x = 1
\]

(3.32b)

\[
T(x,t) = 0 \text{ at } t = 0
\]

(3.33c)

where \( B_i \) is the Biot number which is defined as \( B_i = h_d / k_n \). The solution of Eq. (3.31) can be obtained using integral transform method. The eigenfunction is

\[
\psi_m(x) = \lambda_m \cos(\lambda_m x) + B_i \cdot \sin(\lambda_m x)
\]

(3.34)

The eigenvalue \( \lambda_m \) is the root of the following equation:

\[
\tan(\lambda_m) = \frac{2 \cdot B_i \cdot \lambda_m}{\lambda_m^2 - B_i^2}
\]

(3.35)

Eq. (3.30) can be written as the product the three terms

\[
\frac{\partial \vec{S}(x,t)}{\partial x} = S_o F(x) G(t)
\]

(3.36)
where these three terms are defined as:

\[
S_n = -\frac{c(1-R)H_{inc}^2}{\mu_0 \delta_1} \frac{d^2}{k_\beta T(x)}
\]  

(3.37)

\[
F(x) = \exp\left(-\frac{2x}{\delta}\right)
\]  

(3.38)

\[
G(t) = \text{sinc}^2\left[\Delta_\theta \left(t - \frac{n}{p_f}\right)\right]
\]  

(3.39)

Substitute Eq. (3.36) into Eq. (3.31), one can have

\[
\frac{\partial^2 T(x,t)}{\partial x^2} = S_n F(x)G(t) + \frac{\partial T(x,t)}{\partial t}
\]  

(3.40)

Both sides of Eq. (3.40) are multiplied by the eigenfunction Eq. (3.34) and integrated with respect to \(x\) from zero to one and then one can have

\[
\frac{\partial T(x,t)}{\partial x} \bigg|_{x=1} - \frac{\partial T(x,t)}{\partial x} \bigg|_{x=0} = \psi_n(0) - \psi_n(1) + \frac{\partial \psi_n}{\partial n} T(1,t) + \frac{\partial \psi_n}{\partial n} T(0,t) - \lambda_n^2 \int_0^1 T(x,t) \psi_n(x) dx
\]

\[
= S_n F_n G(t) + \frac{\partial}{\partial t} \int_0^1 T(x,t) \psi_n(x) dx
\]  

(3.41)

where

\[
F_n = \int_0^1 F(x) \psi_n(x) dx
\]

\[
= \frac{\lambda_n \delta^2}{4 + \lambda_n^2 \delta^2} \left\{ \frac{2d}{\delta} + \exp\left(-\frac{2}{\delta}\right) \left[ \lambda_n \sin(\lambda_n) - \frac{2}{\delta} \cos(\lambda_n) \right] \right\}
\]

\[
+ \frac{B \cdot \delta^2}{4 + \lambda_n^2 \delta^2} \left\{ \lambda_n - \exp\left(-\frac{2}{\delta}\right) \left[ \frac{2}{\delta} \sin(\lambda_n) + \lambda_n \cos(\lambda_n) \right] \right\}
\]

(3.42)
Apply the boundary conditions on the first four terms at the left hand side of Eq. (3.41) and define $\bar{T}_n(t)$ as:

$$
\bar{T}_n(t) = \int_0^1 T(x,t) \psi_n(x) dx
$$

(3.43)

Then, Eq. (3.43) can be reduced as:

$$
\bar{T}_n(t) = -S_o \int_0^1 G(\tau) \exp \left[-\lambda_n^2 (t - \tau)\right] d\tau
$$

(3.44)

By the inversion formula, one can have

$$
T(x,t) = \sum_{m=1}^{\infty} \frac{\psi_m(x)}{N_m} \bar{T}_n(t)
$$

(3.45)

where

$$
N_m = \int_0^1 \psi_n^2(x) dx = B_i + \frac{B_i^2 + \lambda_m^2}{2}
$$

(3.46)

Substitute Eq. (3.44) into Eq. (3.45), and the dimensionless temperature distribution is

$$
T(x,t) = -S_o \sum_{m=1}^{\infty} \frac{\psi_m(x)}{N_m} \bar{T}_n(t) \int_0^1 G(\tau) \exp \left[-\lambda_n^2 (t - \tau)\right] d\tau
$$

(3.47)

The integral in Eq. (3.47) is evaluated using extended Trapezoidal rule. Finally, the temperature distribution $T_i(x_i,t_i)$ is obtained by

$$
T_i(x_i,t_i) = T_\infty + T(x,t) \cdot T_\infty
$$

(3.48)

The amount of temperature rise is expressed as

$$
\Delta T_i(x_i,t_i) = T_i(x_i,t_i) - T_\infty = T(x,t) \cdot T_\infty
$$

(3.49)

Given the incident magnetic field intensity $H_{inc}$ and the properties of the metal and surrounding media, the $H_i(x_i,t_i)$ and $S_i(x_i,t_i)$ can be calculated from Eq. (3.17), and Eq. (3.21). Then, temperature distribution and temperature rise can be obtained from Eq. (3.48) and Eq. (3.49).
3.3 Calculated Results and Discussion

In this study, the metal plate made of Ti is considered. Its electrical conductivity is $2.39 \times 10^6 \, \Omega^{-1} \, \text{m}^{-1}$, specific heat is $522 \, \text{J/m} \cdot \text{K}$, thermal conductivity is $21.9 \, \text{W/m} \cdot \text{K}$, mass density is $4500 \, \text{kg/m}^3$, permeability is $1.2589 \times 10^{-6} \, \text{H/m}$. The thickness of Ti plate is 100, 150 and 250 µm. The skin depth of Ti plate in this case is 39.5 µm, so the infinite thickness assumption is still suitable. The reflectivity and the heat transfer coefficient depend on the surrounding of the Ti plate. Consider various environments, the reflectivity ranging from 0.8 to 0.9999 and the heat transfer coefficient ranging from 0.01 to 100 W/m$^2 \cdot \text{K}$ are used in the calculation. During the MRI procedure, the peak flux density of RF magnetic pulse is 14 µT. The pulse repetition rate depends on the pulse sequence which affects the image quality. It is assumed that all the pulses have the same peak flux density. Pulse repetition rate varying from 50 to 300 Hz is used to understand its effect on temperature rise.

First, the transient response of the temperature rise at the surface of the metal plate is calculated and shown in Fig. 3.2. The reflectivity is 0.95, thickness of Ti plate is 250 µm, pulse repetition rate is 175 Hz and heat transfer coefficient is 100 W/m$^2 \cdot \text{K}$. At the beginning, the temperature varies as the RF pulse incidents. The temperature rises as the magnitude of the RF pulse increases. The maximum temperature rise happens when the peak of RF pulse arrives at the metal plate. Then the temperature decreases until the next RF pulse comes. The temperature does not go back to the initial temperature $T_i$, so the peak and valley of the temperature become higher after the second pulse arrives. Therefore, the temperature increases more as the following pulses come. However, the temperature jump due to one single pulse decreases. The temperature
reaches the steady-state value after thirty seconds. At the steady state, the temperature still fluctuates as the RF pulses come and the difference between the peak and valley of the temperature remains constant. Therefore, the mean temperature in one pulse repetition time remains the same at the steady state. In this case, the steady state temperature rise is 0.398 K.

![Graph of temperature rise over time](image)

Figure 3.2 Transient response of the temperature rise at the surface of the Ti plate. Thickness of Ti plate = 250 µm. Time duration of MRI = 30 seconds. Pulse repetition rate = 175 Hz. Reflectivity = 0.95. Convection coefficients = 100 W/m²K

The temperature rise versus the depth for different heat transfer coefficients $h$ is also calculated. Thickness of Ti plate is 250 µm, reflectivity is 0.95, pulse repetition rate is 175 Hz and the time duration is 60 seconds. Larger value of heat transfer coefficient means more heat energy dissipates from metal plate into the surrounding and thus temperature rise is smaller due to less energy is stored in the metal plate. Fig. 3.3 shows the temperature rise at different depths inside the Ti plate. The temperature rise is almost the same at different depths due to the high thermal
conductivity and thinness of Ti plate. The heat energy can distribute to all the Ti plate quickly. The small Biot number which is equal to $1.14 \times 10^{-5}$ also implies that the temperature gradient along the depth is small. Based on Fig. 3.3, the convection affects the temperature significantly. For example, in the steady air, $h = 1 \text{ W/m}^2\cdot\text{K}$, the temperature rise is 6.15 K. The temperature is only 0.77 K at $h = 50 \text{ W/m}^2\cdot\text{K}$ which corresponds to the environment with air blowing to the metal.

Figure 3.3 Temperature rise inside the Ti plate for different convection coefficients. Thickness of Ti plate = 250 µm. Time duration of MRI = 60 seconds. Pulse repetition rate = 175 Hz. Reflectivity = 0.95

As the reflectivity decreases, the temperature rise should increase due to more energy deposited into the Ti plate. The temperature rise versus the depth at various values of reflectivity is shown in Fig. 3.4. The parameters used are that thickness of Ti plate is 250 µm, reflectivity is 0.95, pulse repetition rate is 175 Hz, the time duration is 60 seconds and the heat transfer coefficient is
1 W/m²·K which implies a steady air. The temperature rise is proportion to the amount of energy deposited, so the temperature rise for reflectivity of 0.8 is almost twice as the one for reflectivity of 0.9. The case of reflectivity equal to 0.9998 corresponds to the Ti plate in the steady air. The temperature rise of Ti plate in the steady air is 0.03 K. If there is some air flow, the temperature rise will be smaller, so the temperature rise of Ti plate in the air is not easy to detect by touching it.

The effects of the pulse repetition rate and thickness of Ti plate are studied as well. The temperature rise versus reflectivity at different pulse repetition rate and thickness of Ti plate are plotted in Fig. 3.5, 3.6, 3.7 and 3.8. The pulse repetition rate is 50 Hz for Fig. 3.5, 175 Hz for Fig. 3.6, 200 Hz for Fig. 3.7 and 300 Hz for Fig. 3.8. The thickness of sample is 100, 150 and 250 µm.

Figure 3.4 Temperature rise inside the Ti plate for different reflectivity. Thickness of Ti plate = 250 µm. Time duration of MRI = 60 seconds. Pulse repetition rate = 175 Hz. Convection coefficient = 1 W/m²K
respectively. The values of reflectivity are 0.8, 0.9, 0.95, 0.99, 0.999 and 0.9999. The heat transfer coefficient is 10 \text{ W/m}^2\text{-K}, and time duration of MRI procedure is 60 seconds. The temperature rise is higher for thinner Ti plate because the thinner plate has less heating volume as the amount of energy deposited remains the same. The experimental results from Smith et al. (1998) showed a similar trend. In their experiments, the magnet wire with a diameter of 2 mm had lower temperature rise than the magnet wire with a diameter of 1.6 mm. The thicker Ti plate or wire is preferred when the temperature rise is a concern of safety.

![Graph showing temperature rise versus reflectivity for different thickness of Ti plate.](image)

Figure 3.5 Temperature rise versus the reflectivity for different thickness of the Ti plate. Time duration of MRI = 60 seconds. Pulse repetition rate = 50 Hz. Convection coefficient = 10 \text{ W/m}^2\text{K}
Figure 3.6 Temperature rise versus the reflectivity for different thickness of the Ti plate. Time duration of MRI = 60 seconds. Pulse repetition rate = 175 Hz. Convection coefficient = 10 W/m$^2$K

Figure 3.7 Temperature rise versus the reflectivity for different thickness of the Ti plate. Time duration of MRI = 60 seconds. Pulse repetition rate = 200 Hz. Convection coefficient = 10 W/m$^2$K
Figure 3.8 Temperature rise versus the reflectivity for different thickness of the Ti plate. Time duration of MRI = 60 seconds. Pulse repetition rate = 300 Hz. Convection coefficient = 10 W/m²K

From Fig. 3.5, 3.6, 3.7 and 3.8, it is clear that the case $p_f = 300$ Hz has higher temperature rise than other pulse repetition rates when other parameters are the same. For reflectivity of 0.95 and thickness of 250 µm, the temperature rise at $p_f = 300$ Hz is 5.80 K while it is only 0.99 K at $p_f = 50$ Hz. Higher pulse repetition rate causes higher temperature because more energy is deposited in the same time duration. Besides, higher pulse repetition rate means shorter temporal separation between the pluses, so the time for dissipating heat is shorter. Therefore, the energy in the metal is accumulated more at higher pulse repetition rate, resulting higher temperature in metals.
3.4 Conclusion

An electromagnetic model which considers the shape of RF magnetic pulses and the interaction of RF pulses with metals is developed. From this model, the analytic solutions for magnetic field and Poynting vector inside the metal are derived. The magnetic field and the amount of deposited energy in the metal are calculated. In addition, a thermal model considering the thermal conduction inside the metal is developed as well. This thermal model can be used to calculate the temperature distribution in the metal. Based on these two models, the transient temperature variation of Ti responding to the incident RF pulses is studied. The temporarily maximum temperature happens when the peak of RF pulse incidents on the Ti plate. The effects of the heat transfer coefficient, reflectivity, thickness of Ti plates and pulse repetition rate on temperature variation are discussed as well. Smaller heat transfer coefficient causes higher temperature due to less energy dissipation through the surface of Ti plate. Lower reflectivity results in higher temperature due to more energy deposited into the Ti plate. Higher pulse repetition rate causes higher temperature because more energy deposited and shorter time for cooling between pulses. The thicker metal has less temperature rise due to larger heating volume, which agrees with the experimental data from the literature [Smith et al. (1998)]. Based on the models, lower pulse repetition rate offers less heating of metallic plate during the MRI procedure. Increasing the reflectivity of the metal is a potential way to reduce RF induction heating.
CHAPTER 4: ELECTRICAL CONDUCTIVITY AND DIELECTRIC CONSTANT OF METALS AT 63.86 MHZ MAGNETIC FIELD

4.1 Introduction to Measurement of Electromagnetic Properties of Materials

The properties of material at different frequencies of electromagnetic waves are widely used in numerous applications such as imaging, remote sensing and communication. Similarly, just the electric field [Takuma et al. (2010)] or the magnetic field [Massopust et al. (2006)] are useful in many applications. Several instruments, such as spectrum analyzers and network analyzers, are routinely used to measure the electrical and electromagnetic properties of materials for high frequency electromagnetic waves. In the lower range of radiowaves (kHz to several MHz), plenty of data are available for metals because of the importance of such waves in radio-communication and electromagnetic compatibility [Kaiser et al. (2005)]. To determine the material properties in this radiowave range, the electromagnetic waves, which are generally generated using an antenna in free space or a network analyzer, interact with the material of interest and are transmitted through cables to a spectrum analyzer. In the intermediate frequency range (e.g., 30, 100 MHz), however, there is a need for reliable instruments to measure the electromagnetic response of materials to magnetic fields of high flux densities (e.g., 10-100 μT). This type of energy-material interactions would be useful in non-destructive testing of defects (e.g., cracks and corrosion spots) inside the material, and it will provide a non-intrusive approach to evaluate materials in various applications such as microelectronics, nanoelectronics and biomedical devices.
The electromagnetic properties of metals at 63.86 MHz magnetic field is of technological interest because it corresponds to the Larmor frequency in Magneto-Resonance Imaging (MRI) with 1.5 T static magnetic flux density, and metallic implants are increasingly used in modern medical treatment. In MRI systems, the electric field is suppressed to influence the precession of hydrogen atoms in human tissues by the magnetic field only. Therefore, in addition to the biocompatibility of metallic implants, the interaction between the implant and the energy of the time-varying magnetic field requires attention to account for the potential induction heating ([Shellock (2000)]) of the implants during the MRI process [Shellock et al. (1996); Henderson et al.(2005)].

Numerous studies have been carried out to determine the properties of metals at the optical, THz and microwave frequencies [Johnson et al. (1974); Laman et al. (2008)], and various experimental techniques have been used to determine the optical constants and electronic properties of metals [Hass et al. (1964); Heavens (1965)]. Most of the techniques involved irradiating electromagnetic waves on a sample and measuring the reflectance, phase change on reflection from the sample surface, transmittance or phase change on transmission through the sample. The reflection and absorption properties of Ti sheets are discussed in this study for just the magnetic field based on the near-field effect on impedance. Other properties such as the complex refractive index, relative permittivity and conductivity are determined by the method of inverse problem using transmittance data. To examine the effect of impurity on these properties, Pt was incorporated into some of the samples in trace amounts by a laser diffusion technique. The inverse problem is developed using the solution of Maxwell’s equation with consideration to the near-field impedance.
4.2 Transmission of Metal Sheets for Magnetic Fields

A three-medium system is considered to model the propagation of the magnetic field through the sample as shown in Fig. 4.1. The test samples, which are Ti sheets in this study, are represented by Medium 2, and media 1 and 3 are air in front of and behind the sample, respectively. These three media are considered non-magnetic and homogeneous. The magnetic field, which is generated by a signal generator shown as a current loop in Fig. 4.1, is assumed to propagate in the z direction as a function of distance z and time t and its polarization is in the x-y plane. The front and back surfaces of the sample are \( d_1 \) and \( d_2 \) distant from the current loop, respectively. The incident magnetic field is partially reflected at both the air-sample interfaces and absorbed inside the sample. There are forward and backward propagating fields in media 1 and 2 due to reflection, and there is only a forward propagating field in medium 3. \( H_{in}(z, t) \) and \( H_r(z, t) \) are the incident \( (H_{1+}(z, t)) \) and reflected \( (H_{1-}(z, t)) \) magnetic field strengths in medium 1, respectively, while \( (H_{2+}(z, t)) \) and \( (H_{2-}(z, t)) \) denote the forward and backward moving magnetic field strengths in the sample, respectively. \( (H_{3+}(z, t)) \) is the forward moving magnetic field strength in medium 3 where the backward moving magnetic field strength, \( H_{3-}(z, t) = 0 \).
Figure 4.1 A three-layer system for the interaction between the magnetic field and sample.

Denoting these forward and backward moving fields by $\mathbf{H}_j(z, t) = \mathbf{H}_{j+}(z, t) + \mathbf{H}_{j-}(z, t)$ for $j = 1, 2, 3$, the Maxwell equation can be written as

$$\frac{\partial^2 \mathbf{H}_j(z,t)}{\partial z^2} = \mu_j \sigma_j \frac{\partial \mathbf{H}_j(z,t)}{\partial t} + \mu_j \varepsilon_j \frac{\partial^2 \mathbf{H}_j(z,t)}{\partial t^2} \quad (4.1)$$

where $\mu_j$, $\sigma_j$ and $\varepsilon_j$ are the permeability, electrical conductivity and permittivity of $j$-th medium, respectively. The electric field, which is produced due to magnetic induction by the time-varying magnetic field, can be written as $\mathbf{E}_j(z, t) = \mathbf{E}_{j+}(z, t) + \mathbf{E}_{j-}(z, t)$ where $\mathbf{E}_{j+}(z, t)$ and $\mathbf{E}_{j-}(z, t)$ are the forward and backward moving electric fields, respectively, in $j$-th medium. $\mathbf{E}_j(z, t)$ is related to the magnetic field by the following expression:

$$\frac{\partial \mathbf{H}_j(z,t)}{\partial z} = -\sigma_j \mathbf{E}_j(z,t) - \varepsilon_j \frac{\partial \mathbf{E}_j(z,t)}{\partial t} \quad (4.2)$$

where the second term on the right hand side of Eq. (4.2) represents the displacement current $\frac{\partial \mathbf{D}_j(z,t)}{\partial t}$ with the electric displacement $\mathbf{D}_j(z, t) = \varepsilon_j \mathbf{E}_j(z, t)$. Now the boundary conditions for Eq. (4.1) can be written as
assuming that the magnetic and electric fields are parallel to the air-sample interfaces.

Expressing \( \mathbf{H}_j(z,t) \), \( \mathbf{E}_j(z,t) \) and \( \mathbf{E}_{in}(z,t) \) as sinusoidal functions of \( t \), i.e.,

\[
\mathbf{H}_j(z,t) = \mathbf{H}_j(z) \exp(-i\omega t) \tag{4.4a}
\]
\[
\mathbf{E}_j(z,t) = \mathbf{E}_j(z) \exp(-i\omega t) \tag{4.4b}
\]
\[
\mathbf{H}_{in}(z,t) = \mathbf{H}_{in}(z) \exp(-i\omega t) \tag{4.4c}
\]

where \( \omega \) is the frequency of the magnetic field. Eqs. (4.1) and (4.2), and boundary conditions (4.3a-f) can be simplified using Eqs. (4.4a-c). Consequently, boundary conditions (4.3d,e) can be expressed in terms of the magnetic field using Eq. (4.2). Also Eq. (4.1) becomes a second order ordinary differential equation for \( H_j(z) \) with a complex wave vector given by

\[
\hat{k}_j = \frac{\omega}{c} \sqrt{\frac{\mu_{rj}}{\epsilon_{0}} \left( \epsilon_{rj} + i \frac{\sigma_{j}}{\omega \epsilon_{0}} \right)}
\]

where \( c \) is the speed of light in vacuum, \( \mu_{rj} \) and \( \epsilon_{rj} \) are the relative permeability and relative permittivity, respectively, and \( \epsilon_{0} \) is the permittivity of free space. Since \( \mu_{rj} = 1 \) for non-magnetic materials, the complex refractive index is expressed as

\[
\hat{n}_j = \sqrt{\hat{\epsilon}_{rj}} = \sqrt{\frac{\epsilon_{rj} + i \frac{\sigma_{j}}{\omega \epsilon_{0}}}{\epsilon_{0}}} \equiv n_j + i\kappa_j \tag{4.5}
\]

where \( \hat{\epsilon}_{rj} \) is the complex dielectric constant, and \( n_j \) and \( \kappa_j \) are the refraction and absorption indices, respectively, of \( j \)-th medium. In the case of metals and long wavelengths, the imaginary
part in the radical of Eq. (4.5) is much larger than the real part \(\varepsilon_{ij}\) and, therefore, the real part is usually neglected. \(\varepsilon_{ij}\) is kept in this study to investigate any effect that it might have on the values of \(n_j\) and \(\kappa_j\).

Solving Eq. (4.1) and satisfying the boundary conditions, the overall transmission coefficient of the metal sample (medium 2), \(t(d)\), can be expressed as follows [Heavens (1965)] in terms of its interfacial transmission and reflection coefficients, where \(d\) is the thickness of the sample given by \(d = d_2 - d_1\).

\[
t(d) = \frac{H_{11}(d_2)}{H_{in}(d_1)} = \frac{t_{12}t_{23}\exp(ik_2d)}{1 - r_{12}r_{23}\exp(i2k_2d)}
\]

(4.6)

Here \(t_{12}\) and \(t_{23}\) are the transmission coefficients for the magnetic fields entering from medium 1 to medium 2 and from medium 2 to medium 3, respectively. Similarly, \(r_{12}\) and \(r_{23}\) are the reflection coefficients for the magnetic fields reflected back to medium 1 from the interface of media 1 and 2, and to medium 2 from the interface of media 2 and 3, respectively. Although the absorption of the field is very high in metals, multiple internal reflections need to be considered for thin metal sheets, especially when its thickness is less than the skin depth. In fact, the metal samples are chosen to be very thin to allow sufficient transmission of the field so that the field strength exceeds the noise level of the field-measuring sensor. This criterion defines the sample thickness depending on the strength of the field generator and the sensitivity of the sensor to accurately measure the field for determining the electromagnetic properties of metals at various frequencies.
Based on the solutions of Eq. (4.1) for the magnetic fields, \( H_j(z), j = 1, 2, 3 \), and the boundary conditions, the interfacial transmission and reflection coefficients can be expressed as:

\[
\begin{align*}
 t_{lm} &= \frac{2Z_l}{Z_l + Z_m} \quad \text{for } l, m = 1, 2, 3 \\
 r_{lm} &= \frac{Z_l - Z_m}{Z_l + Z_m} \quad \text{for } l, m = 1, 2, 3
\end{align*}
\]  
(4.7)

where \( Z_j(z) \) is given by the following expression [Kaiser (2005)] as a function of \( z \):

\[
Z_j(z) = -\frac{1}{\varepsilon_0 c n_j} \left[ -\frac{i}{k_j z} \frac{1}{(\hat{k}_j z)^2} + \frac{i}{k_j z} \frac{1}{(\hat{k}_j z)^2} \right]
\]  
(4.9)

Eq. (4.9) is used to consider the near-field impedance in this study because the wavelength in air corresponding to the frequency 63.86 MHz is \( \lambda_a = 4.7 \) m and the metal sample is placed at 1.5 mm distant from the field generator (current loop in Fig. 4.1), which conforms to the near-field criterion \( |\hat{k}_1| z \ll 1 \). Now the transmittance of the metal sample, \( T(d) \), can be written as:

\[
T(d) = t(d) t^*(d)
\]  
(4.10)

where \( t^*(d) \) is the complex conjugate of \( t(d) \). Substituting Eqs. (4.6-4.9) into Eq. (4.10), the resulting expression for transmittance is

\[
T(d) = \frac{16n_a n_m (u^2 + v^2)}{p_1(d)^2 + q_1(d)^2}
\]  
(4.11)

where \( u, v, p_1(d) \) and \( q_1(d) \) are defined by the following expressions in terms of \( F_1(d), F_2(d), G_1(d), G_2(d), x_a(z), y_a(z), x_m(z) \) and \( y_m(z) \):

\[
u = n_2 \left[ x_a(d_1) x_m(d_1) - y_a(d_1) y_m(d_1) \right] - \kappa_2 \left[ x_a(d_1) y_m(d_1) + x_m(d_1) y_a(d_1) \right]
\]  
(4.12a)
\[ v = \kappa_2 \left[ x_a(d_1) x_m(d_1) - y_a(d_1) y_m(d_1) \right] + n_2 \left[ x_a(d_1) y_m(d_1) + x_m(d_1) y_a(d_1) \right] \] (4.12b)

\[ p_1(d) = \exp \left( \frac{\omega c}{c} \kappa_2 d \right) \left[ F_1(d) \cos \left( \frac{\omega c}{c} n_2 d \right) + F_2(d) \sin \left( \frac{\omega c}{c} n_2 d \right) \right] \]

\[ + \exp \left( - \frac{\omega c}{c} \kappa_2 d \right) \left[ G_1(d) \cos \left( \frac{\omega c}{c} n_2 d \right) - G_2(d) \sin \left( \frac{\omega c}{c} n_2 d \right) \right] \] (4.12c)

\[ q_1(d) = \exp \left( \frac{\omega c}{c} \kappa_2 d \right) \left[ F_2(d) \cos \left( \frac{\omega c}{c} n_2 d \right) - F_1(d) \sin \left( \frac{\omega c}{c} n_2 d \right) \right] \]

\[ + \exp \left( - \frac{\omega c}{c} \kappa_2 d \right) \left[ G_2(d) \cos \left( \frac{\omega c}{c} n_2 d \right) + G_1(d) \sin \left( \frac{\omega c}{c} n_2 d \right) \right] \] (4.12d)

\[ F_1(d) = \left[ x_a(d_1) n_2 - y_a(d_1) \kappa_2 + x_m(d_1) n_1 \right] \left[ x_a(d_2) n_3 + x_m(d_2) \kappa_2 + y_a(d_2) \kappa_2 \right] \]

\[ - \left[ x_a(d_1) \kappa_2 + y_a(d_1) n_2 + y_m(d_1) n_1 \right] \left[ y_m(d_2) n_3 + x_m(d_2) \kappa_2 + y_m(d_2) n_3 \right] \] (4.12e)

\[ F_2(d) = \left[ x_a(d_1) n_2 - y_a(d_1) \kappa_2 + x_m(d_1) n_1 \right] \left[ y_m(d_2) n_3 + x_m(d_2) \kappa_2 + y_a(d_2) \kappa_2 \right] \]

\[ + \left[ x_a(d_1) \kappa_2 + y_a(d_1) n_2 + y_m(d_1) n_1 \right] \left[ y_m(d_2) n_3 + x_m(d_2) \kappa_2 + y_a(d_2) \kappa_2 \right] \] (4.12f)

\[ G_1(d) = \left[ x_a(d_1) n_2 - y_a(d_1) \kappa_2 - x_m(d_1) n_1 \right] \left[ x_a(d_2) n_3 - x_m(d_2) \kappa_2 + y_a(d_2) \kappa_2 \right] \]

\[ - \left[ x_a(d_1) \kappa_2 + y_a(d_1) n_2 - y_m(d_1) n_1 \right] \left[ y_m(d_2) n_3 - x_m(d_2) \kappa_2 - y_a(d_2) \kappa_2 \right] \] (4.12g)

\[ G_2(d) = \left[ x_a(d_1) n_2 - y_a(d_1) \kappa_2 - x_m(d_1) n_1 \right] \left[ y_m(d_2) n_3 - x_m(d_2) \kappa_2 - y_a(d_2) \kappa_2 \right] \]

\[ + \left[ x_a(d_1) \kappa_2 + y_a(d_1) n_2 - y_m(d_1) n_1 \right] \left[ x_m(d_2) n_3 - x_m(d_2) \kappa_2 + y_m(d_2) \kappa_2 \right] \] (4.12h)

\[ x_a(z) = \frac{\left( \frac{\omega c}{z} \right)^4}{1 - \left( \frac{\omega c}{z} \right)^4 + \left( \frac{\omega c}{z} \right)^2} \] (4.12i)

\[ y_a(z) = \frac{-\left( \frac{\omega c}{z} \right)^4}{1 - \left( \frac{\omega c}{z} \right)^4 + \left( \frac{\omega c}{z} \right)^2} \] (4.12j)
\[
x_n(z) = \frac{\omega(n_2 + \kappa_2)z - \left(\frac{\omega}{c}\right)^2(n_2^2 - 2n_2\kappa_2 - \kappa_2^2)z^2 + \left[\frac{\omega}{c}\kappa_2z - \left(\frac{\omega}{c}\right)(n_2^2 - \kappa_2^2)z^2\right]^2}{\left[\frac{\omega}{c}n_2z + 2\left(\frac{\omega}{c}\right)n_2\kappa_2z^2\right]^2 + \left[1 + \frac{\omega}{c}\kappa_2z - \left(\frac{\omega}{c}\right)(n_2^2 - \kappa_2^2)z^2\right]^2}
\]

\[
y_n(z) = \frac{-\left[\frac{\omega}{c}n_2z + 2\left(\frac{\omega}{c}\right)n_2\kappa_2z^2\right]}{\left[\frac{\omega}{c}n_2z + 2\left(\frac{\omega}{c}\right)n_2\kappa_2z^2\right]^2 + \left[1 + \frac{\omega}{c}\kappa_2z - \left(\frac{\omega}{c}\right)(n_2^2 - \kappa_2^2)z^2\right]^2}
\]

Eq. (4.11) shows that the transmittance depends on the sample thickness and the optical constants \(n_2\) and \(\kappa_2\) nonlinearly. Therefore, the transmittances need to be determined for metal sheets of at least two different thicknesses using the measured data for the incident and transmitted magnetic field strengths, \(\bar{H}_{in}(d_1)\) and \(\bar{H}_{3+}(d_2)\), respectively. The experimental values of transmittance are given by \(\bar{T}(d) = \left[\bar{H}_{3+}(d_2)/\bar{H}_{in}(d_1)\right]^2\), which can be substituted into Eq. (4.11) to calculate \(n_2\) and \(\kappa_2\) by solving nonlinear algebraic equations. Knowing \(n_2\) and \(\kappa_2\), other electromagnetic properties such as the relative permittivity \(\varepsilon_{r_2}\), electrical conductivity \(\sigma_2\), absorption coefficient \(\alpha\) and reflectivity \(R\) can be determined from the following expressions:

\[
\varepsilon_{r_2} = n_2^2 - \kappa_2^2
\]

\[
\sigma_2 = 2\omega\epsilon_0n_2\kappa_2
\]

\[
\alpha = \frac{2\omega}{c}\kappa_2
\]

\[
R = \frac{(x_n n_2 - y_n \kappa_2 - n_1 x_{21})^2 + (x_n \kappa_2 + y_n n_2 - n_1 y_{21})^2}{(x_n n_2 - y_n \kappa_2 + n_1 x_{21})^2 + (x_n \kappa_2 + y_n n_2 + n_1 y_{21})^2}
\]

Both reflectivity and reflectance are defined as the ratio of the reflected intensity to the incident intensity. Reflectivity is independent of the thickness of metal sheets. However, the magnitude of the reflected magnetic field varies with the thickness of metal sheets due to multiple internal
reflections in thin metal sheets. Thus, reflectance $R(d)$ is used for thin metal sheets and defined as:

$$R(d) = \frac{p_2(d)^2 + q_2(d)^2}{p_1(d)^2 + q_1(d)^2} \quad \text{(4.14)}$$

where $p_2(d)$ and $q_2(d)$ are defined by the following expressions in terms of $F_3(d)$, $F_4(d)$, $G_3(d)$, $G_4(d)$:

$$p_2(d) = \exp\left(\frac{\omega}{c} \kappa_2 d \right) \left[ F_3(d) \cos\left(\frac{\omega}{c} n_2 d\right) + F_4(d) \sin\left(\frac{\omega}{c} n_2 d\right) \right]$$

$$q_2(d) = \exp\left(\frac{\omega}{c} \kappa_2 d \right) \left[ F_3(d) \cos\left(\frac{\omega}{c} n_2 d\right) - F_4(d) \sin\left(\frac{\omega}{c} n_2 d\right) \right] \quad \text{(4.15a)}$$

$$p_4(d) = \exp\left(\frac{\omega}{c} \kappa_2 d \right) \left[ G_3(d) \cos\left(\frac{\omega}{c} n_2 d\right) + G_4(d) \sin\left(\frac{\omega}{c} n_2 d\right) \right]$$

$$q_4(d) = \exp\left(\frac{\omega}{c} \kappa_2 d \right) \left[ G_3(d) \cos\left(\frac{\omega}{c} n_2 d\right) - G_4(d) \sin\left(\frac{\omega}{c} n_2 d\right) \right] \quad \text{(4.15b)}$$

$$F_3(d) = [x_u(d_1)n_2 - y_u(d_1)\kappa_2 - x_m(d_1)n_1][x_m(d_2)n_3 + x_u(d_2)n_2 - y_u(d_2)\kappa_2]$$

$$- [x_u(d_1)\kappa_2 + y_u(d_1)n_2 - y_m(d_1)n_1][y_m(d_2)n_3 + x_u(d_2)\kappa_2 + y_u(d_2)n_2] \quad \text{(4.15c)}$$

$$F_4(d) = [x_u(d_1)n_2 - y_u(d_1)\kappa_2 - x_m(d_1)n_1][y_m(d_2)n_3 + x_u(d_2)\kappa_2 + y_u(d_2)n_2]$$

$$+ [x_u(d_1)\kappa_2 + y_u(d_1)n_2 - y_m(d_1)n_1][x_m(d_2)n_3 - x_u(d_2)n_2 - y_u(d_2)\kappa_2] \quad \text{(4.15d)}$$

$$G_3(d) = [x_u(d_1)n_2 - y_u(d_1)\kappa_2 + x_m(d_1)n_1][x_m(d_2)n_3 - x_u(d_2)n_2 + y_u(d_2)\kappa_2]$$

$$- [x_u(d_1)\kappa_2 + y_u(d_1)n_2 + y_m(d_1)n_1][y_m(d_2)n_3 - x_u(d_2)\kappa_2 - y_u(d_2)n_2] \quad \text{(4.15e)}$$

$$G_4(d) = [x_u(d_1)n_2 - y_u(d_1)\kappa_2 + x_m(d_1)n_1][y_m(d_2)n_3 - x_u(d_2)\kappa_2 - y_u(d_2)n_2]$$

$$+ [x_u(d_1)\kappa_2 + y_u(d_1)n_2 + y_m(d_1)n_1][x_m(d_2)n_3 - x_u(d_2)n_2 + y_u(d_2)\kappa_2] \quad \text{(4.15f)}$$

When the thickness of Ti sheet becomes larger, the value of reflectance approaches the value of reflectivity.
4.3 Laser Platinum Diffusion Experiment

Thin sheets of Ti and were used as the metal sample in this study. Each sample was a square sheet of side 20 mm and thickness either 25 or 50 μm. Separate diffusion experiment was carried out by placing each sheet in a laser diffusion chamber as shown in Fig. 4.2. To diffuse Pt into the sheets, Pt(acac)$_2$ [platinum(II) acetylacetonate, Pt(C$_5$H$_7$O$_2$)$_2$] was used as the precursor, which was dissolved in acetylacetone [CH$_3$CHCH$_2$CHCH$_3$] and then the solution was heated in a bubbler at 130°C until it evaporated. A carrier gas, argon, transport the gaseous Pt(acac)$_2$ to the diffusion chamber to achieve a total pressure of 15 psi inside the chamber. A Nd:YAG pulsed laser of wavelength 1064 nm, power 3 W, scanning speed 8 mm/s for 25 μm thick sheet and 4 mm/s for 50 μm thick sheet, and beam diameter 764 μm on the surface of the sheet was used as the localized heating source. Pt atoms are produced due to thermal decomposition of the precursor molecules at the laser-heated surface and the atoms subsequently diffuse into the sheets. After creating a laser-diffused track by a single pass of the laser over the sheet, the sheet was shifted in the transverse direction to create another track and this process was continued to irradiate the entire surface of the sheet. These platinized samples as well as untreated (as-received) samples were used for transmission measurements to determine their electromagnetic properties.
4.4 Measurement of Transmitted Magnetic Fields

Each sample was placed between two HP 11940A probes, one of which acts as a magnetic field source and the other as a magnetic field sensor as shown in Fig. 4.3. The sample size of length and width 20 mm each was too small to prevent the magnetic field from circumventing around the sample and, therefore, the size was inadequate in enabling the sensor to receive only the transmitted magnetic field. A sample holder was constructed with two copper plates of thickness 1.5 mm, length 100 mm and width 70 mm each to block the permeation of the magnetic field toward the sensor. It had a square window of side 15 mm around its center to allow the magnetic field to pass through the sample holder. The sample was placed between the two copper plates at this window. Therefore, the magnetic field generated by the source can propagate through the window to incident on the sample and the transmitted magnetic field can be detected by the sensor behind the sample as shown in Fig. 4.3. The source and sensor were placed at the same
horizontal level and the sample holder was fixed perpendicular to an optical table to achieve normal incidence of the magnetic field on the sample. A magnetic field of strength 13.0 mA/m at 63.86 MHz was obtained by connecting the source probe to a signal generator that produces AC signal at this frequency. The sensor probe was connected to a spectrum analyzer to measure the amplitude of the transmitted magnetic field. In the absence of any sample in the window, the sensor probe allows measuring the amplitude of the incident magnetic field.

Figure 4.3 Apparatus for transmittance measurement.

4.5 Results and Discussion

The model is validated by considering the results presented by Joensen et al. (1973). They conducted an experiment to determine the refraction and absorption indices of gold at the optical frequency of 474 THz corresponding to the wavelength, 632.8 nm, of a helium-neon laser. Their samples were gold films of different thicknesses deposited on glass substrates for which they measured the powers of both the incident and transmitted laser beams and reported the refraction and absorption indices of gold as 0.2±0.1 and 3.71±0.25, respectively. Applying their transmittance data to Eq. (4.11), the values of \( n_2 \) and \( \kappa_2 \) were calculated as 0.29 and 3.60,
respectively, which compare well with the reported values. Due to rounding error while solving the nonlinear Eq. (4.11) to determine $n_2$ and $\kappa_2$ for a given value of transmittance, a different value of transmittance is obtained when the calculated values of $n_2$ and $\kappa_2$ are substituted back into Eq. (4.11). To verify computational accuracy, the transmittance data for different gold film thicknesses [Joensen et al. (1973)] are applied to Eq. (4.11) and a set of values are calculated for $n_2$ and $\kappa_2$. These calculated values are substituted back into Eq. (4.11) to determine the transmittance. The calculated and experimental transmittances are plotted as optical density, which is given by $-\log(T(d))$, for different film thicknesses in Fig. 4.4, indicating good agreement between the experimental and calculated results.

![Figure 4.4 The calculated and experimental optical densities based on the results presented by Joensen et al. (1973).](image)

For Ti sheets in this study, the sensor probe in the apparatus in Fig. 4.3 generates induced voltage corresponding to the incident and transmitted magnetic field strengths and this response ($H'$) is
measured in units of dBμV. The spectrum analyser provides a scaling factor of $10^{(H' + 48.5)/20}$ to convert the field strength from the measured unit to the unit of μA/m for $H_{tn}$ and $H_{3+}$. These data are used to determine the experimental transmittance ($\tilde{T}$) of different samples as listed in Table I. The refraction and absorption indices are determined by solving the nonlinear Eq. (4.11) using a method of error minimization. In this approach, different values of $n_2$ are chosen arbitrarily and $\kappa_2$ is taken as $\kappa_2 = n_2 + \Delta \kappa$ where $\Delta \kappa$ is generally very small since $n_2 \approx \kappa_2$ for metals. The values of $n_2$ and $\kappa_2$ are substituted into Eq. (4.11) to calculate the transmittance $T$ and the error between the calculated and experimental transmittances is defined as $T_{err} = |(T - \tilde{T})/\tilde{T}|$. These errors are plotted as a function of $n_2$ in Figs. 4.5, which shows that the error is almost zero for two sets of $(n_2, \kappa_2)$, one for samples of thickness 25 μm and the other for 50 μm. Since $n_2$ and $\kappa_2$ are independent of the sample thickness, the values of $n_2$ and the errors at the points of intersection of the curves for the sample thicknesses 25 and 50 μm are considered and then only one value of $n_2$ is selected corresponding to the least error. Based on this selection, $\kappa_2$ is obtained from the parametric value of the error curve.
Table 4.1 Values of the induced voltage, transmitted magnetic field strength and transmittance for as-received and platinized Ti sheets based on measurement.

<table>
<thead>
<tr>
<th>Sample</th>
<th>As-received</th>
<th>Platinized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of Ti sheets $d$ (µm)</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Induced voltage (dBµV)</td>
<td>5.85</td>
<td>1.35</td>
</tr>
<tr>
<td>Incident magnetic field strength $\overline{H}_{in}$ (mA/m)</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Transmitted magnetic field strength $\overline{H}_{3+}$ (µA/m)</td>
<td>521.8</td>
<td>310.8</td>
</tr>
<tr>
<td>Transmittance ($%$), $\overline{T}=100\times(\overline{H}<em>{3+}/\overline{H}</em>{in})^2$</td>
<td>0.161</td>
<td>0.057</td>
</tr>
</tbody>
</table>
Figure 4.5 The error between the calculated and experimental transmittances plotted as the function of $n_2$ in the case of $\kappa_2 = n_2 + 0.5$ and $\kappa_2 = n_2 + 1$. 
The effect of $n_2$ and $\kappa_2$ on the transmittance error, $T_{\text{err}}$, is listed in Table 4.2 and the electrical conductivity, $\sigma_2$, relative permittivity, $\varepsilon_{r2}$, and reflectivity, $R$, are determined using Eqs. (4.13a,b,d). This table shows that the error and reflectivity do not vary when $n_2$ and $\kappa_2$ differ by a small amount. The error decreases from 13% to 10.2% when $n_2$ and $\kappa_2$ differ by a fairly large amount. $\varepsilon_{r2}$ is generally much smaller than $\sigma_2$ for metals, which does not occur when $|n_2 - \kappa_2| \geq 3$ as shown in Table 4.2. In this study, the values of $n_2$ and $\kappa_2$ are taken as 17994 and 17995, and 18819 and 18820 for the as-received and platinized Ti sheets, respectively, as listed in Table 4.3. Other material properties, which are determined using Eqs. (4.13a-d), and the transmittance errors are also listed in Table 4.3.

Table 4.2 Effect of $n_2$ and $\kappa_2$ on the error in transmittance and the values of conductivity and relative permittivity of a platinized sample.

<table>
<thead>
<tr>
<th>$(n_2, \kappa_2)$</th>
<th>$T_{\text{err}}$ (%)</th>
<th>$T_{\text{err}}$ (%)</th>
<th>$\sigma_2$ ($\Omega^{-1}\text{m}^{-1}$)</th>
<th>$\varepsilon_{r2}$</th>
<th>$R$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d = 25 \mu m$</td>
<td>$d = 50 \mu m$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(18819,18818)</td>
<td>13.0</td>
<td>13.0</td>
<td>$2.51 \times 10^6$</td>
<td>$3.8 \times 10^4$</td>
<td>94.84</td>
</tr>
<tr>
<td>(18819,18819)</td>
<td>13.0</td>
<td>13.0</td>
<td>$2.51 \times 10^6$</td>
<td>0</td>
<td>94.84</td>
</tr>
<tr>
<td>(18819,18820)</td>
<td>13.0</td>
<td>13.0</td>
<td>$2.51 \times 10^6$</td>
<td>-$3.8 \times 10^4$</td>
<td>94.84</td>
</tr>
<tr>
<td>(18819,18821)</td>
<td>13.0</td>
<td>13.0</td>
<td>$2.51 \times 10^6$</td>
<td>-$7.5 \times 10^4$</td>
<td>94.84</td>
</tr>
<tr>
<td>(18819,18822)</td>
<td>13.0</td>
<td>13.0</td>
<td>$2.51 \times 10^6$</td>
<td>-$1.1 \times 10^5$</td>
<td>94.84</td>
</tr>
<tr>
<td>(18819,20019)</td>
<td>10.2</td>
<td>15.9</td>
<td>$2.70 \times 10^6$</td>
<td>-$4.7 \times 10^7$</td>
<td>94.85</td>
</tr>
</tbody>
</table>
Table 4.3 Calculated properties of as-received and platinized Ti.

<table>
<thead>
<tr>
<th>Sample</th>
<th>As-received</th>
<th>Platinized</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$ (µm)</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>$n_2$</td>
<td>17994</td>
<td>17994</td>
</tr>
<tr>
<td>$\kappa_2$</td>
<td>17995</td>
<td>17995</td>
</tr>
<tr>
<td>$\sigma_2$ (m$^{-1}$Ω$^{-1}$)</td>
<td>2.30×10$^6$</td>
<td>2.30×10$^6$</td>
</tr>
<tr>
<td>$\varepsilon_{r2}$</td>
<td>-3.60×10$^4$</td>
<td>-3.60×10$^4$</td>
</tr>
<tr>
<td>$\alpha$ (mm$^{-1}$)</td>
<td>24.1</td>
<td>24.1</td>
</tr>
<tr>
<td>$R$ (%)</td>
<td>94.61</td>
<td>94.61</td>
</tr>
<tr>
<td>$R(d)$ (%)</td>
<td>97.61</td>
<td>95.83</td>
</tr>
<tr>
<td>$T(d)$ (%)</td>
<td>0.199</td>
<td>0.043</td>
</tr>
<tr>
<td>$T_{err}$ (%)</td>
<td>23.7</td>
<td>23.7</td>
</tr>
</tbody>
</table>

The reflectivity of the platinized sample is 94.84% while it is 94.61% for the as-received sample. This increase in the reflectivity is due to the increased conductivity from 2.30×10$^6$ m$^{-1}$Ω$^{-1}$ of the as-received sample to 2.51×10$^6$ m$^{-1}$Ω$^{-1}$ of the platinized sample. The conductivity of the platinized sample increases by 9.1% when compared to that of the as-received sample since Pt has higher conductivity than Ti. For the 50 µm thick as-received Ti sheet, the reflectance and transmittance are 95.83% and 0.043%, respectively, indicating that the absorbance is 4.12% since the incident magnetic energy is equal to the sum of the reflected, absorbed and transmitted...
magnetic energies by the conservation of energy. For the 50 µm thick platinized Ti sheet, on the other hand, the absorbance is 4.08%. Therefore, the platinized Ti sheet absorbs less magnetic energy and the reduction in the absorbance is 0.9% when compared to that of the as-received sample.

Table 4.2 shows that the relative permittivity of the platinized sample is negative for certain values of \( n_2 \) and \( \kappa_2 \), especially when \( \kappa_2 > n_2 \) as indicated by Eq. (4.13a). This effect occurs depending on the direct current (DC) conductivity, \( \sigma_0 \), and the electron relaxation time, \( \tau_e \), in metals as can be seen from the expression of the relative permittivity given by Drude’s model [Ashcroft et al. (1967)], i.e.,

\[
\varepsilon_{r2} = 1 - \sigma_0 \tau_e \frac{1}{\varepsilon_0 (1 + \omega^2 \tau_e^2)}. \]

Generally \( \tau_e \approx 10^{-14} \text{ s} \) for metals and the DC conductivity of Ti [Lide (1997)] is \( \sigma_0 = 2.56 \times 10^6 \text{ m}^{-1} \Omega^{-1} \). Substituting these values into the expression for \( \varepsilon_{r2} \) and noting that \( \omega = 63.86 \text{ MHz} \), \( \varepsilon_{r2} \) is found to be \(-2.9 \times 10^3\). For metals and long wavelengths, \( \varepsilon_{r2} \) is usually neglected because \( \varepsilon_{r2} \ll \sigma_2 / \omega \varepsilon_0 \). Therefore, \( n_2 \approx \kappa_2 \) as indicated by Eq. (4.5) and the results obtained by the numerical calculation based on Eq. (4.11) and experimental transmittance data. \( \varepsilon_{r2} \) is kept in the electromagnetic analysis in this study, because it provides a means of understanding how this property can be modified by incorporating certain materials, such as Pt, into metals to attain negative relative permittivity. Although \( \mu_{r2} \) is taken as 1 for nonmagnetic materials in this study, it can be kept in the electromagnetic analysis for magnetic materials to understand how this property can be set to a negative value by modifying the composition of metals. Therefore, the measurement and data analysis techniques of this study would be useful to develop metamaterials for which both \( \varepsilon_{r2} \) and \( \mu_{r2} \) are negative.
4.6 Conclusion

Transmission measurements have been carried out and a mathematical model is presented to determine the electromagnetic properties of metals. Particularly the reflectivity of metals for just magnetic fields that vary with time at low frequencies, such as 30 – 100 MHz, is of interest. Since commercial instruments are not readily available for such frequency ranges, the inverse problem approach of this study provides a good alternative. Ti sheets of thicknesses 25 and 50 μm were considered as test samples, and Pt was diffused into some of the samples using a laser diffusion technique to understand how the properties of metals can be modified at the low frequency of interest. The refraction and absorption indices of Ti are determined for a magnetic field of frequency 63.86 MHz. Other electromagnetic properties of Ti such as the relative permittivity, conductivity, absorption coefficient and reflectivity are also calculated. The electrical conductivities of the platinized and as-received samples are found to be \(2.30 \times 10^6\) and \(2.51 \times 10^6\) m\(^{-1}\)Ω\(^{-1}\), respectively, which is an increase by 9.1%, and, consequently, the reflectivity of the former is higher than the latter. This increment in conductivity is due to Pt increasing the free electron density in Ti. Additionally, the absorbance of the platinized sample decreases by 0.9% when compared to that of the as-received sample, indicating that the sample would be heated less by the time-varying magnetic field.
CHAPTER 5: DESIGN OF FLAT-TOP BEAM SHAPING OPTICS BASED ON VECTOR DIFFRACTION THEORY

5.1 Introduction to Transformation of Gaussian Beams into Flat-top Beams

Most laser devices typically produce laser beams of Gaussian or similar beam profiles. However, a spatially uniform irradiance profile is necessary to have better control of the concentration profile of the diffusant. Numerous techniques have been demonstrated to transform Gaussian laser beams into flat-top beams of uniform irradiance profile. The flat-top beam can be produced by refractive [Ozaki et al. (1989)], diffractive [Brown (2000)] and absorptive optical elements [Belvaux et al. (1975)]. Due to the poor optical conversion efficiency of the absorptive elements, they are unsuitable for high power lasers. Both refractive and diffractive optical elements can have high optical conversion efficiency. A beam shaping lens (BSL) is designed based on vector diffraction theory to obtain an irradiance profile of improved uniformity by considering the diffraction effect and the longitudinal component of the laser polarization.

5.2 Lens Design Considering Polarizations Based on Vector Diffraction Theory

A beam shaping lens is shown in Fig. 5.1 for transforming a Gaussian beam into a flat-top beam. The incident Gaussian beam has a radius $w'$ and the flat-top beam has a radius $w$. The center thickness of the lens is $t_c$. The distance between the back surface of the lens and the target plane is $D$. The design of the beam shaping lens is based on vector diffraction theory which accounts for the polarization of the laser.
If a region is free of electrical charges and the field at the aperture plane $S'$ is $\vec{U}'(\vec{r}')$, the diffracted field at any radial vector $\vec{r}$ and distance is given by [Jackson (1999); Gillen et al. (2010)]:

$$\vec{U}(\vec{r}) = \frac{1}{2\pi} \nabla \times \iint_{S'} \hat{\vec{z}} \times \vec{U}'(\vec{r}') G da'$$  \hspace{1cm} (5.1)

where $G$ is the Green function,

$$G = \frac{\exp(-i\beta \rho)}{\rho}$$  \hspace{1cm} (5.2)

$\beta$ is the wave number which is equal to $2\pi/\lambda_L$, $\lambda_L$ is the wavelength of the laser, $\hat{\vec{z}}$ is the unit vector in the direction of laser beam propagation and $da'$ is the differential area on the aperture plane. $\rho$, which is the distance from a point on the lens to a point on the target plane $S$, can be written as

$$\rho = |\vec{r} - \vec{r}'| = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$$  \hspace{1cm} (5.3)

where $(x',y',z')$ and $(x,y,z)$ are the Cartesian coordinates of points on the aperture and target planes, respectively. Substituting Eqs. (5.2) and (5.3) into Eq. (5.1), one can express the three components of $\vec{U}(\vec{r})$ as:
\[ U_j(x, y, z) = \frac{i\beta z}{2\pi} \iint_{S_1} U'_j(x', y', 0) \left(1 + \frac{1}{i\beta \rho}\right) \frac{\exp(-i\beta \rho)}{\rho^2} \, dx' \, dy', \quad j = x, y \] (5.4)

\[ U_z(x, y, z) = -\frac{i\beta}{2\pi} \iint_{S'} \left[U'_x(x', y', 0)(x - x') + U'_y(x', y', 0)(y - y')\right] \times \left(1 + \frac{1}{i\beta \rho}\right) \frac{\exp(-i\beta \rho)}{\rho^2} \, dx' \, dy' + \frac{1}{2\pi} \iint_{S} \left[\frac{\partial U'_x(x', y', 0)}{\partial x'} + \frac{\partial U'_y(x', y', 0)}{\partial y'}\right] \frac{\exp(-i\beta \rho)}{\rho} \, dx' \, dy' \] (5.5)

Assuming \( \rho \gg \lambda, z \gg x'-x \) and \( z \gg y'-y \), one can express Eqs. (5.4) and (5.5) as:

\[ U_j(x, y, z) = \frac{i\beta}{2\pi x^2} \iint_{S_1} U'_j(x', y', 0) \Phi_{xy} \, dx' \, dy', \quad j = x, y \] (5.6)

\[ U_z(x, y, z) = -\frac{i\beta}{2\pi y^2} \iint_{S'} \left[U'_x(x', y', 0)(x - x') + U'_y(x', y', 0)(y - y')\right] \Phi_{xy} \, dx' \, dy' + \frac{i\beta}{2\pi y^2} \iint_{S} \left[\frac{\partial U'_x(x', y', 0)}{\partial x'} + \frac{\partial U'_y(x', y', 0)}{\partial y'}\right] \Phi_{xy} \, dx' \, dy' \] (5.7)

where \( \Phi_{xy} \) is defined as:

\[ \Phi_{xy} = \exp\left\{ -i \frac{\beta z}{2} \left[1 + \frac{(x-x')^2 + (y-y')^2}{2z^2}\right]\right\} \] (5.8)

Eq. (5.6) is identical to the Fresnel diffraction equation derived from scalar diffraction theory. The longitudinal component, which is given by Eq. (5.7), does not appear in scalar diffraction theory.

Assuming that the incident beam has a Gaussian irradiance profile and that the beam shaping lens modifies only the phase, the field at the back surface of the lens can be expressed as:

\[ U'_j(x', y', 0) = U'_0(x', y', 0) \exp\left(-\frac{x'^2 + y'^2}{w'^2} + i\phi'(x', y')\right), \quad j = x, y \] (5.9)

where \( U'_0 \) is the amplitude of the electric field of the incident laser beam and \( \phi'(x', y') \) is the optical phase contributed by the beam shaping lens. \( \phi'(x', y') \) can be expressed as follows in
terms of refractive index $n$, center thickness $t_c$ and surface sag $\Delta t(x', y')$ of the beam shaping lens as shown in Fig. 5.2.

$$\phi'(x', y') = \beta t_c - \beta(n - 1) \cdot \Delta t(x', y')$$  \hspace{1cm} (5.10)

The laser irradiance on the target plane is given by:

$$I(x, y, z) = \sum_j |U_j|^2, j = x, y, z$$  \hspace{1cm} (5.11)

Eqs. (5.6), (5.10) and (5.11) show that the laser irradiance on the target plane depends on the optical phase altered by the thickness of the beam shaping lens. So a flat-top beam can be obtained by designing the surface sag, $\Delta t(x', y')$, of the beam shaping lens.

![Figure 5.2 Thickness and surface sag of lens.](image)

5.3 Theoretical Results for Lens Shape and Irradiance Profile

In this study, the design of the beam shaping lens is based on fused silica of refractive index 1.44963 at a wavelength of 1064 nm. Other relevant parameters for the design are $w' = 0.5$ mm, $w = 5.5$ mm, $t_c = 8$ mm, $D = 80$ mm and the lens diameter $D_l = 25.4$ mm. Plano-convex lenses are considered in this study since they are fabricated more easily than plano-concave lenses. The surface sag of the lens is expressed as:
\[ \Delta t(x', y') = -\frac{0.248 \times (x'^2 + y'^2)}{1 + \sqrt{1 + (1-19) \times 0.248 \times (x'^2 + y'^2)}} \]  
(5.12)

which can be rewritten in the cylindrical coordinate as follows:

\[ \Delta t(r') = -\frac{0.248 \times r'^2}{1 + \sqrt{1 + (1-19) \times 0.248 \times r'^2}} \]  
(5.13)

The surface sag of the designed lens is plotted in Fig. 5.3, showing that the variation in thickness of the beam shaping lens. The beam radius is 0.5 mm which is incident at the central region of the lens. The lens has a curved shape near the central region as shown in the inset in Fig. 5.3. The shape of the lens varies almost linearly for \( r' > 2 \) mm.

![Figure 5.3 Surface sag of the beam shaping lens. The inset shows the surface sag at central portion of the beam shaping lens.](image)

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The theoretical irradiance profile of the laser beam on the observation plane is plotted in Fig. 5.4 where the irradiance is normalized to the center irradiance of the flat-top beam. Based on the design, the flat-top laser beam has a uniform intensity in a circular area with a radius of 5.5 mm on the plane where is 100 mm behind the beam shaping lens. The fluctuation of irradiance in the circular region is less than 2%.

![Theoretical irradiance profile of the laser beam at observation plane](image)

Figure 5.4 Theoretical irradiance profile of the laser beam at observation plane

5.4 Design of Single Polarization Beam Shaping Lens and Theoretical Results of Lens Shape and Irradiance Profile

Consider a laser beam incident on the surface of a uniaxial crystal shown in Fig 5.5. In general, the refracted beam is a mixture of two modes, ordinary beam and extra-ordinary beam. In the case of normal incidence, the wave vectors of ordinary and extra-ordinary beam are normal to the interface. However, the directions of their energy flow are not necessarily the same and
depend on the orientation of the optical axis of the uniaxial crystal. Assuming that the incident beam propagates along the $z$-axis and that the optical axis is tilt $\Theta$ from the $z$-axis as shown in Fig. 5.5, the direction of energy flow of ordinary beam is normal to the surface while the direction of energy flow of extra-ordinary beam deviates an angle $\gamma$ from the $z$-axis. The relationship between $\gamma$ and $\Theta$ can be expressed as:

$$\tan(\gamma) = \left(1 - \frac{n_0^2}{n_e^2}\right) \frac{\tan(\theta)}{1 + \frac{n_0^2}{n_e^2} \tan^2(\theta)}$$

(5.14)

where $n_o$ is the refractive index for ordinary beams and $n_e$ is the refractive index for extra-ordinary beams. Exiting from the crystal, both the beams propagate along the $z$-axis again since their wave vectors are parallel to the $z$-axis in the crystal and the air. Due to the deviation of energy flow inside the crystal, the extra-ordinary beam is laterally shifted from the ordinary wave. The lateral displacement $\delta_l$ is determined by

$$\delta_l = d_c \tan(\gamma)$$

(5.15)

where $d_c$ is the thickness of the crystal. Therefore, the ordinary beam and extra-ordinary beam separate after passing through the uniaxial crystal which optical axis is not normal or parallel to the surface. Since the two propagation modes are the eigenmodes, the polarizations of the both beams are orthogonal. Therefore, the oriented uniaxial crystal plate can act as a polarizing beam splitter. Blocking either ordinary beam or extra-ordinary beam, one can obtain an output beam with only one polarization.
The laser beam from the Nd:YAG laser is a collimated and randomly polarized Gaussian beam so it is assumed that the phase of incident laser beam is constant over all the front surface of beam shaping lens. The design of the polarization beam shaping lens is based on calcite crystal of ordinary refractive index 1.64237 and extraordinary refractive index 1.47968 at a wavelength of 1064 nm. Other relevant parameters for the design are \( w' = 0.5 \) mm, \( w = 5.5 \) mm, \( t_c = 25 \) mm and \( D = 100 \) mm. In order to have a maximum lateral displacement, the calcite crystal is cut so that its optical axis is 45° tilt from the surface normal, i.e. \( \Theta = 45° \). Both plano-convex and plano-concave lenses are designed in this study. The surface sag of the plano-convex lenses is expressed as:

\[
\Delta t(r') = -\frac{0.1797 \times r'^2}{1 + \sqrt{1 + (1 - 33.214) \times 0.1797 \times r'^2}}
\]  

(5.16)

The surface sag of the plano-concave lenses is expressed as:

\[
\Delta t(r') = \frac{0.16724 \times r'^2}{1 + \sqrt{1 + (1 - 47.6901) \times 0.16724 \times r'^2}}
\]  

(5.17)

The surface sags of both cases are plotted in Fig. 5.6 and 5.7. The base radius of the aspheric concave surface is 6.0 mm. It is difficult to manufacture and to polish the aspheric concave
surface with a base radius smaller than 13 mm due to the dimension of the tools. The aspheric convex lens is preferred from the respect of manufacturers in most cases.

Figure 5.6 Surface sag of plano-convex calcite beam shaping lens
The theoretical irradiance profiles of both cases are plotted in Fig. 5.8 and 5.9 where the irradiance is normalized to the center irradiance of flat-top beams. The output beams have flat irradiance profiles within a circular region of a radius 5.5 mm where the irradiance variation is less than 2%.
Figure 5.8 Normalized irradiance profile of output beam for plano-convex calcite beam shaping lens

Figure 5.9 Normalized irradiance profile of output beam for plano-concave calcite beam shaping lens
A beam shaping lens system is designed based on vector diffraction theory. This beam shaping lens can transform the incident Gaussian beam into a flat-top beam with improved irradiance uniformity. The variation of the irradiance in a circular area with a radius of 5.5 mm is less than 2%.

A novel beam shaping lens system which can transform the incident randomly polarized Gaussian beam into a linearly polarized flat-top beam is designed. The beam shaping lens which is made of calcite crystals can split the incident beam into an ordinary beam and an extra-ordinary beam. A linearly polarized flat-top beam is obtained on the target plane 100 mm behind the beam shaping lens. A plano-concave and a plano-convex polarization beam shaping lens are designed. The variation of the irradiance profile is less than 2% inside a circular area of radius 5.5 mm in both cases.
CHAPTER 6: EXPERIMENTAL STUDY FOR THE EFFECTS OF POLARIZED LASER BEAMS ON THE MODIFICATION OF MATERIAL PROPERTIES

6.1 Experimental Setup

Thin sheets of Ti and Ta were used as the metal sample in this study. Each sample was a square sheet of side 20 mm and thickness 25 or 50 µm. In order to increase the absorption of the laser energy, the 50 µm thick Ta sheets were rubbed by sand paper (grade 2000). All the Ti and Ta sheets were cleaned in the acetone and deionized water ultrasonic bath.

Diffusion experiments were conducted by placing each sample in a laser diffusion chamber as illustrated in Fig. 6.1. 0.2 g of the Pt precursor (Pt(acac)_2 [platinum(II) acetylacetonate, Pt(C_5H_7O_2)_2]) was dissolved in 20 cm³ of acetylacetone [CH_3COCH_2COCH_3] and the solution was heated in a bubbler using a hot plate maintained at 130°C. The chamber was vacuumed to the pressure of 5×10⁻³ torr. Then argon was passed through the bubbler as a carrier gas to transport the Pt precursor vapour to the diffusion chamber to achieve a total pressure of 103.4 kPa inside the chamber. A Nd:YAG laser of wavelength 1064 nm was used to heat the metal sample, resulting in thermochemical decomposition of the Pt precursor. The Pt atoms that are produced due to this chemical reaction diffuse into the metal sample. The laser processing parameters were chosen to ensure no melting of the sample and to achieve sufficiently high temperatures for the formation and diffusion of Pt atoms. We, therefore, have two sets of samples for each of Ti and Ta sheets, which are as-received and laser-platinized samples, to investigate the effect of Pt on the transmission properties.
To understand the effect of laser polarization on the diffusion of Pt in Ti and Ta sheets, the beam shaping lens and polarizers are used as shown in Fig. 6.2 to generate polarized flat-top laser beams. Since the laser system produces a randomly polarized laser beam in this study, only a beam shaping lens is used to generate a randomly polarized flat-top laser beam. A linear polarizer and a beam shaping lens generate a linearly polarized flat-top laser beam. Using a linear polarizer, quarter wave plate and a beam shaping lens, a circularly polarized flat-top beam is produced. Using a linear polarizer, a phase plate [Machavariani et al. (2007)] and a beam shaping lens, an azimuthally polarized flat-top beam is produced.
Figure 6.2 Optical elements used to generate polarized flat-top laser beams.
The laser processing parameters were chosen to ensure no melting of the sample and to achieve sufficiently high temperatures for the formation and diffusion of Pt atoms. In order to estimate the surface temperature of samples, the reflectivity of Ti and Ta sheets was measured. The surface roughness of samples was measured using a Zygo optical surface profiler in order to study the relation between reflectivity and surface roughness. The Zygo optical surface profiler uses a white light source which has a central wavelength of 475 nm with a bandwidth of 125 nm.

For the Ti sheets, two laser scanning speeds $u = 6 \text{ mm/s}$ and $12 \text{ mm/s}$ were chosen for each of the three different laser powers $P_L = 6, 9$ and $12 \text{ W}$, and five polarizations were tested for each power. Due to the thermophysical properties of Ta, requiring more energy to heat it for diffusing Pt into the material, the Ta sheets were treated at the laser scanning speeds of $u = 3 \text{ mm/s}$ and $6 \text{ mm/s}$ for each of the three different laser powers $P_L = 10, 13$ and $16 \text{ W}$ for the above-mentioned three polarizations. The 50 μm thick Ta sheets were rubbed using the sand paper (Grade 2000) to increase the absorption of the laser energy because no plume was observed from the unrubbed 50 μm thick Ta sheets. The sample was placed 21 mm below the beam shaping lens (BSL in Fig. 6.2) inside the vacuum chamber. A beam expander consisting of a plano-concave lens and a plano-convex lens was used to expand the output beam of the laser system from a radius of 0.75 mm to 0.8 mm. The radius of the flat-top laser beam was 1 mm on the surface of the sample. The irradiance profile on the sample surface was measured using a CCD camera-based profilometer, showing a fairly uniform energy distribution across the laser beam as presented in Fig. 6.3.
The concentration of the elements in the Ti and Ta sheets were determined by Energy-dispersive X-ray spectroscopy (EDS). All of the Ti and Ta sheets were cleaned in the acetone and deionized water ultrasonic bath before the EDS measurement. The acceleration voltage of the electron in EDS was 15 keV. The change in composition of Ti and Ta sheets is expected to modify the conductivity and transmittance of Ti and Ta sheets. The transmittance of the as-received samples and all of the laser treated samples are measured using the setup described in.

The conductivity of the as-received samples and some of the laser treated samples are measured using the four-point probe method as shown in Fig 6.5. After applying a constant current $I_c$...
through the two outer current probes, the voltage gradient $V_m$ is measured by the two inner voltage probes. The conductivity $\sigma$ of each sample can be determined by:

$$\sigma = K \frac{l_c}{V_m w_p d}$$  \hspace{1cm} (6.1)

where $K$ is the correction factor which depends on the geometric of current probes and samples, $s_p$ is the separation between the two inner voltage probes, $w_p$ is the width of the current probe and $d$ is the thickness of the sample. In this study, $s$ is 15 mm, $w_p$ is 20 mm and $d$ is 25 or 50 μm. The value of $K$ is calculated by measuring the known electrical conductivity of thin copper sheets with the same dimension as the Ti and Ta samples. $K$ is 1.043 for 25 μm thick sheets and 1.029 for 50 μm thick sheets in this study.

![Figure 6.4 Illustration of four-point method which is used to measure the conductivity of samples](image)

The experimental setup for measuring the transmitted magnetic field is described in section 4.3.
6.2 Results for Concentrations of Carbon Oxygen Platinum in Ti and Ta Sheets

The concentration of impurities in the Ti samples is plotted in Fig. 6.5 for two thicknesses, two scanning speeds and two polarizations of laser: azimuthal polarization (Az) and linear polarization (L⊥) which polarization direction is perpendicular to the scanning direction of the laser beam. The as-received 25 μm Ti sample has carbon (C) impurity and the as-received 50 μm Ti sample has C and oxygen (O) impurity. The difference in chemical compositions of 25 and 50 μm Ti samples leads to distinct color appearances: silver 25 μm Ti samples and yellowish 50 μm Ti samples. After the laser diffusion, the concentration of C and O does not change significantly. Pt atoms go into the Ti samples and the concentration of Pt atoms is higher at the slower scanning speed due to higher surface temperature and longer laser-substrate interaction time. The surface temperature of Ti sheets can be estimated from:

\[
T_s = T_i + \frac{P_L (1-R)\tau}{2\omega u \Delta d \rho_m c_p + 2\omega u \tau^2 h_b + 2\omega u \tau^2 h_s}
\]  

where \(T_s\) is the surface temperature, \(T_i\) is initial surface temperature, \(P_L\) is the laser power, \(R\) is the measured reflectivity of metal sheets at the laser wavelength, \(\omega\) is the radius of laser beam, \(u\) is the laser scanning speed, \(d\) is the thickness of metal sheet, \(\rho_m\) is the mass density of metal sheet, \(c_p\) is the specific heat of metal sheet, \(h_b\) is the free convection coefficient at the surface of metal sheet, \(h_s\) is the heat transfer coefficient in the metal sheet and \(\tau\) is the interaction time which is equal to \(2\omega/u\). The properties of Ti and Ta sheets are listed in Table 6.1 and the measured reflectivity of Ti and Ta samples for azimuthal polarization (Az) and linear polarization (L⊥) which polarization direction is perpendicular to the scanning direction of the laser beam is plotted in Fig. 6.6. The calculated surface temperature is plotted in Fig. 6.7. The
surface temperature is higher at the lower scanning speed and thus the concentration of Pt atoms is higher for the Ti samples treated at the scanning speed of 3 mm/s.
Figure 6.5 Concentration of elements in Ti samples
Table 6.1 Density and thermal properties of Ti and Ta

<table>
<thead>
<tr>
<th>Metal</th>
<th>Mass density, ρ_m (kg/m^3)</th>
<th>Specific heat, C_p (J/kgK)</th>
<th>Free convection coefficient, h_b (W/m^2K)</th>
<th>Heat transfer coefficient, h_s (W/m^2K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>4500</td>
<td>522</td>
<td>200</td>
<td>2.2×10^4</td>
</tr>
<tr>
<td>Ta</td>
<td>16600</td>
<td>140</td>
<td>200</td>
<td>5.8×10^4</td>
</tr>
</tbody>
</table>

Figure 6.6 Measured reflectivity of Ti and Ta samples for azimuthal polarization (Az) and linear polarization (L⊥) which polarization direction is perpendicular to the scanning direction of the laser beam.
The concentration of impurities in the Ta samples is plotted in Fig. 6.8 for two thicknesses, two scanning speeds and two polarizations of laser. The as-received Ta samples have C and O impurity. After the laser diffusion, Pt atoms go into the Ta samples and the concentration of Pt atoms is higher at the slower scanning speed due to higher surface temperature. The Pt concentration in 50 μm Ta samples treated at the scanning speed 6 mm/s is zero because the surface temperature is not high enough to diffuse sufficient amount of Pt into the Ta sheets. The plume was not observed when the 50 μm Ta samples were treated at the scanning speed of 6 mm/s. The concentration of O also increased after the treatment.

The Ta samples irradiated by the linearly polarized laser beam have slightly higher Pt concentration than by the azimuthal polarized laser beam. The surface temperature difference between samples which are irradiated by linearly and azimuthally polarized laser is small.
Therefore, the slightly higher Pt concentration in the samples might attribute to enhanced diffusion due to the linearly polarized laser beam. The linearly polarized laser beam excites the local vibration mode of impurities and substrate and the polarization direction parallel to the concentration gradient of Pt atoms. However, the differences are within the error bar range. Increasing the interaction time might be able to cause larger differences in the concentration of Pt atoms.
Figure 6.8 Concentration of the elements in Ta samples
6.3 **Results for Transmittance and Conductivity of Ti and Ta Sheets**

In this study, the output of the magnetic field sensor in Fig. 4.3 was voltage induced by the time-varying magnetic field and this response \((H')\) was measured in units of dB\(\mu\)V. The spectrum analyser, however, involves a scaling factor of \(10^{(H' + 49.5)/20}\) to convert the field strength from the measured unit to the unit of \(\mu\)A/m for the incident magnetic field \(\vec{H}_{in}\) in and the transmitted magnetic field \(\vec{H}_{t}\). These data were used to determine the experimental transmittance \((\tilde{T})\) of different samples using the following expression:

\[
\tilde{T} = \frac{\vec{H}_{t}}{\vec{H}_{in}} \times 100\%
\]  

(6.3)

The concentration of the elements in the Ti samples is analyzed using energy-dispersive X-ray spectroscopy (EDS) and plotted in Fig. 6.9 with the corresponding transmittance values for linear and azimuthal polarizations, respectively. The electrical conductivity of Ti sheets is plotted in Fig. 6.10. The transmittances of the platinized Ti are lower than the as-received samples, indicating that the diffused Pt atoms modify the interaction between the magnetic field and the Ti sample. The reduction in the transmittance of the platinized Ti samples is due to increased electrical conductivity since Pt has higher conductivity than Ti as listed in Table 6.2. The surface temperature is higher at the lower scanning speed, resulting higher concentration of Pt in the Ti samples, higher conductivity and lower transmittance. The surface temperature of thinner samples is higher, resulting higher Pt concentration in the 25 \(\mu\)m Ti samples than that in the 50 \(\mu\)m Ti samples.
Figure 6.9 Transmittance and impurities concentration of Ti samples
The transmittance of Ti is lower for linearly polarized laser-treated samples than for the case of azimuthal polarization, which might be due to the following reason. Since the electric field affects the motion of electrons in atoms and this motion influences the oscillation of the nuclei, i.e., the direction of lattice vibrations, the motion of the Pt atoms and the oscillation of Ti atoms in the samples are controlled by the oscillation of the electric field. The electric field of the linearly polarized laser beam oscillates at the same direction during the laser diffusion process.
and excites the local vibration modes of Pt and Ti atoms, resulting more diffusion of Pt, higher conductivity and lower transmittance. In addition, the oscillation of electric field is parallel to the gradient of Pt concentration, which might enhance the diffusion of Pt atoms. In azimuthal polarization, the oscillation direction of the electric field is tangential to the circumference and the movement of a Pt or Ti atom is always parallel to the tangential direction. The directions of the movements of all atoms in the irradiation area, however, are still equally distributed in any directions, which might not excite the local vibration modes of Pt and Ti atoms. The concentration of Pt in Ti treated by linearly polarized laser at the scanning speed \( u = 12 \text{ mm/s} \) is lower than the one in Ti treated by azimuthally polarized laser might be attributed to the following reason. The minimum detectable concentration of \(<1000 \text{ ppm}\) is commonly quoted in textbooks and can be as low as 0.01 At.% \([\text{Lee (1993)}]\) under the conditions where there is no interference from another peak. However, the numbers are obtained at the best case situation and might have relative errors of 100%. Therefore, the data for Pt concentration in Ti sheets treated at the scanning speed \( u = 12 \text{ mm/s} \) might not be reliable due to the small values near the detection limit.

The transmittance, impurity concentration and electrical conductivity of Ta are plotted in Fig. 6.11 and 6.12 for two polarizations. The values of transmittance and electrical conductivity of Ta shows a trend opposite to that of Ti. The transmittances of platinized Ta samples are higher than that of the untreated (as-received) sample. The Pt atoms still diffuse into Ta sheets, which should increase the conductivity of Ta sheets. The Pt atoms might not increase the conductivity of Ta as much as that of Ti because the conductivity of Pt is closer to Ta than to Ti. The increased concentration of O, therefore, dominates the modification of the properties of Ta sheets, resulting
in lower conductivity and higher transmittance. The transmittance of the Ta sheets increases when laser-treated at slower scanning speed, because the temperature of the sheets increases and the oxidation increases with temperature. The concentration of Pt in Ta sheets is higher at the slower scanning speed due to higher surface temperature. The surface temperature of the 25 μm Ta samples is higher than the 50 μm Ta samples, resulting higher concentration of Pt in 25 μm Ta. With regard to the effect of polarization, the linearly polarized beam influences the direction of atom vibrations in a preferred way and excites the local vibration modes of Pt and Ta atoms. The Ta samples treated with linearly polarized lasers, therefore, exhibit slightly higher Pt concentration than the other samples treated with azimuthally polarized lasers.
Figure 6.11 Transmittance and impurities concentration of Ta samples
The transmittance and conductivity of Ti is plotted in Fig. 6.13, 6.14 and 6.15 for random (R), linear (L\text{||} and L\text{\perp}), azimuthal (Az) and circular (Cir) polarizations, respectively, as a function of laser power at which the samples were treated. L\text{||} denotes the case of linear polarization parallel to the scanning direction. The graphs are labeled with Ar and Pt to represent the Ar-treated and platinized samples, respectively. The Ar-treated and platinized samples have lower transmittances than the untreated (as-received) sample. It can be attributed to annealing. High surface temperature due to either higher laser power or slower scanning speed might anneal the Ti samples and reduce defect densities, causing higher electrical conductivity in the treated samples and, therefore, more reflection of the magnetic field.
Figure 6.13 Transmittance of 25 µm thick Ti samples treated at different laser parameters and gas atmosphere.
Figure 6.14 Transmittance of 50 µm thick Ti samples treated at different laser parameters and gas atmosphere.
Figure 6.15 Conductivity of Ti samples treated at different laser parameters and gas atmosphere.

The transmittances of the platinized Ti samples are lower than the Ar-treated samples, indicating that the diffused Pt atoms modify the interaction between the magnetic field and the Ti sample.
The reduction in the transmittance of the platinized Ti samples might be due to increased electrical conductivity since Pt has higher conductivity than Ti as listed in Table 6.2. The samples treated at higher laser power or lower scanning speed exhibit lower transmittance because more Pt atoms are expected to diffuse into the Ti sheets at higher temperatures.

The transmittance and conductivity of Ta is plotted in Fig. 6.16, 6.17 and 6.18 for four polarizations, showing a trend opposite to that of Ti. The transmittances of platinized Ta samples are higher than that of the untreated (as-received) sample. The increase of transmittance might be attributed to the reduced conductivity of treated Ta samples resulting from the oxidation. The net effect of diffused Pt and oxidation in Ta is the reduction in the electrical conductivity of Ta sheets since the conductivity of Pt is closer to Ta than to Ti as shown in Table 6.2, resulting in higher transmittances of the laser-treated Ta sheets as shown in Fig. 6.16 and 6.17. The transmittance of the Ta sheets increases when laser-treated at either higher laser power or slower scanning speed, because oxidation may be enhanced at higher temperature.
Figure 6.16 Transmittance of 25 µm thick Ta samples treated at different laser parameters and gas atmosphere.
Figure 6.17 Transmittance of 50 µm thick Ta samples treated at different laser parameters and gas atmosphere.
Figure 6.18 Conductivity of Ti samples treated at different laser parameters and gas atmosphere.
6.4 Effect of Polarization on the Reflectivity due to Rough Surfaces

The reflectivity of isotropic, homogeneous materials with perfectly smooth surface can be determined from the Fresnel equations [Born et al. (1983)]:

\[
R_{Fp} = \frac{(n^2 - n \cos \theta_t)^2 + (2n^2 \kappa - n \cos \theta_t)^2}{(n^2 + n \cos \theta_t)^2 + (2n^2 \kappa + n \cos \theta_t)^2}
\]

\[
R_{Fs} = \frac{(\cos \theta_i - n \cos \theta_t)^2 + \kappa \cos^2 \theta_t}{(\cos \theta_i + n \cos \theta_t)^2 + \kappa \cos^2 \theta_t}
\]

where \(R_{Fp}\) and \(R_{Fs}\) are the Fresnel reflectivities for \(p\)-polarization and \(s\)-polarization, respectively, \(\theta_i\) and \(\theta_t\) are the incident and refraction angles, respectively, \(n\) and \(\kappa\) are the refractive index and absorption index of the material, respectively. \(\theta_t\) is given as follows in terms of the incident angle \(\theta_i\):

\[
\theta_t = \arcsin \left( \frac{\sin(\theta_i)}{n + i\kappa} \right)
\]

However, the surface roughness and the anisotropic orientation of crystalline planes are expected to affect the reflectivity. A model [He et al. (1991)], which considers the surface roughness, polarization and shadowing, is used in this study to calculate the theoretical reflectivity of samples irradiated by polarized laser beams. The surface properties can be described by an effective roughness, \(\rho_{eff}\), in terms of the root-mean-square surface roughness, \(\rho_{rms}\), as given by:

\[
\rho_{eff} = \rho_{rms} \frac{1}{\sqrt{1 + \left( \frac{\zeta_0}{\rho_{rms}} \right)^2}}
\]

where \(\zeta_0\) is the root of the following equation:

\[
\sqrt{\frac{\pi}{2}} \zeta_0 = \frac{\rho_{rms}}{4} [K(\theta_t) + K(\theta_r)] \exp \left( - \frac{\zeta_0^2}{2\rho_{rms}^2} \right)
\]
with \( K(\theta) = \tan \theta \cdot \text{erfc} \left( \frac{L_c}{2 \rho_{\text{rms}}} \cot \theta \right) \) and \( L_c \) as the coherence length of surface height. \( \theta_i \) and \( \theta_r \) are the incident and reflected angles, respectively.

The bidirectional reflectance distribution function (BRDF) \( \vec{R}_b \) consists of two components [Smith et al. (1972); Smith et al. (1981); Cook et al. (1982); He et al. (1991)]:

\[
\vec{R}_b(\theta_r, \rho_{\text{rms}}) = \vec{R}_{bs}(\theta_i, \rho_{\text{rms}}) + \vec{R}_{bd}(\theta_r, \rho_{\text{rms}})
\]  

(6.9)

where \( \vec{R}_{bs} \) is specular BDRF, \( \vec{R}_{bd} \) is diffuse BDRF. It should be noted that \( \theta_r \neq \theta_i \) for diffused reflection of the laser beam. The two components can be expressed as:

\[
\vec{R}_{bs} = \frac{R_F F_s(\theta_i) \exp(-F_p)}{\cos \theta_i d\omega_i}
\]  

(6.10)

\[
\vec{R}_{bd} = \frac{R_F F_D F_s(\theta_i) F_s(\theta_r)}{\pi \cos \theta_i \cos \theta_r}
\]  

(6.11)

where \( R_F \) is the Fresnel reflectivity which is given by Eqs. (6.4) and (6.5) for \( p \) - and \( s \) -polarizations, respectively and \( d\omega_i \) is the solid angle of the incident beam which is taken as \( \pi/1024 \). For other polarizations, such as random, circular and azimuthal polarizations, \( R_F \) is taken as the arithmetic average of \( R_{Fp} \) and \( R_{Fs} \). \( F_s(\theta) \) is the shadowing function, \( F_p \) is the surface roughness function, \( F_G \) is the geometrical function and \( F_D \) is the light distribution function, which are given by

\[
F_s(\theta) = \frac{1 - \frac{1}{2} \text{erfc} \left( \frac{L_c \cot \theta}{2 \rho_{\text{rms}}} \right)}{1 + \frac{1}{2} \frac{\rho_{\text{rms}}}{\sqrt{2 \pi L_c \cot \theta}} \text{erfc} \left( \frac{L_c \cot \theta}{2 \rho_{\text{rms}}} \right)}
\]  

(6.12)

\[
F_p = \left[ \frac{4 \pi \rho_{\text{eff}}}{\lambda_l} \cos^2 \theta_i \right]^2
\]  

(6.13)

\[
F_G = \left( \frac{k_d \hat{k}_d}{k_{dz}} \right)^2 \frac{1}{|\hat{k}_r \times \hat{k}_l|} \left[ (\hat{s}_r \cdot \hat{k}_l)^2 + (\hat{p}_r \cdot \hat{k}_l)^2 \right] \left[ (\hat{s}_i \cdot \hat{k}_r)^2 + (\hat{p}_i \cdot \hat{k}_r)^2 \right]
\]  

(6.14)
Here, $\hat{k}_m$, $\hat{p}_m$ and $\hat{s}_m$ are the unit vectors along the direction of the laser beam propagation and the $p$- and $s$-polarizations, respectively, with the subscript $m = i$ and $r$ for the incident and reflected beams, respectively. $\vec{k}_d$ is the change in the wave vector due to the reflection, which is given by $\vec{k}_d = \hat{k}_r - \hat{k}_i = k_{dx}\hat{x} + k_{dy}\hat{y} + k_{dz}\hat{z}$, where $\hat{x}$, $\hat{y}$ and $\hat{z}$ are the unit vectors along the $x$, $y$ and $z$ axes in Cartesian coordinates and $k_{dx}$, $k_{dy}$ and $k_{dz}$ are the $x$-, $y$- and $z$-components of the vector $\vec{k}_d$, respectively.

Integrating $\bar{R}_b(\theta_r, \rho_{rms})$ over the acceptance angle, $\Delta\theta_a$, of the photodetector, i.e. from $\theta_{rs} - \frac{1}{2}\Delta\theta_a$ to $\theta_{rs} + \frac{1}{2}\Delta\theta_a$, the total bidirectional reflectance for rough surfaces, $\bar{R}_{sr}$, is obtained from the following expression where $\theta_l$ is used in the limits of integration since the specular reflection angle $\theta_{rs} = \theta_l$:

$$\bar{R}_{sr} = \int_{\theta_l - \frac{1}{2}\Delta\theta_a}^{\theta_l + \frac{1}{2}\Delta\theta_a} \bar{R}_b \, d\theta_r$$

Similarly the total reflectance around the specular direction for a smooth surface ($\bar{R}_{ss}$) can be obtained from Eq. (6.16) by considering a very small value of the surface roughness that is taken as $\rho_{rms} = 0.1$ nm in this study. A photodetector of diameter 25.4 mm was used in this study to measure the reflected power of a laser beam of wavelength 1064 nm in the specular reflection direction for various samples in order to calculate the experimental reflectance. This dimension of the detector and its placement from the sample resulted in $\Delta\theta_a = 28^\circ$ for the theoretical reflectance. For the case of smooth surface, the Fresnel reflectivity ($R_F$) is obtained from Eqs. (6.4) and (6.5), and then the reflectivity of the rough surfaces is calculated using the following expression:
The surface roughness is measured using an optical profiler based on white light interferometry at the center wavelength of 475 nm with a bandwidth of 125 nm. The reflectivity is measured using a Nd:YAG laser at the wavelength of 1064 nm. The reflectivity of the samples is measured and compared with the theoretical values as shown in Fig. 6.19 and 6.20 for random (R), p- (L_p), circular (Cir) and azimuthal (Az) polarizations, respectively. The Fresnel reflectivity for random, circular and azimuthal polarizations is equal to \( \left( R_{Fp} + R_{Fs} \right) / 2 \). The complex refractive indexes of Ti and Ta at the wavelength of 1064 nm are 3.47+i3.4 and 0.93+i5.75 [Lide (1991)], respectively. The measured surface roughness is listed in Table 6.3. The values of coherent length of surface height, \( L_c \), which are listed in Table 6.3, are selected as best fits to calculate the theoretical reflectivity for the Ti and Ta samples. The surface of Ti sheets can be seen as smooth because the reflectivity of Ti samples is close to the Fresnel reflectivity and the surface roughness of Ti samples is much smaller than the laser wavelength. On the other hand, the surface of Ta samples is rough because the reflectivity of Ta samples is lower than half of the Fresnel reflectivity and the surface roughness which is comparable to the laser wavelength. The reflectivity of the Ta samples at the incident angle of 45° is higher than at normal incidence due to the smaller effective surface roughness at oblique incidence. This phenomenon is not significant for Ti samples due to the smoother surface. At the normal incidence, the reflectivity of the samples is the same for the all polarizations. At oblique incidence, the reflectivity for p-polarized laser beams will be lower than the one for randomly, circularly, azimuthally and s-polarized laser beams.
The theoretical values of surface roughness of Ti samples are different from the experimental data. There are two possible reasons. The surface of Ti samples can be seen smooth due to their small surface roughness and the model is based on the approximation that either the surface is very rough i.e. \((2\pi\rho_{rms}/\lambda)^2 \gg 1\), or the surface slope is gentle i.e. \(\rho_{rms}/L_c \ll 1\) [Stogryn (1967); Hering et al. (1970)]. Changing the surface roughness for the scattering model gives a matched theoretical reflectivity for Ti sheets. The theoretical results show lower reflectivity for \(p\)-polarization compared with other polarizations. For the same polarization, higher reflectivity is obtained at oblique incidence than at normal incidence due to the smaller effective surface roughness.

![Figure 6.19](image-url)

Figure 6.19 Experimental data and theoretical results of reflectivity of Ti samples for random (R), \(p\)- (L\(_p\)), circular (Cir) and azimuthal (Az) polarizations.
Figure 6.20 Experimental data and theoretical results of reflectivity of Ta samples for random (R), p- (Lp), circular (Cir) and azimuthal (Az) polarizations.

Table 6.3 Surface properties of Ti and Ta samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Surface roughness, $\rho_{rms}$ ((\mu)m)</th>
<th>Adjusted surface roughness, $\rho_{fit}$ ((\mu)m)</th>
<th>Coherent length of surface height, $L_c$ ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti 25 (\mu)m</td>
<td>0.205</td>
<td>0.025</td>
<td>2</td>
</tr>
<tr>
<td>Ti 50 (\mu)m</td>
<td>0.235</td>
<td>0.04</td>
<td>2</td>
</tr>
<tr>
<td>Ta 25 (\mu)m</td>
<td>0.4</td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>Ta 50 (\mu)m unrubbed</td>
<td>0.8</td>
<td>0.8</td>
<td>6</td>
</tr>
<tr>
<td>Ta 50 (\mu)m rubbed</td>
<td>0.847</td>
<td>0.847</td>
<td>7</td>
</tr>
</tbody>
</table>
6.5 Conclusion

Laser Pt diffusion treatments are studied for two polarizations of a Nd:YAG laser using thin sheets of Ti and Ta as test samples. Trace Pt atoms diffuse into the Ti and Ta. The concentration of Pt atoms is higher at lower scanning speed due to higher surface temperature. The samples treated by a linearly polarized laser beam have slightly higher concentration of Pt. The enhanced diffusion from linearly polarized laser beams can be attributed to two reasons: (i) The linearly polarized laser beam can excite the local vibration modes of impurities and substrate, and (ii) The polarization direction is parallel to the concentration gradient of Pt atoms.

The effect of impurity on the transmission of a radiofrequency (63.86MHz) magnetic field is examined. Pt decreases the transmittance of Ti and O increase the transmittance of Ta samples, respectively, compared to that of untreated (as-received) samples. For Ti sheets, the reduction in the transmittance can be attributed to the increased electrical conductivity due to two effects: (i) The higher electrical conductivity of Pt than that of Ti allows the diffused Pt atoms to enhance the conductivity of the Ti sheets and, thereby, reduce the transmittance of the samples, and (ii) Linearly polarized lasers control the direction of lattice vibrations and excite the local vibration modes of atoms so as to enhance the diffusion of Pt into the Ti sheets, resulting in higher conductivity and lower transmittance of the samples. However, laser diffusion treatment has opposite effects for Ta sheets, which can be attributed to the surface oxidation. Also, the diffusion of Pt atoms might not enhance the conductivity of Ta as much as that of Ti because Pt and Ta have almost the same conductivities. Consequently, the magnetic field can pass through...
the sample without being reflected and absorbed, resulting in higher transmittance of the Ta samples.

The reflectivity of rough surfaces depends on the surface roughness, incident angle and polarization. The theoretical reflectivity of rough surfaces is calculated based on a model considering surface roughness and polarizations and is compared with the experimental data. The surface of Ti samples can be seen smooth due to their small surface roughness compared with the laser wavelength and Ta samples have rough surfaces.
CHAPTER 7: EXPERIMENTAL DATA FOR MECHANICAL STRENGTH AND THERMAL EFFECT IN MRI HEATING FOR TANTALUM AND MP35N PACEMAKER LEAD WIRES

7.1 Experimental Setup for Laser Diffusion on Ta and MP35N Wires

Wires of Ta and MP35N alloy were used as the wire sample in this study. The diameter of these wires was 100 µm. Separate diffusion experiment was carried out by passing each wire in a laser diffusion chamber as shown in Fig. 7.1. The metal wire passes through two rubber plugs which are used as vacuum seals. The preparation and transportation of Pt precursor Pt(acac)$_2$ were described in section 4.2. A Nd:YAG laser of wavelength 1064 nm and beam diameter 764 µm on the surface of the wire was used as the localized heating source. The wire was pulled by a spool which was driven by a motor at constant speeds.
Figure 7.1 Setup for laser Pt diffusion on Ta and MP35N wires

The laser processing parameters were chosen to ensure no melting of the wire and to achieve sufficiently high temperatures for the formation and diffusion of Pt atoms. The surface temperature of wires can be determined by:
\[ T_s = T_i + \frac{4P_L(1 - R_F)}{\pi r_w^2 u \rho_m C_p} \]  

(7.1)

where \( T_s \) is surface temperature, \( T_i \) is initial surface temperature, \( P_L \) is laser power, \( R_F \) is the Fresnel reflectivity of wire at the laser wavelength, \( r_w \) is the radius of wire, \( u \) is the laser scanning speed, \( \rho_m \) is the mass density of metal and \( C_p \) is the specific heat of metal. The parameters for laser treatment are shown in Table 7.1. Table 7.1 Parameters of laser treatment for Ta and MP35N wires. The density and thermal properties of Ta, Ta_2O_5, MP35N and Pt are listed in Table 7.2. Error! Reference source not found. [Patnaik (2002)]. Thermal capacitance is equal to the product of mass density times specific heat. The calculated temperatures of Ta and MP35N wires are plotted in Fig. 7.2.
Table 7.1 Parameters of laser treatment for Ta and MP35N wires

<table>
<thead>
<tr>
<th>Sample</th>
<th>Laser power (W)</th>
<th>Winding speed (mm/s)</th>
<th>Number of laser pass</th>
<th>Backfill pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-treated Ta wire</td>
<td>7</td>
<td>8</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Laser-platinized Ta wire</td>
<td>7</td>
<td>8</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Laser-platinized MP35N wire</td>
<td>5</td>
<td>11</td>
<td>1</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 7.2 Mass density and thermal properties of Ta, Ta₂O₅, MP35N and Pt

<table>
<thead>
<tr>
<th></th>
<th>Mass density (kg/m³)</th>
<th>Melting point (°C)</th>
<th>Specific heat (J/kg·K)</th>
<th>Thermal capacitance (10⁶J/K)</th>
<th>Thermal conductivity (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta</td>
<td>16600</td>
<td>2996</td>
<td>140</td>
<td>2.32</td>
<td>57.5</td>
</tr>
<tr>
<td>Ta₂O₅</td>
<td>8200</td>
<td>1785</td>
<td>306</td>
<td>2.51</td>
<td>0.28</td>
</tr>
<tr>
<td>MP35N</td>
<td>8430</td>
<td>1378</td>
<td>754</td>
<td>3.54</td>
<td>11.2</td>
</tr>
<tr>
<td>Pt</td>
<td>21450</td>
<td>1772</td>
<td>133</td>
<td>2.85</td>
<td>71.6</td>
</tr>
</tbody>
</table>
Figure 7.2 Calculated surface temperature of Ta and MP35N wires
7.2 Testing of Laser-Treated Ta and MP35N Pacemaker Lead Wires in Real MRI Environment for Temperature Reduction and Mechanical Strengths

We have three sets of samples for each of Ta and MP35N wires, which are as-received, thermo-treated and laser-platinized samples, to investigate the effect of Pt on the mechanical strength and induction heating in real MRI environment.

Ta and MP35N wires of diameter 100 μm each were laser-treated in the absence of Pt precursor and laser-platinized in the presence of Pt precursor at the University of Central Florida. These wires were tested for thermal effects and mechanical strengths by the researchers in Medtronic, Inc. at Minneapolis, Minnesota. For thermal effects, the wires were subjected to radiofrequency magnetic fields that are typically generated during MRI, and reduction in heating by the field was observed for certain laser-platinized wires.

Lead tip heating (LTH) is defined as the temperature near the tip of wires minus the room temperature. The measured LTH for Ta and MP35N wires are plotted in Fig. 7.3. The Pt concentration in Ta wire was determined using EDS. The Pt concentration in the platinized Ta wire is 1.98 at% as shown in Fig. 7.4. The LTH for laser-platinized Ta wire is 19 °C less than the as-received Ta wire. Based on the discussions in Chapter 6, not only Pt atoms should diffuse into Ta wires but also oxygen concentration increases, resulting in smaller LTH through the following two mechanisms: (i) Higher magnetic transmittance due to lower electric conductivity means less energy deposited in the wire and (ii) The thermal capacitance of laser-platinized tantalum wire is higher due to diffused Pt atoms and more Tantalum oxides. The LTH for as-
received and laser-platinized MP35N wires are the same due to the low Pt concentration which is 0.07 at%.

![Graph showing lead tip heating for Ta and MP35N wires in real MRI environment.](image)

Figure 7.3 Heating at Lead tips of Ta and MP35N wires in real MRI environment
As-received Ta wires

Pt concentration = 0 at%

Laser platinized Ta wire

Pt concentration = 1.98 at%

Figure 7.4 Pt concentration in Ta wires
Figure 7.5 Pt concentration in MP35N wires

As-received MP35N wire
Pt concentration = 0 at%

Platinized MP35N wire
Pt concentration = 0.07 at%
The maximum stress which a sample can withstand when it is pulled is called ultimate tensile strength. Spin fatigue life is the number of stress cycles that a sample sustains before the sample fractures. Ultimate tensile strengths and spin fatigue lives were also measured by the researchers in Medtronic, Inc. and listed in Table 7.3 and Table 7.4 for Ta and MP35N wires, respectively. Heat generated during processing can affect wire mechanical properties Ta softens and can embrittle if not protected by inert gas or vacuum MP35N can overage (harden) or anneal (soften), depending on amount of heating. Fatigue performance is impacted by changes in mechanical properties Oxidation and shear force from the pulling of the wire winding spool during the diffusion process may reduce the fatigue life of the treated Ta and MP35N wires. There are more defects on the surface of laser-platinized Ta wires than as-received Ta wires as shown in Fig. 7.6, which may reduce the fatigue life.
### Table 7.3 Ultimate tensile strength and spin fatigue lives of Ta wires

<table>
<thead>
<tr>
<th></th>
<th>Ultimate tensile strength (ksi)</th>
<th>Spin Fatigue life (cycle)</th>
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</thead>
<tbody>
<tr>
<td>As-received Ta wire</td>
<td>340</td>
<td>13570524</td>
</tr>
<tr>
<td>Thermo-treated Ta wire</td>
<td>170</td>
<td>540</td>
</tr>
<tr>
<td>Laser-platinized Ta wire</td>
<td>140</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 7.4 Ultimate tensile strength and spin fatigue lives of MP35N wires

<table>
<thead>
<tr>
<th></th>
<th>Ultimate tensile strength (ksi)</th>
<th>Spin Fatigue life (cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-received MP35N wire</td>
<td>260</td>
<td>169551495</td>
</tr>
<tr>
<td>Laser-platinized MP35N wire</td>
<td>170</td>
<td>11448</td>
</tr>
</tbody>
</table>
Figure 7.6 50× magnitude optical microscope images of as-received and platinized Ta and MP35N wires.
Some Ta wires were laser-treated at laser power 3 W in various atmospheres. The surfaces of those Ta wires are shown in Fig. 7.7 and 7.8. Severe oxidation happened on the surfaces of the Ta wires treated in Air and Vacuum, resulting in black appearance. The Ta wire treated in argon looks similar to the as-received Ta wires. There are some brown-orange residues on the platinized Ta wire, which may come from the Pt precursor.

Figure 7.7 20× magnitude optical microscope images of Ta wires treated at various atmospheres.
Figure 7.8 50× magnitude optical microscope images of Ta wires treated at various atmospheres.
Pt diffusion was applied on some Ta wires at various laser powers. The laser parameters are listed in Table 7.5. The surfaces of those Ta wires are shown in Fig. 7.9 and 7.10. There are some brown-orange residues on the platinized Ta wires, which may come from the Pt precursor. Some black residues were observed on the platinized Ta wires treated at higher laser powers. The black residues might be due to the oxidation.

The scanning electron microscopy (SEM) images were taken for the as-received Ta wire and the Ta wire platinized at laser power 3 W. Under the magnification of 2000, the surface cracks did not reduce after laser Pt diffusion. It may be due to the surface temperature was not high enough at the case of laser power 3 W.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Laser power (W)</th>
<th>Scanning speed (mm/s)</th>
<th>Backfill pressure (psi)</th>
<th>Number of laser pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta-01</td>
<td>3</td>
<td>8</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>Ta-02</td>
<td>5</td>
<td>8</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>Ta-03</td>
<td>7</td>
<td>8</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>Ta-04</td>
<td>9</td>
<td>8</td>
<td>15</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 7.9 20x magnitude optical microscope images of as-received and platinized Ta wires treated with various laser powers.
Figure 7.10 50x magnitude optical microscope images of as-received and platinized Ta wires treated with various laser powers.
Figure 7.11 2000× SEM images of as-received and platinized Ta wires.
Some MP35N wires were laser-treated at laser power 3 W in various atmospheres. The surfaces of those MP35N wires are shown in Fig. 7.12 and 7.13. Severe oxidation happened on the surfaces of the MP35N wires treated in Air and Vacuum, resulting in black residues. The MP35N wire treated in argon has a similar surface to the as-received MP35N wire. The surface of the MP35N wire treated in Pt precursor atmosphere has less white defects than the as-received MP35N wire.

![Figure 7.12 20x magnitude optical microscope images of MP35N wires treated at various atmospheres.](image)

As-received

Air

Vacuum

Argon

Pt-precursor
Figure 7.13 50× magnitude optical microscope images of MP35N wires treated at various atmospheres.
Pt diffusion was applied on some MP35N wires at various laser powers. The parameters for laser Pt diffusion are listed in . The surfaces of those MP35N wires are shown in Fig. 7.14 and 7.15. The white patterns were gone after Pt diffusion process. However, there are some brown-orange residues on the platinized Ta wires treated at the laser power 7W, which may come from the Pt precursor.

The SEM images were also taken for the as-received MP35N wire and the MP35N wire platinized at laser power 3 W. Under the magnification of 1000, the net patterns on the edge of the wire and line patterns at center were gone after laser Pt diffusion. However, some black spots appeared at the center after laser Pt diffusion. The black spots after treatment might be the residues.

Under the magnification of 2000, the black spots on the edge of the wire and line patterns at center were gone after laser Pt diffusion. The black spots at the edge may be the surface cracks and removed by laser treatment. However, some black spots which appeared after treatment might be the residues.
### Table 7.6 Laser Pt diffusion parameters for MP35N wires

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Laser power (W)</th>
<th>Scanning speed (mm/s)</th>
<th>Backfill pressure (psi)</th>
<th>Number of laser pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP35N-01</td>
<td>3</td>
<td>8</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>MP35N-02</td>
<td>4</td>
<td>8</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>MP35N-03</td>
<td>4</td>
<td>11</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>MP35N-04</td>
<td>5</td>
<td>11</td>
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<td>1</td>
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<td>MP35N-05</td>
<td>7</td>
<td>11</td>
<td>15</td>
<td>1</td>
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</table>
Figure 7.14 20× magnitude optical microscope images of as-received and platinized MP35N wires treated with various laser powers.
Figure 7.15 50× magnitude optical microscope images of as-received and platinized Ta wires treated with various laser powers.
Figure 7.16 1000× SEM images of as-received and platinized MP35N wires.
Figure 7.17 2000× SEM images of as-received and platinized MP35N wires.
7.3 Conclusion

Laser Pt diffusion and thermo-treatment were applied on the Ta and MP35N wires. The Pt concentration in laser platinized Ta and MP35N wires was determined using EDS. The ultimate tensile strength, fatigue lives and lead tip heating in real MRI environment of those wires were measured. The platinized Ta wires showed a reduction in lead tip heating in the real MRI environment. The diffused Pt increases the conductivity of Ta wires, resulting in more reflection of magnetic field. In the case of the platinized MP35N wire, the reduction was only 1 °C due to low concentration of Pt. The weaker ultimate tensile strength and shorter fatigue lives of laser-treated Ta and MP35N wires may attribute to the oxidation and heating treatment.
CHAPTER 8: SUMMARY AND FUTURE WORK

8.1 Summary

Magnetic resonance imaging (MRI) has become one of the premier non-invasive diagnostic tools, with around 60 million MRI scans applied each year. MRI of the patients with implanted elongated devices such as pacemakers and deep brain stimulation systems is considered contraindicated due to the induction heating issues. This study proposes an approach to reduce the induction heating by modifying the properties of materials using laser diffusion techniques.

The electromagnetic and thermal models are developed to determine the distribution of magnetic flux density and temperature in metals. Pt is chosen as the added element for this study based on the theoretical results for temperature in the metals during the MRI.

An electromagnetic model which considers the shape of RF magnetic pulses and the interaction of RF pulses with metals is developed. From this model, the analytic solutions for magnetic field and Poynting vector inside the metal are derived. In addition, a thermal model considering the thermal conduction inside the metal is developed as well. Based on these two models, the transient temperature variation of Ti responding to the incident RF pulses is studied. The effects of the heat transfer coefficient, reflectivity, thickness of Ti plates and pulse repetition rate on temperature variation are discussed as well. Increasing the reflectivity of the metal is a potential way to reduce RF induction heating.
A mathematical model is presented to determine the electromagnetic properties of metals based on the transmission measurements. Ti sheets of thicknesses 25 and 50 μm were considered as test samples, and Pt was diffused into some of the samples using a laser diffusion technique to understand how the properties of metals can be modified at the low frequency of interest. The electrical conductivities of the platinized and as-received samples are found to be $2.30 \times 10^6$ and $2.51 \times 10^6$ m$^{-1}$Ω$^{-1}$, respectively, which is an increase by 9.1%, and, consequently, the reflectivity of the former is higher than the latter. Additionally, the absorbance of the platinized sample decreases by 0.9% when compared to that of the as-received sample, indicating that the sample would be heated less by the time-varying magnetic field.

A beam shaping lens system is designed based on vector diffraction theory. This beam shaping lens can transform the incident Gaussian beam into a flat-top beam with improved irradiance uniformity. The variation of the irradiance in a circular area with a radius of 5.5 mm is less than 2%. Additionally, a novel beam shaping lens system which can transform the incident randomly polarized Gaussian beam into a linearly polarized flat-top beam is designed. A linearly polarized flat-top beam is obtained on the target plane 100 mm behind the beam shaping lens. The variation of the irradiance profile is less than 2% inside a circular area of radius 5.5 mm.

Laser Pt diffusion treatments are studied for four polarizations of a Nd:YAG laser using thin sheets of Ti and Ta as test samples. Trace Pt atoms diffuse into the Ti and Ta. The concentration of Pt atoms is higher at lower scanning speed due to higher surface temperature. The samples treated by a linearly polarized laser beam have slightly higher concentration of Pt. The enhanced diffusion from linearly polarized laser beams can be attributed to two reasons: (i) The linearly
polarized laser beam can excite the local vibration modes of impurities and substrate, and (ii) The polarization direction is parallel to the concentration gradient of Pt atoms.

The effect of impurity on the transmission of a radiofrequency (63.86MHz) magnetic field is examined. Pt decreases the transmittance of Ti and O increase the transmittance of Ta samples, respectively, compared to that of untreated (as-received) samples. For Ti sheets, the reduction in the transmittance can be attributed to the increased electrical conductivity due to the Pt diffusion. However, laser diffusion treatment has opposite effects for Ta sheets, which can be attributed to the surface oxidation. Additionally linearly polarized lasers control the direction of lattice vibrations and excite the local vibration modes of atoms so as to enhance the diffusion of Pt into the Ti and Ta sheets.

The reflectivity of rough surfaces depends on the surface roughness, incident angle and polarization. The theoretical reflectivity of rough surfaces is calculated based on a model considering surface roughness and polarizations and is compared with the experimental data. The surface of Ti samples can be seen smooth due to their small surface roughness compared with the laser wavelength and Ta samples have rough surfaces.

Laser Pt diffusion and thermo-treatment were applied on the Ta and MP35N wires. The Pt concentration in laser platinized Ta and MP35N wires was determined using EDS. The ultimate tensile strength, fatigue lives and lead tip heating in real MRI environment of those wires were measured. The platinized Ta wires showed a reduction in lead tip heating in the real MRI environment. The diffused Pt increases the conductivity of Ta wires, resulting in more reflection
of magnetic field. In the case of the platinized MP35N wire, the reduction was only 1 °C due to low concentration of Pt. The weaker ultimate tensile strength and shorter fatigue lives of laser-treated Ta and MP35N wires may attribute to the oxidation and heating treatment.

8.2 Future Work

In this study, all the models are developed for plane sheets. The induction heating is severe in the case of elongated implanted conductive devices such as pacemakers and DBS systems which have a long metal wire. Developing the models for the metal wires is necessary in order to solve the induction heating issues for elongated implanted conductive devices. The Ta and MP35N wires were treated by randomly polarized laser beams. It is also necessary to treat the Ta and MP35N wires using other polarized laser beams.

Diffusing Pt can modify the properties of Ti and Ta sheets. However, MP35N alloy is widely used for implanted devices. The composition of MP35N alloy is listed in Table 8.1 [Davis et al. (2000)]. Diffusant selection, properties of treated MP35N samples and mechanisms for property changes need to be studied due to the distinct composition of MP35N from Ti and Ta.

The mechanical properties such as ultimate tensile strength and fatigue life of laser-treated Ta and MP35N wires are smaller than the as-received wires. Oxidation is one of the possible reasons. The other possible reasons need to be determined and solved in order to maintain the original mechanical properties. Building up a high vacuum chamber which can accommodate all
the wire winding components may avoid oxidation of wires and applied shear force during the laser diffusion process.

<table>
<thead>
<tr>
<th>Table 8.1 Chemical composition of MP35N</th>
</tr>
</thead>
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<tr>
<td><strong>Element</strong></td>
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<tr>
<td>Co</td>
</tr>
<tr>
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<tr>
<td>Cr</td>
</tr>
<tr>
<td>Mo</td>
</tr>
<tr>
<td>Fe</td>
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<tr>
<td>Ti</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>Mn</td>
</tr>
<tr>
<td>Si</td>
</tr>
</tbody>
</table>

The concept of frequency selective surface may be applicable to this study. Creating patterns with different conductivity on the surface of materials as shown in Fig 8.1 changes the effective impedance of the materials, which may increase the reflectivity of the materials at a fixed frequency. The lower conductivity areas can be created by diffusing carbon, nitrogen and oxygen in the substrate. The dimensions of the patterns can be determined such that the reflectivity of the materials reaches the theoretical maximum. In the case of long wires, the patterns can be a one-dimensional conductivity change along the wires as shown in Fig. 8.2. These patterns on the wires may be considered as one-dimensional periodic structures such as gratings.
Figure 8.1 Creating patterns on the surface of materials to have high reflectivity at a fixed frequency

Figure 8.2 Illustration of one-dimensional patterns on a wire.
LIST OF REFERENCES


Bokor, N. and Davidson, N. (2001), Beam shaping with diffuse light using a single reflection, 

Borek, G. T., Brown, D. R. and Clark, R.(1999), High-performance diffractive optics for beam 


Brown, D. R. (2000), Laser beam shaping with diffractive diffusers in Dickey, F.M. (ed), Laser 
Beam Shaping, Marcel Dekker, New York, pp. 249-271.

14, pp. 231-235.

metals based on transmission measurements at 64 MHz, Proc. ICIPE, edited by Alain, J. 

pp. 204.

Cook, R. L. and Torrance, K. E. (1982), A reflectance model for computer graphics, ACM 

International, Materials Park, pp. 380-381.

3-5.


Gray, R.W., Bibensa, W.T. and Shellok, F.G. (2005), Simple design changes to wires to substantially reduce MRI-induced heating at 1.5 T: implications for implanted leads, Magnetic Resonance Imaging, Vol. 23, pp. 887-891.


safe: In vitro and in vivo assessment of safety and function at 1.5 T, Circulation, Vol. 110, No. 5, pp.475-482.


Sutton, R., Kanal, E., Wilkoff, B.L., Bello, D., Luechinger, R., Jenniskens, I., Hull, M. and Sommer, T. (2008), Safety of magnetic resonance imaging of patients with a new
Medtronic EnRhythm MRI SureScan pacing system: clinical study design, Trials, Vol. 9. pp. 68-75.


patients with a pacemaker system designed for the magnetic resonance environment, Heart Rhythm, Vol. 8, pp. 65–73.


