8-2010

INDUCTION ASSISTED THERMOGRAPHY FOR INSPECTION OF MICRO DEFECTS ON SHEET METALS

Sree Pamidi
Clemson University, harshapamidi@gmail.com

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INDUCTION ASSISTED THERMOGRAPHY FOR INSPECTION OF MICRO DEFECTS ON SHEET METALS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

by
Sree Harsha Pamidi
August 2010

Accepted by:
Dr. Mohammed Omar, Committee Chair
Dr. Laine Mears
Dr. Steve Hung
ABSTRACT

The work focuses on Induction assisted Thermography as a non-contact and non-destructive method of Inspecting micro defects on sheet metals used for making automotive body panels. Induction heating as a source of excitation to elevate the temperatures of sheet metals for uniform heating and detect ability of the defect is the main objective of the study.

Experiments are done on sheet metal samples with defects using excitation techniques like Pulse and Electromagnetic Induction. The thermal images obtained from the infrared camera are used to quantitatively analyze the detect ability of defects on sheet metals. The limitations of using Pulse technique and advantages of using Electromagnetic Induction technique for these kinds of defects are discussed.

Spatial distribution of temperature for various experimental conditions is also discussed to optimize induction heating requirements.
ACKNOWLEDGMENTS

I would like to acknowledge Dr. Mohammed Omar for his valuable support during this work. I would like to thank Dr. Laine Mears and Dr. Steve Hung for their valuable suggestions and comments.

I would also like to thank my friends Rohit Parvataneni, Bhanu Singh, Suhas Vedula, Konda Reddy, Yi Zhou, and Ahmad Mayyas for their help in conducting the experiments and in my thesis review.
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Chapter 1

1.1 Introduction

Defects and flaws in products fabricated in the manufacturing firms play havoc with the performance of the product immediately or in the near future. It is necessary the product be tested before it can be put to use and is one of the main reasons why quality control of engineering system is an essential entity in a manufacturing chain. A small defect in a product can go undetected while being fabricated during a manufacturing process which could lead to the rejection of the product in a market. For example, defects on the surface of the steel sheets manufactured in steel manufacturing industries can lead to the rejection of the whole coil at an OEM. Quality control in the recent past more often has been tagged to Non-destructive testing and to noncontact measurements in a more specific way. Noncontact in one sense is more helpful for online inspection of a part reducing the time consumed for inspection. But, the major advantage of a noncontact inspecting system lies in its ability to evaluate a component without causing any damage to the component i.e., none of its physical, mechanical and functional properties are altered.

The ability of evaluating a product with several readily available noncontact testing techniques made it easy for the manufacturing giants to adopt Non-destructive testing as one of the finest state-of-the-art technologies. Non-destructive testing techniques such as Infrared thermography, Acoustic emission testing, Electromagnetic testing, Ultrasonic testing, Radiography, Eddy current testing, Magnetic resonance imaging, and etc., are in use in the present day quality control engineering.
1.2 Non-Destructive Testing

Non-destructive testing can be defined as a test or evaluation of a component without altering its physical, mechanical and functional properties and does not affect its future usability. The NDT techniques in present use are discussed below:

1) Acoustic emission testing
2) Ultrasonic testing
3) Radiography
4) Eddy current testing
5) Infrared thermography

1.1(a) Acoustic Emission testing:

Acoustic Emission refers to the generation of transient elastic waves, due to structural reorganization of a material or sudden redistribution of internal stresses due to change in the structure of a material(s) under external loading [1]. Structural changes in a material due to external loading may result from crack initiation and growth, slip and dislocation movements, twinning or phase transformation [2]. It results from a rapid or spontaneous release of elastic energy or said to occur when the stresses in a material relax.

AE’s originate from a point source and radiate energy in spherical wave fronts. These wave fronts cause disturbance in the molecules present on the boundary or surface of the material. A Transducer detects the movements of these molecules, converts the movements into electrical voltage signals and these signals are further analyzed to
evaluate a defect in a component. These waves fall in the ultrasonic region within the range of 20 KHz and 1 MHz

The main disadvantage with this type of testing is that AE signals are generally very weak in nature. The sensors detect all types of background noises and it becomes difficult to discriminate the AE signals from other background noise signals. Therefore pre-amplifiers and filters must be effectively used to face these challenges. AE’s give qualitative results only; therefore it has to be used in combination with other NDT methods to obtain quantitative results.

1.1(b) Ultrasonic testing:

Ultrasonic testing has been useful as an NDE method because of its ability to penetrate through opaque objects and detect internal irregularities like cracks and defects. A pulse is given to the work piece and the Ultrasonic waves generated in the work piece are detected with the help of a piezoelectric transducer. The frequency range of 0.1MHz to 15MHz is generally used.

Four different kinds of Ultrasound wave modes are used for detection of irregularities in a material. Longitudinal wave mode, Compression wave mode, Surface wave mode and Lamb waves [3]. Each wave mode has its own importance and used for various applications like weld testing, fatigue crack detection of in-service bridges and inspection of thin materials.

The main disadvantage of this type of testing is that the Ultrasonic wave propagation is influenced by the geometry of the component. So, the wave patterns cannot be relied upon for complex geometries. The other disadvantage is that the
piezoelectric transducers are fragile and cannot survive high temperatures. So, they need a coupling agent such as water or gel and some gels have the problem of air bubble accumulation which can attenuate the reflected signals.

1.1(c) Radiography:

Radiography is an NDT technique in which the image of an object is obtained by penetrating radiations such as x-rays or γ-rays. The images which are recorded using radiography are called as radiographs. Radiograph is a projection of the object and hence the contrast in a radiograph is a result of different degree of absorption, thickness, non-uniform distribution, discontinuities, and chemical composition of the material [4]. Since radiographs are projected images access to other side of the material is required for complete inspection. Radioscopy, Xerography, Radiometry etc are the different techniques in x-rays imaging. Although the image gives a projection of the object one cannot infer the depth details of the object using Radiography.

1.1(d) Eddy Current testing:

Eddy current testing is based on Faraday’s law of electromagnetic induction. Faraday’s law states that when a conductor cuts a magnetic field an electric field is created in the conductor. The alternating magnetic field which exists around a coil carrying current induces oscillating eddy currents in to a conducting material due to electromagnetic induction. These eddy currents flow parallel to the coil windings. If the conducting material has a defect, a variation in the eddy current flow is observed and the loading on the coil and its impedance is affected by the phase and magnitude of the eddy current.
Suppose a crack exists in a conductor it obstructs the eddy current flow and reduces the loading, ultimately increasing the effective impedance. A change in voltage across the coil can be accounted for a crack or irregularity on the conductor. Also changes in the electrical conductivity or magnetic permeability of the material being tested can cause a change in the eddy current flow and subsequent changes in the phase and amplitude of the measured current can be observed. One of the main draw backs is that Eddy current testing can be applied to only conducting materials and if the defect lies parallel to the testing probes it is very difficult to detect them.

1.3 Thermography

Thermography or Infrared thermography is an effective NDT technique in which the heat distribution in an object and variation in this distribution with time is captured using an infrared detector. Every object radiates or emits electromagnetic radiations with different wavelengths. The infrared detectors detect these radiations in the infrared region of the electromagnetic spectrum and produce thermograms or infrared images. The energy emitted by a surface at a given temperature is the spectral radiance and is defined by Planck’s Law [5]. Variations in the radiance of an object with time can be detected by these infrared detectors and this property can be exploited to detect discontinuities on the surface and sub-surface defects. Any discontinuity or defect when excited would appear darker or brighter depending up on the emissivity difference between itself and the surrounding, and this emissivity depends on the nature, size, shape and orientation of the defect.
Thermal emissions:

All objects are composed of atoms which vibrate according to the amount of energy present in them. These vibrating atoms produce electromagnetic radiation with particular wavelengths. As a result, these objects continually emit radiation at a rate with a wave-length distribution that depends upon the temperature of the object and its spectral emissivity, $\varepsilon (\lambda)$.

Emissivity of an object is the ability of a material to emit thermal radiation. It is a function of wavelength, temperature, material type and surface condition of the radiating body. It is the most important factor in thermal imaging because, every object has its own emissivity and, the infrared image holds the information about distribution of infrared radiance of that particular object which varies accordingly with the emissivity of the object.

1.4 Classification of Thermography Techniques

Infrared thermography can be further classified into two categories:

1) Passive thermography
2) Active thermography

Passive thermography:

Passive thermography technique uses natural thermal contrast between the region of interest and its surrounding to detect discontinuities or defects in an object. The thermal contrast occurs naturally i.e., no source of excitation is used to get the thermal contrast. The region of interest may be at a higher or lower temperature from its
surroundings. Its applications include condition monitoring, surveillance, medical imaging etc.

Active thermography:

Active thermography uses the application of heat sources to excite an object and induce a thermal contrast between the region of interest and its surrounding. This kind of thermography is active in several industries for quality control of the engineering systems. Table 1.1 shows the classification of Infrared thermography.

![Classifications of Thermography Technique Diagram]

**Table 1.1 Classifications of Thermography Technique**

The excitation methods in Active thermography are further classified into three types:

I. Optical excitation
II. Electromagnetic excitation

III. Mechanical excitation

1.4 a) Optical Excitation Method:

In this kind of excitation the material or the work specimen is heated to attain a certain temperature using short high intensity pulses from various sources like Halogen lamps, Xenon flash lamps or by modulation techniques.

Pulse thermography:

Pulse thermography also known as thermal wave imaging is a technique in which thermal images of a material are captured based on the infrared radiations emitted by a material when subjected to periodical excitation with a certain lock-in frequency. It can also be termed as transient thermography because it deals with exciting the material in active mode and capturing the images of the material in cooling mode after the excitation [6]. A short and high intensity pulse is induced in the material by means of optical excitation sources like Halogen lamps, Xenon flash lamps or Quartz lamps. The thermal pulse induced, alters the temperature of the material and a measurement of the temporal evolution of the material temperature is done with the help of an Infrared camera.

The thermal excitation rapidly increases the temperature of the material, and the heat generated in it is dissipated throughout the material by diffusion. Whenever a defect or discontinuity occurs the diffusion rate varies and the temperature at the defect appears to be different from that of the surrounding material. This variation in the temperature is captured by the Infrared camera as a variation in the radiance. Fourier transforms are performed with the help of camera software to convert these variations in the radiance to
actual temperature difference values. Further the captured images can be processed by image processing to enhance the visibility of the defect. The location of a defect in a material effects the observation time, i.e., deeper defects appear later in the and also with a reduced contrast. The observation time and contrast are given by [7]

\[ t = \frac{z^2}{\alpha} \quad \text{and} \quad c = -\frac{1}{z^3} \quad (1.1) \]

Where
\[ t = \text{observation time} \]
\[ z = \text{depth} \]
\[ c = \text{loss of thermal contrast} \]
\[ \alpha = \text{thermal diffusivity} \]

The images can be captured and observed in two ways. One is by transmission and the other by reflection. In transmission, the heat source is placed on one side of the material while the camera is placed on the other side and it captures the transmitted radiations. In reflection, both the camera and the heat source are placed on the same side of the material and the camera captures the reflected images from the material. Reflection approach is more dependable when surface defects are to be detected.

Figure 1.1 Experimental setup for Pulse thermography
Although Pulse thermography is an efficient technique in detecting surface and sub-surface defects there are also some drawbacks with this technique. The noise from highly reflective materials is so high that the signal to noise ratio gets below one indicating more noise than the actual signal. Orientations of the defect and variations in its emissivity also have significant effects. One of the most important drawbacks is non-uniform heating of the material due to the orientation of the heating source.

b) **Lock-in or Modulated thermography:**

In lock-in thermography a continuous sinusoidal heat wave is used to excite a material as opposed to pulse technique. The material is subjected to modulated heat source which induces a thermal wave on the surface of the material and it propagates through the material. One of the main advantages of this technique is its averaging nature which increases its sensitivity which is higher when compared to the nominal sensitivity of the camera used. The depth of penetration of the sinusoidal wave depends on its frequency. Lower frequency indicates higher depth of penetration, can be used for testing very thick materials, and vice-versa.

Whenever a defect or void in a material occurs the propagating thermal wave is reflected back to the surface. These reflected waves interfere with the surface waves and produce an oscillating radiation pattern which can be measured on the surface with the help of an infrared detector [8]. The infrared detector captures a series of images and compares the temperatures at each and every point calculating the phase angle and the amplitude at those points. This is done by synchronizing the image recording frequency with the modulation frequency and a steady state is reached.
The radiations reflected from the surface of the object do not disturb the amplitude and phase images because they have the same phase angle and amplitude. Therefore issues relating to reflections are eliminated. Also the phase image is not disturbed by variations in the emissivity and non-uniform heating in the material. But the main drawback with this technique is its longer measuring time when compared to pulse thermography since it is averaged over a number of lock-in periods. For accessing information about different depths one has to take several measurements using different lock-in frequencies and also in an order.

Figure 1.2 Experimental setup for Lock in thermography

The thermal wave attenuates and penetrates only to a certain depth in the object and is mainly dependent on the wave cycle time. Material properties like heat conductivity, heat capacity and density also affect attenuation [8]. The range of the magnitude image is given by “μ” also called as thermal depth range.

\[
\mu = \sqrt{\frac{2k}{\omega \rho c}} \quad (1.2)
\]
Where \( k \) = heat conductivity
\( \omega \) = modulation frequency
\( \rho \) = density
\( c \) = heat capacity

After this depth is reached the amplitude of the heat wave reduces to 37% of the surface value.

1.4 b) Electromagnetic or Eddy Current Excitation:

Electromagnetic or Eddy current thermography uses the same principle of eddy current testing but the only difference is that the surface or sub surface defects are detected not by the voltage difference across the coil. This technique makes use of alternating current to locally heat a conducting material and then the surface temperatures are mapped using a thermal imaging infrared camera.

Induction heating is mainly based on Electromagnetic Induction and Joule heating. Whenever power is supplied to an induction coil a potential difference or voltage is induced in the coil and this voltage results in the flow of electric current through the coil. Faraday’s law of Electromagnetic Induction is the principle behind this phenomenon. The current flow in the coil induces alternating magnetic field in the coil and a conductor brought in its vicinity is heated up due to Joule heating. The electromotive force induced in the coil is given by

\[
E = N \frac{d\Phi_B}{dt} \quad (1.3)
\]

Where \( E \) = electro-motive force (Volts)
\( N \) = no. of turns in the coil
\( \Phi_B \) = magnetic flux through the coil (Weber)

And the Joule heating in the conductor is given by

\[
Q = I^2 \cdot R \tag{1.4}
\]

Where \( Q \) = heat induced in the conductor
\( I \) = current in the conductor (Amps)
\( R \) = resistance in the conductor (Ohms)

But in many cases the Joule heating cannot be given as a simple equation mentioned above. It might be different because of non-uniform heating of the conductor. Several factors like: depth of penetration or skin depth, permeability of the material, geometry of the material, material conductivity, and proximity of the coil affect the eddy current response in a conductor [9].

**Skin effect:**

The tendency of an alternating current to distribute itself on the surface of a conductor and decay rapidly as the depth increases is called the skin effect. Skin depth varies greatly with the electrical conductivity, permeability of the work piece and also the frequency of current at the Induction coil. Skin depth \( (\delta) \) in a rectangular slab is given by

\[
\delta = \sqrt{\frac{2}{\omega \sigma \mu}} \tag{1.5}
\]

Where \( f \)= frequency (Hz)
\( \sigma \) = electrical conductivity of the conductor (S/m)
\( \mu \) = permeability of the conductor (H/m)


1.4 c) Mechanical Excitation Method:

As opposed to external excitation in optical excitation techniques mechanical excitation method is used to excite a material internally. This internal excitation is achieved by means of mechanical oscillations, with a sonic or ultrasonic transducer for both burst and amplitude modulated simulation.

Vibrothermography:

Vibrothermography also known as Ultrasound thermography is a mechanical excitation technique which uses mechanical waves to directly stimulate internal defects and without heating the material [11]. Ultrasonic waves travelling freely through a uniform material when obstructed by a defect produce a combination of absorption, scattering and dispersion of the waves which appear in the form of heat. The heat produced at the cracks or defects travel to the surface in all directions due to conduction. The heat signature thus released from the defect can be captured using an infrared camera. Ultrasonic waves are very useful in NDT because defect detection is independent from its orientation inside the material and both internal and open surface defects can be detected. Most of the transducers operate between 15 KHz and 50 KHz. These sonic and ultrasonic waves are mechanical elastic waves and unlike magnetic waves need a medium to propagate. They use a coupling agent between the transducer and work piece to effectively transmit the waves without losses.

1.5 Thermal Imaging Cameras

Infrared radiations are similar to visible light radiations, but with a longer wavelength. While visible light energy is emitted by objects only at a very high
temperature, infrared radiations are emitted by all objects at ordinary temperatures. Thermal imagers sense infrared energy which varies with the temperature of object in a scene and produce images which have the thermal signature of the scene. Optics is used to focus the Infrared energy on to the Infrared detectors. The information is then sent to sensor electronics for image processing. The signal processing circuitry translates the infrared detector data into an image that can be viewed as a thermal image on a PC.

The infrared spectrum can be divided into three regions based on the detectors used to capture the infrared radiations:

1) Near Infrared 0.75µm – 1.5µm
2) Middle Infrared 1.5µm – 20µm
3) Far Infrared 20µm - 1000 µm

Photographic emulsions, photo emissive cells, photoconductive and photovoltaic detectors can be used for detecting radiations in the near Infrared region. Thermal, photoconductive and photovoltaic detectors for middle Infrared and thermal detectors can be used for measuring the radiations in the far infrared region. All these detectors can be classified into two types:

1) Thermal detectors (uncooled cameras)
2) Photon detectors (cooled cameras)

1.5 a) Thermal detectors:

Thermal detectors are heat detectors in which the incident radiation absorbed produces a change in the temperature of the material and the resultant change in some of the physical properties of the material is used to produce an electrical output [12]. The
photons incident due to infrared radiation do not influence the thermal effects in thermal detectors. The signal is obtained because of the radiant power but not the because of the spectral content so the thermal changes in it are independent of the wavelength.

Pyroelectric detector, Bolometer, Thermopiles, Golay cells and superconductors are the different types of thermal detectors. A variation in the internal spontaneous polarization is measured in Pyroelectric detectors whereas a change in the electrical resistance is measured in case of a bolometer. Unlike photon detectors thermal detectors do not need cryogenic coolers to cool the Focal plane arrays. The sensitivity of thermal detectors is comparatively very low to that of photon detectors and the response rate is also slow because time is consumed in heating up the device after the energy has been absorbed by the detector. But, they are cheap, easy to use.

**Bolometer:**

Bolometer is a thermal detectors in which the temperature and conductivity changes are caused due to the incident radiation on the detector. The temperature of the detector depends on the power absorbed and radiated by the detector. The energy variation with time is given as

\[
dU/dt = W_s + W_e - W_d \tag{1.6}
\]

Where \( W_s \) = signal energy

\( W_e \) = energy from the environment

\( W_d \) = energy radiated by the detector

And the energy radiated by the detector is given by

\[
W_d = A\sigma T^4 \tag{1.7}
\]
Where \( A \) = area of the detector
\[
\sigma = \text{Stefan’s constant}
\]
\( T \) = temperature at which energy is radiated

The sensitivity of a thermal detector is given by
\[
S_F = \frac{1}{4\sigma T^4} = \frac{1}{\kappa}
\]  \hspace{1cm} (1.8)

Where \( \kappa = \text{thermal conductance} \)

Hence the sensitivity of the detector is dependent on the energy radiated by the detector and is inversely related to the detector energy.

Bolometer is made of metals or semiconductors elements (thin chips) made by sintering powdered mixtures of ferrous oxides and mounting them on dielectric substrate which in turn is mounted on metallic heat sink and is usually a part of a bridge circuit consisting of active bolometer and compensated bolometer. The incident radiation produces a temperature rise which decreases the resistance, and in order to produce an electrical current the compensated bolometer comes into play to produce a bias voltage in the circuit. The sensitivity decreases with increase in thermal conductance and hence is inversely related. Bolometer is a very slow detector since the thermal conductance is large and the energy radiated by the detector is very high and thus the sensitivity is reduced.

**Pyroelectric detectors:**

Pyroelectric detectors consist of wafers of metal electrodes with a thin layer of Ferro-electric material sandwiched between them. These detectors produce surface electric charge when heated and this is due to the inherent electrical polarization of the
ferromagnetic material whose magnitude is a strong function of temperature [12]. A variation in the absorption of radiation or irradiance of the detector causes a change in the temperature of the detector. A temperature change either expands or contracts the crystal wafer producing a change in the polarization of the material. A charge on the capacitor due to variations in the polarization of the Pyroelectric element causes a voltage across the circuit and this voltage can be observed until the detector is subjected to irradiance. These kinds of detectors find their application in surveillance applications rather than using them for measuring purposes.

**Thermopiles:**

A thermopile is a combination of series-connected thermocouples. Thermocouples are devices which produce thermoelectric EMF. A thermocouple consists of both hot and cold junction. The incident radiation is used to increase the temperature of the hot junction while the cold junction is shielded. A voltage occurs in the circuit due to Seebeck effect. Heavily doped semiconductors are used to increase the electrical conductivity and reduce the thermal conductivity. To maximize the voltage output these thermocouples are connected in series and further connected to amplifiers to increase the signal.

**1.5 b) Photon detectors:**

In photon detectors the effects occur due to direct conversion of incident photons into conducting electrons within the material i.e., the radiation is absorbed within the material by interaction with electrons. The photonic excitation of the electron from a non-conducting state to a conducting state changes the electron energy distribution and as a
result a change in the electrical output is observed. As opposed to thermal detectors, photon detectors show wavelength dependence of the response per unit incident radiation power. Although photon detectors need cryogenic cooling of the focal plane arrays one can get very good signal to noise performance with very good efficiency.

The signal of photon detector is so small that it is swamped by the thermal noise at normal temperature and hence cooling of the photon detector is necessary. Four types of cooling mechanisms are currently in use, they are: cooling by liquefied gas (like liquid Nitrogen, liquid Helium, and liquid Hydrogen), cooling by Joule-Thomson expansion of a high pressure gas, cooling by cryogenic cycles (Stirling cycle, Gifford-Macmahon cycle, Vuilleumier cycle and open cycles) and cooling by thermoelectric effect.

Photon detectors are further divided into photo emissive detectors and Quantum well detectors [13]. Quantum well detectors are further divided into intrinsic detectors and extrinsic detectors. Examples: photoconductive and photovoltaic detectors. The Noise equivalent temperature difference (NETD) which is measure of the sensitivity of the camera is very high for photon detectors when compared to that of thermal detectors. Also the resolution of such detectors is high compared to that of thermal detectors. The only drawback is that due to the cooling mechanism required they are bulky and very expensive.

**Photo emissive detectors:**

In this kind of detector a photon incident on the detector interacts with a solid surface or a gas (usually a Cathode) releasing a photoelectron which is collected at the positive electrode the anode. The photo emissive cells give an output which is a measure
of the number of electrons released from a solid due to the incident photons on the detector [14]. These cells are made up of photocathode and anode surrounded by vacuum and enclosed in a glass.

The sensitivity and the efficiency of these detectors depend on the energy that is supplied to the electrons to make them move from the photocathode to the anode through the vacuum. Some cells contain inert gases instead of vacuum which increase the sensitivity by ionizing the gas. If the energy supplied by the photons incident on the photocathode is higher than the energy required for binding the electrons to the photocathode, the electrons transit from the cathode to the anode resulting in a current.

Photomultipliers consisting of a series of electrodes called the dynodes or a dynode chain held at appropriate potentials produce a secondary-electron multiplication process at the cathode. An electron produced at a dynode collides with the other dynodes and produce several electrons and the multiplication process occurs with increasing number of dynodes. In such a fashion several electrons reach the anode for each incident photon. Vacuum phototubes, Gas-filled phototubes, Gas-filled X-ray detectors, Ionization chambers etc are other types of photo emissive detectors.

**Photoconductive detectors:**

Photoconductive detectors are semiconductor detectors in which the absorbed photons produce electron-hole pairs (photoelectric effect) in the crystal lattice or the semiconductor material. Electrons are raised from the valence band to the conduction band if the photon energy exceeds the energy gap between the valence band and the
conduction band and the current flow is proportional to the irradiance of the semiconductor material. The materials can be either intrinsic or extrinsic.

For intrinsic photoconductors the energy of the incident photon should be greater than that of the forbidden gap band. Lead sulfides (Pbs), Indium Antimonide (InSb), Mercury-Cadmium-Teluride (HgCdTe) are the different kinds of intrinsic semiconductor detectors. Extrinsic semiconductors are doped with certain impurities which reduce the energy required by the photon to excite the electrons in the valence band to enter the forbidden gap and then the conduction band. Germanium or Silicon doped with Gold, Mercury, and Copper, etc are the different kinds of extrinsic semiconductor devices.

**Photovoltaic detectors:**

These kinds of detectors produce a current flow within a semiconductor device which has the potential of modifying the potential barrier in a junction in the semiconductor. A local change in the electric field $E$ caused due to the presence of junctions in the semiconductor distorts the conduction and valence bands between the n and p regions [14]. If the photons incident on the semiconductor have sufficient energy to cause a transition inside the semiconductor electrons and holes are freed which diffuse across the junction under the influence of the electric field.

The absorption of photons in the p and n type regions contribute in the creation of current by diffusion and as a result the potential barrier is modified. Thus electric current is produced which is an electric signal. Indium Arsenide (InAs), Indium Antimonide (InSb), Cadmium Mercury Telluride (TeCdHg), and etc., are the different materials used for constructing photovoltaic detectors.
Chapter 2

Induction

Until Ampere’s experiments on a current carrying conductor and a magnetic compass, electricity and magnetism were considered as unrelated phenomenon. Ampere discovered that a magnetic field existed in circular loops in a plane perpendicular to a current carrying wire. Electromagnetic induction was first discovered by renounced scientist Michael Faraday in the year 1831. He showed that the basis for metal heating by Induction is due to the magnetic field which is a property of space that surrounds an electric current and a magnet.

In his primary experiments, Faraday wound a coil of wire around an iron ring with its other end connected to a battery. He wound another coil of wire to the iron ring and this time he connected it to a Galvanometer. He made sure that none of the coils came in contact with each other. When he connected the primary coil to the battery he observed that the current flowed through the coil and a magnetic field was established in both the coils. No current existed in the secondary coil as long as current flowed in the primary coil. But for a brief moment when the battery was switched on and the current in the primary coil rose from zero and a small current was observed in the secondary coil and similarly a small deviation in the Galvanometer was observed when the current in the primary coil was shut off. He discovered that the current was generated in the secondary coil due to changing magnetic flux within the secondary coil.

The resistance in the secondary coil defines the strength of the current in the secondary coil. An electromotive force is induced in the secondary coil with a change in
the magnetic flux through the circuit and rapid changes in the flux indicate greater
electromotive force induced. **Faraday’s law** of Electromagnetic induction states that:
“The Electromotive force (EMF) induced in a circuit is directly proportional to the time
rate of change of magnetic flux through the circuit [15]” or simply it can be written as the
EMF generated in a circuit due to changing magnetic flux is equal to the rate of change of
magnetic flux through the circuit. Electromotive force \(E\) generated in a circuit when the
magnetic flux in the circuit changes by an amount \(d\Phi_B\) in a time interval \(dt\) is given by

\[
E = \frac{d\Phi_B}{dt} \tag{2.1}
\]

The direction of the EMF generated by time varying magnetic flux linking an
electric circuit is given by **Lenz’s law**. The EMF induced in an electric circuit always
acts in such a direction that the current it drives around the circuit opposes the change in
magnetic flux which produces the EMF. So the above equation combined with **Lenz’s
law** can be written as

\[
E = - \frac{d\Phi_B}{dt} \tag{2.2}
\]

The negative sign indicates that the EMF generated always tends to oppose the
changing magnetic flux which generates the EMF.

We have been discussing Faraday’s law and Lenz’s law but what are the practical
applications of these laws? Why is the term induction important for the present work?
What is induction heating?

**2.1 Induction Heating**

Induction heating is a noncontact heating method dependent on electromagnetic
heating which is caused by energy absorption from an alternating magnetic field
generated by an induction coil. The conductivity of the material or the work piece is responsible to the degree up to which it can be heated. Induction can be used to heat conductive bodies while indirect heating is used for nonconductive bodies. There are the two modes of electromagnetic energy absorption when it comes to induction heating. They are [15]:

1. Eddy current losses and

2. Hysteresis losses.

Alternating magnetic field flowing through a conductive material (Steel, Copper, Graphite, and Aluminum etc) generates eddy currents within the conductive material and these currents cause Joule heating due to electrical resistance of the conductive body. For Eddy currents to flow within a conductive material it is required that the conductive material offers a conductive path. Joule heating only occurs when Eddy currents flow though the material and electrical resistance is offered by the conductive material. Heating in most of the materials is due to Eddy Currents generated within the material.

Hysteresis losses or hysteresis heating in a material occurs due to the friction between the domains in a magnetic material (like ferromagnetic materials) caused by the orientation of external magnetic field. For Non magnetic materials like Copper, Aluminum etc, heat generation due to hysteresis heating is almost considered to be zero. The heating percentage by hysteresis losses is very low in compact materials at lower frequencies and diminishes close to zero at higher frequencies. For practical applications only the heating due to Eddy currents is taken into account and Hysteresis heating is ignored in most of the cases.
2.2 Principles of Induction Heating and Sequence of Phenomenon

The two most important physical phenomena responsible for Induction heating are (discussed in the first chapter):

1. Electromagnetic induction and
2. Joule heating

Sequence of phenomena that occur in an induction heating process:

i. The power supplies convert the line power to required power with required frequency, current and voltage and the generator supplies a current to the induction coil.

ii. These currents travel along the direction of the coil and magnetic field lines are generated in a direction perpendicular to the plane of flow of current (given by right hand thumb rule). The magnetic field lines never end and always form a continuous loop. Since alternating currents are supplied to the coil the magnetic field is also alternating in nature.

iii. A conductor placed in this alternating magnetic field couples with it and as a result a voltage is generated within the conductor. The induced voltage or EMF generated induces Eddy currents within the conductor whose direction is opposite to the coil current direction.

iv. The electrical resistance of the conductor opposes the flow of Eddy currents and as result heat is generated within the conductor.
2.3 Magnetic Flux from an Electromagnetic coil

The magnetic flux ($\Phi_B$, units: Weber or J/A) generated in a coil is given as a product of the magnetic field ($B$, units: Tesla or N/Am) generated and the area ($A$) of the coil

$$\Phi_B = B.A$$  \hspace{1cm} (2.3)

If a solenoid coil is taken into account a uniform magnetic field is generated at the centre of the coil and the field appears to be very weak on the outside as most of the flux lines are concentrated in the centre of the coil. The density of the magnetic flux lines is very high in the centre of the coil and the density appears to spread on the outer side of the coil. The magnetic field hugely depends on the magnetic permeability ($\mu$, units: H/m) of the material and is a product of magnetic permeability and auxiliary magnetic ($H$, units: A/m)) field generated.
The ability of a material to support the formation of a magnetic field within it is defined as the magnetic permeability of a material and it is a product of relative permeability ($\mu_r$, units: no units) and permeability constant ($\mu_0$, units: H/m).

$$\mu = \mu_0 \cdot \mu_r$$  \hspace{1cm} (2.5)

The Eddy currents generated in a conductive material produce a magnetic field according to the thumb rule. The distribution of the magnetic field around the Eddy current field caused due to alternating current in the coil is given by Biot-Savart law [16]. The equation is given as

$$B = (\mu_0 I/4\pi) \oint \frac{dl \cdot \hat{f}}{r^2}$$  \hspace{1cm} (2.6)

Where

- $dl$ = vector whose magnitude is equal to length of differential element
- $\hat{f}$ = displacement unit vector in the direction pointing from the wire element towards the point at which the field is being computed
- $I$ = current
- $r = r \hat{f}$ = full displacement vector from the wire element to the point at which the field is being computed

When a circular coil of certain diameter is used to produce Eddy currents in a rectangular plate with very less thickness the Biot-Savart law is re-written as

$$B(x, y, t) = \left(\mu_0 I(t)/2\pi\right) \frac{1}{\sqrt{[(b+r)^2+z^2]}} \left[ \frac{b^2-r^2-z^2}{(b-r)^2+z^2} E(m) + K(m) \right]$$  \hspace{1cm} (2.7)

Where

- $b$ = diameter of the coil
\[ r = \sqrt{x^2 + y^2} \]

\[ I(t) = I_0 \sin(\omega t) \] is the current in the loop

\[ m = 4br / [(b+r)^2+z^2] \]

K(m) and E(m) are the complete elliptic integrals of first and second kind respectively.

Assuming uniform distribution of Eddy current density on the plate the induced Eddy current has two components \( J_x \) and \( J_y \) expressed in terms of stream function \( u = u(x, y, t) \) as

\[ J_x = \frac{\partial u}{\partial y}; \quad J_y = -\frac{\partial u}{\partial x} \quad (2.8) \]

\( J_x \) and \( J_y \) are the two components Eddy current density

It is scalar quantity and when used in 2D problems the solution is of the type

\[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \frac{\partial B_{total}}{\partial t} = \left[ \frac{\partial B}{\partial t} + \frac{\partial B_s}{\partial t} \right] \quad (2.9) \]

The Eddy current magnetic field is given by Biot-Savart law as

\[ B_s(x, y, t) = \mu_0 \frac{\mu_0 h}{4\pi} \iint_S \frac{(x-x')(\frac{\partial u}{\partial x})(x',y',t) + (y-y')(\frac{\partial u}{\partial y})(x',y',t)}{[(x-x')^2 + (y-y')^2]^{3/2}} \, dx' \, dy' \quad (2.10) \]

### 2.4 Skin depth or Reference depth (δ)

When dealing with Alternating current in a conductor the current distribution across the conductor is not uniform unlike DC which establishes uniform distribution of current in the conductor. When a conductor is subjected to high frequency Alternating current the reaction field created in the work piece compensates for the coil field inside the work piece. The magnetic fields attenuate with increasing depth of the work piece.
and eddy currents are observed only on the surface of the work piece i.e., the current density remains maximum on the surface of the conductor and decreases with increasing depth of the conductor. This phenomenon is called the “Skin effect” and the depth up to which the current distribution is found to be substantial is called as “Skin depth or Reference depth”. Normally 80% of the heat produced within a work piece can be observed on the surface on the work piece and it gradually reduces with thickness. It is given by

\[ \delta = \sqrt{\frac{2}{\omega \sigma \mu}} \]  

(2.11)

Where  
\( \delta \) = Skin depth or penetration depth (mm)  
\( \omega \) = Induction angular frequency (r/s)  
\( \sigma \) = conductivity of the material (S/m)  
\( \mu \) = permeability of the conductor (H/m)

Induction angular frequency “\( \omega = 2\pi f \)” where f is frequency of current at the inductor. “\( \mu_r \)” is the relative permeability of the material and has no units, while “\( \mu_0 \)” is the permeability constant whose value is equal to \( 4\pi \times 10^{-7} \) H/m = 1.2566 x 10^{-6} H/m. The relative permeability and the conductivity of a material have specific values.

The peak frequency in an induction system depends upon the skin depth (\( \delta \)) to thickness (d) ratio and the electrical conductivity (\( \sigma \)) of the material. When skin depth is much greater than the thickness of the sample (\( \delta>d \)), it is case is considered to be as volumetric heating where the entire material along its thickness is uniformly heated. But when the skin depth is smaller or almost equal to the thickness of the sample (\( \delta\leq d \)) then
it is called surface heating [17]. In surface heating only the surface of the sample is heated while the uniformity of heat distribution over the thickness of the sample cannot be guaranteed.

Table 2.1 Skin depth or Penetration depth for different materials at different frequencies (Sources: Wikipedia, Introduction to electromagnetic compatibility by Clayton R. Paul. Pp: 301)

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative permeability</th>
<th>Permeability constant(H/m)</th>
<th>Conductivity (S/m)</th>
<th>Induction frequency(Hz)</th>
<th>Angular frequency(ω)</th>
<th>Skin depth(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1</td>
<td>1.25664E-06</td>
<td>59,170,000</td>
<td>150000</td>
<td>942000</td>
<td>0.168979228</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.1</td>
<td>1.25664E-06</td>
<td>37,450,000</td>
<td>150000</td>
<td>942000</td>
<td>0.202517171</td>
</tr>
<tr>
<td>Steel</td>
<td>1000</td>
<td>1.25664E-06</td>
<td>1,389,000</td>
<td>150000</td>
<td>942000</td>
<td>0.034876507</td>
</tr>
<tr>
<td>Copper</td>
<td>1</td>
<td>1.25664E-06</td>
<td>59,170,000</td>
<td>200000</td>
<td>1256000</td>
<td>0.146340304</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.1</td>
<td>1.25664E-06</td>
<td>37,450,000</td>
<td>200000</td>
<td>1256000</td>
<td>0.175385015</td>
</tr>
<tr>
<td>Steel</td>
<td>1000</td>
<td>1.25664E-06</td>
<td>1,389,000</td>
<td>200000</td>
<td>1256000</td>
<td>0.030203941</td>
</tr>
<tr>
<td>Copper</td>
<td>1</td>
<td>1.25664E-06</td>
<td>59,170,000</td>
<td>250000</td>
<td>1570000</td>
<td>0.130890747</td>
</tr>
<tr>
<td>Aluminum</td>
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<td>37,450,000</td>
<td>250000</td>
<td>1570000</td>
<td>0.156869126</td>
</tr>
<tr>
<td>Steel</td>
<td>1000</td>
<td>1.25664E-06</td>
<td>1,389,000</td>
<td>250000</td>
<td>1570000</td>
<td>0.027015226</td>
</tr>
<tr>
<td>Copper</td>
<td>1</td>
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<td>300000</td>
<td>1884000</td>
<td>0.119486358</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.1</td>
<td>1.25664E-06</td>
<td>37,450,000</td>
<td>300000</td>
<td>1884000</td>
<td>0.143201265</td>
</tr>
<tr>
<td>Steel</td>
<td>1000</td>
<td>1.25664E-06</td>
<td>1,389,000</td>
<td>300000</td>
<td>1884000</td>
<td>0.024661415</td>
</tr>
</tbody>
</table>

Table 2.1 shows the penetration depth of Copper, Aluminum and Steel for different Induction frequencies. Relative permeability ($\mu_r$) and electrical conductivity ($\sigma$) of the material are the two factors controlling the penetration depth of the material.
Skin effect decreases with an increase in the permeability of the material. Permeability is a measure of materials ability to resist the formation of a magnetic field inside it. If a material is a very good conductor then its permeability is very low and the wave penetrates only through a small depth heating only the surface of the material. The relative permeability for ferrous material is very high and it considerably affects the Eddy current response in a conductor.

Figure 2.2 Skin depths Vs Frequency

In steel the penetration depth for different frequencies is very low due to of skin effect. Considerably the penetration depth for Copper and Aluminum are higher due to lower relative permeability and higher electrical conductivities.

Frequency of the current also effects skin depth of a magnetic material. With higher frequencies lower skin depth is achieved and with lower frequencies higher skin depth is achieved. High frequency currents can be used for surface heating and lower
frequencies are used for volumetric heating; applications include forging, brazing, material testing, soldering and hardening etc.

In thick flat bodies the current density drops exponentially and at the skin depth the current density is only 37% of the value found at the surface of the work piece. Power density which is an important term and it drops as the square of the current density. Its value is found to 13.5% of its value on the surface of the work piece.

2.5 Electromagnetic Phenomenon in Induction System

Due to several electromagnetic effects the current distribution within an Induction system is not uniform. The after effect of non uniform distribution of current is non uniform heat distribution in a work piece. The non uniform currents are produced due to several electromagnetic phenomena like proximity effect, coil effect, ring effect, end and edge effects [18].

Proximity effect:

Induced currents within a conducting material tend to flow very close to the actual current flowing within the inducing coil. The induced currents flow in a loop which has the shape of the coil inducing currents in the work piece. In actual practical applications apart from the actual conducting material several other materials fall in close proximity with the current carrying coil. Electric currents induced within the other parts generate their own magnetic fields and these fields affect the current density and power density distribution of the induction system. The proximity effect is predominantly observed if the induction system frequency is very high and is placed very close to the conducting material.
Ring effect:

Consider a current carrying coil whose shape is that of a ring. The magnetic flux lines are concentrated inside the ring. So, the density of magnetic field is intense on the inner side of the ring. While the magnetic field lines spread out on the outer surface of the ring. Due to this most of the current is distributed on the inside surface of the ring. If a work piece is located on the inside surface of the ring, due to skin and proximity effects the coil current is concentrated on the inner surface of the ring and the magnetic flux lines are concentrated in the centre of the ring. This improves the coupling efficiency of the coil with the work piece and is a positive effect. While on the other side if the Induction coil is placed within a work piece the magnetic flux lines are not concentrated within the work piece and poor coupling exists between the coil and work piece which is a negative effect in heating a work piece.

End effect in cylindrical systems:

End effects are caused due to irregular distribution of magnetic field lines on the ends of a work piece. For uniform distribution of induction heat it is required to predict accurately the electromagnetic field distribution in an induction system. In the zone “x” the magnetic flux lines tend to cut the end of cylindrical work piece. Due to good coupling, higher current is induced which leads to higher power absorption in that area. With increasing frequency the end effect grows stronger but simultaneously the length of this region shrinks with increasing frequency. The end effect in cylindrical work pieces always increases the power at the end while for magnetic materials the end effect may increase or decrease the power depending on the frequency. The end effect in the zone
“y” is not predominant due to weak distribution of magnetic flux lines and the power distribution declines with the length of the work piece.

Fig 2.3: End effects in cylindrical systems

Edge effect in slabs:

Uniform magnetic fields in slabs are complicated to achieve due to both end effect and edge effect. The magnetic field is uniformly distributed along the edges of the slab and remains constant. The induced currents cut the edges of the slab and return back on the same path taking the shortest route. This tendency if induced currents return back is opposed by skin effect. Low frequencies lead to under heating of the edge area and high frequencies lead to overheating of the edge areas. For uniform distribution of heat, higher frequencies are suggested because additional power is required to compensate for the thermal losses on the edges. The edge effects interact with each other if the slab is not wide enough and lead to distorted heating.
2.6 Current density, Power density and Power Absorbed by a work piece

Current density (I) and power density (P) are distributed exponentially over the work piece within the penetration depth layer and at a certain distance from the surface [15]. They are given as

\[ I(x) = I_o \exp \left(-\frac{x}{\delta}\right) \quad (2.12) \]
\[ P = P_o \exp \left(-2\frac{x}{\delta}\right) \quad (2.13) \]

Where \( I_o = \) Current density
\( P_o = \) Power density
\( x = \) distance of current and power density distribution from the surface
\( \delta = \) penetration depth or skin depth

These distributions for current and power densities are applicable only for flat and thick bodies and materials with constant electromagnetic properties like electrical conductivity and magnetic permeability. The above equations may not be applicable for materials with complex shapes.

Power absorbed (Pw) by a work piece with simple shapes placed in a uniform magnetic field is calculated as

\[ P_w = \frac{1}{\sigma \delta} A_s K H^2 \quad (2.14) \]

Where \( P_w = \) Power absorbed by the work piece
\( A_s = \) Area of the work piece surface exposed to magnetic field
\( K = \) Power transfer factor dependent on geometry, material and frequency
\( H = \) Magnetic field intensity on the work piece
Conduction, Convection and Radiation are three basic phenomena of heat transfer in an Induction system. Conduction heat transfer occurs when two bodies at different temperatures exchange heat when put in contact with each other. Fourier’s law of heat conduction describes the heat transfer between two bodies and is given as:

\[ \dot{q}_x = -\lambda(t)(\frac{dT}{dx}) \]  

(2.15)

Where \( \dot{q}_x \) = heat flux by conduction (W/m\(^2\))

\( \lambda(t) \) = Thermal conductivity (W/mK)

\( \frac{dT}{dx} \) = temperature gradient

In convection, the heat transfer is due to fluids which carry the heat from the work surface to the ambient air and is given by Newton’s law.

\[ \dot{q}_c = \alpha(T_{\text{sur}} - T_{\text{amb}}) \]  

(2.16)

Where \( \dot{q}_c \) = heat flux due to convection (W/m\(^2\))

\( \alpha \) = convection heat transfer coefficient (W/m\(^2\)K)

\( T_{\text{sur}}, T_{\text{amb}} \) = Surface and ambient temperatures (K)

Radiation heat transfer is given by Stefan-Boltzmann law which states that heat transfer rate is proportional to radiation loss coefficient and fourth power of temperature.

**Thermal energy for Induction heating:**

A mathematical model for electromagnetic induction and the heat transfer was given by N. Biju et al [17]. They used Maxwell’s equations in deriving the model. Ampere’s law was considered for deriving it which was written as

\[ \sigma \frac{dA}{dt} + \nabla \times \mu^{-1} \nabla \times A + \sigma \nabla V = J^e + \frac{\varepsilon d^2A}{dt^2} \]  

(2.17)
Where

\[ A = \text{magnetic vector potential} \]
\[ V = \text{electric potential (V)} \]
\[ J = \text{external current density (A/m}^2\text{)} \]
\[ \varepsilon = \text{permittivity of the medium (F/m)} \]
\[ \mu = \text{magnetic permeability (H/m)} \]
\[ \sigma = \text{electrical conductivity (S/m)} \]

They formulated the problem for axially symmetric structures with current passing only in the angular direction by considering only the \( A_{\phi} \) component of the magnetic potential. The gradient of electric potential was given as \( \nabla V = -V_{\text{loop}}/2\pi r \) since electric field existed only in the azimuthally. For time harmonic analysis magnetic vector potential was given as \( A = A_{\phi}e^{j\omega t} \). Equation (2.17) was rewritten as

\[
(\omega \sigma - \omega^2 \varepsilon)A_{\phi} + \nabla \times (\mu^{-1}\nabla \times A_{\phi}) = \frac{\sigma V_{\text{loop}}}{2\pi r} + J_{\phi} \text{e} \quad (2.18)
\]

The boundary conditions taken were magnetic insulation on the domain boundary, \( A_{\phi} = 0 \) and continuity of magnetic fields on the interior boundaries, \( n \times (H_1 - H_2) = 0 \).

The heat transfer equation for axisymmetric problems is expressed as

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( kr \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + Q = \rho c_p \frac{\partial T}{\partial t} \quad (2.19)
\]

Where \( \rho \) is material density (kg/m\(^3\)), \( c_p \) is specific heat (J/kg K), \( T \) is temperature (K), and \( k \) is thermal conductivity (W/mK). The boundary conditions were taken as defined temperature at the domain boundaries, \( T = T_{a} \) (ambient temperature) and heat flux at other boundaries,

\[
k \frac{\partial T}{\partial t} = h(T_\infty - T) + \varepsilon \sigma \left( T_a^4 - T^4 \right) \quad (2.20)
\]
Where \( h \) is the convective heat transfer coefficient \((\text{W/m}^2\text{K})\), \( T_\infty \) is the external temperature \((\text{K})\), \( \varepsilon \) is the emissivity and \( \sigma \) is the Stefan-Boltzmann constant.

NTsopelas et al., [19] analyzed the thermal field assuming the plate to be very thin and the temperature \( T(x, y, t) \) distributed uniformly across the thickness of the plate and neglecting the heat losses through circumferential surface. The energy balance equation for small control volume, \( dV = wdA \) or the temperature value of the plate due to all thermal sources is given as:

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} - \frac{h_1 + h_2(T-T_a)}{w k} - \frac{(\varepsilon_1 + \varepsilon_2)\sigma_{SB}(T^4 - T_a^4)}{w k} + \frac{P(x,y,t)}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \tag{2.21}
\]

Where \( T_a = \) ambient temperature

\( h_1, h_2 = \) mean heat transfer coefficients for the two faces of the plate

\( \varepsilon_1, \varepsilon_2 = \) emissivity’s

\( k = \) thermal conductivity

\( \alpha = \) thermal diffusivity

The first term in the equation \( \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \) gives the temperature diffusion throughout the plate and the term \( \frac{P(x,y,t)}{k} \) indicates the heat generated due to induction current. They concluded that for longer heating periods the terms related to convective heat transfer and radiation heat transfer represent less than 5% of the total energy balance. The heat transfer in the process was mainly due to the conduction phenomenon in the material.
Chapter 3

Problem and Initial approach

3.1 Inspection of Steel sheets

Steel sheets used in a wide variety of finished products, including automotive bodies, appliances, electrical machinery, steel furniture, construction materials, and containers etc are subjected to inspection after they are manufactured. Automotive OEM’s as well as other Industries prefer to use steel sheets with no defects on the surface. Defects on the surface of the steel sheets can lead to rejection of the whole coil by Automotive OEM’s and therefore it is a challenge for the steel manufacturers to inspect these coils for minute defects.

Impurities present in the manufacturing environment or ambient atmosphere affect the quality of steel sheets while being manufactured. Huge number of impurities present in the steel will certainly damage the aesthetics of the material. Defects mainly occur when solid impurities accumulate on the surface of the molten metal which is further solidified. In the manufacturing process of steel molten steel is cast into large blocks and during the casting process Aluminum is added to the molten steel for the impurities to float on the surface which are later removed from the surface. Surface defects due to impurities are common while manufacturing steel.

The steel extracted after removing the impurities is subjected to coating to prevent it from corrosion. A material with the characteristics of good corrosion resistance is used as a protective coating on a variety of products and in many exposure conditions. The most common metallic coating for corrosion resistance used on steel is Zinc coating. The
ability of Zinc to form dense, adherent corrosion product films and a rate of corrosion which is below that of ferrous materials makes it perform better compared to other kinds of coatings generally used. Zinc coating offers good resistance to galvanic corrosion.

Solid impurities along with other defects like dents, scratches etc are embedded into the coating surface during roughing and product rolling operations. It is a major issue in terms of appearance of the material since the same steel is used for making the body panels of automobiles.

Even though surface defects and geometry variations are present within the material after the rolling process they appear invisible to the naked eye due to the smooth and reflective nature of the surface. Defects on Class A surfaces of the automobile panels are certainly not desirable since the visibility of such defects is enhanced when the automobile panels are painted in the painting booths. Different kinds of defects that can occur on the steel sheets or coils are given below:

Fig 3.1: Dross

Fig 3.2: Zinc powder attached to coating surface
3.2 Thermal Imaging cameras and Specifications

Two types of cameras were used to record the thermal image sequences and the spatial distribution of temperature with time is recorded using these cameras. The two cameras used are:

- FLIR A40M - micro-bolometric imaging system, with a resolution of 320X240 pixels and a NETD of 0.08K.
- FLIR Phoenix DTS cooled camera with a maximum resolution of 640X512 pixels and with the capturing rate of up to 20Kfps. This camera has a detector material made of Indium Antimonide (InSb).

Noise Equivalent Temperature Difference (NETD):

Noise equivalent temperature difference is a measure of sensitivity of the infrared camera. It describes the smallest temperature difference it can measure in a 2-D spatial distribution.
Signal to noise ratio (SNR):

Signal to noise ratio is defined as the scene temperature difference signal to the total noise signal of the Infrared imaging system. If the value is equal to one then it can be said the scene temperature difference is equal to the total noise in the detector or the whole Infrared system.

<table>
<thead>
<tr>
<th>Description of The Cameras</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Model Name</strong></td>
</tr>
<tr>
<td><strong>Camera Images</strong></td>
</tr>
<tr>
<td><strong>Resolution of the Camera</strong></td>
</tr>
<tr>
<td><strong>Focal Plane Array Cooling(FPA)</strong></td>
</tr>
<tr>
<td><strong>Sensitivity(NETD)</strong></td>
</tr>
<tr>
<td><strong>Types of Lens used</strong></td>
</tr>
<tr>
<td><strong>Frame Rate</strong></td>
</tr>
</tbody>
</table>

Table 3.1 Specifications of Thermal Imaging Cameras
Non-Uniformity Correction:

Photo detectors are usually arranged in an array at the focal plane of any infrared imaging system. Non-uniformity or a small difference in the individual photo response of the individual detectors for the same illumination causes spatial fixed pattern noise. Hot and cold pixels appear for the same amount of illumination and are caused due to variation in the pixel size, material, temperature difference etc. The digitization electronics involved in multiplexing the individual detector responses further degrade the performance of the Infrared imaging systems. Hence a correction technique which responds aptly to changing photo responses is required. There are two types of non-uniformity correction techniques [20], they are:

a) Two point non-uniformity correction technique and
b) Scene based non-uniformity correction

In two point non-uniformity correction technique two uniform sources are used and a linear correction is applied to each detector. For this kind of technique it is required that the non-uniformity correction is performed before capturing or acquiring an image sequence. While in scene based NUC corrections are made while the camera is in the operating mode of acquiring images. Scene based NUC approach can adapt to varying photo responses of the detectors due to changing operating conditions.

3.3 Test Samples

The samples used for testing were acquired from Nippon Steel Corporation, Japan. These samples have a good surface finish and the surfaces were reflective. Six test samples were considered for the experiments each having certain kind of defect on them
and were marked for easy identification. The emissivity for steel is 0.85 and the camera has been calibrated accordingly for emissivity corrections.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Defect Kind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>Dross</td>
</tr>
<tr>
<td>Sample 2</td>
<td>Zinc Powder attached to coating surface</td>
</tr>
<tr>
<td>Sample 3</td>
<td>Dent on the outer surface of the coating</td>
</tr>
<tr>
<td>Sample 4</td>
<td>Dent on the inner surface of the coating</td>
</tr>
<tr>
<td>Sample 5</td>
<td>-</td>
</tr>
<tr>
<td>Sample 6</td>
<td>Line Defect</td>
</tr>
</tbody>
</table>

Table 3.2 Defect description

### 3.4 Heat Sources for Thermal Excitation

Three kinds of heat sources have been used for the thermal excitation of the samples-Halogen lamps, Flash lamps, and Induction heater.

**Halogen heating:**

The source of heat is from halogen lamps. In conventional gas-filled tungsten-filament lamps, the tungsten molecules evaporate from the hot filament and are carried to cooler inner surfaces of the bulb by convection currents of the inert fill gas. These vapors gradually form thin film on the inner surface and reduce the life of the lamps. Unlike conventional gas filled lamps, Tungsten-Halogen lamps make use of regenerative process of Halogen cycle to increase its life. When power is supplied to Tungsten-Halogen lamps the filament temperature rises to 2800K to 3400K and bulb temperature simultaneously increases to $250^0$ C to $600^0$ C.
This temperature from the bulbs is used to generate heat required to excite the steel sample. The halogen lamps used for the experiments consisted of eight bulbs each with a power output of 500 W. The testing procedure consisted of heating the test sample by exposing it to the halogen lamp pulses. The heating and cooling curves are recorded using the thermal imaging system.

Flash heating:

In Flash heating a short pulse from the flash source is used to thermally excite the material. The Flash lamps are concentric in shape and the whole exciting system is built using four lamps with a power output of 6000W/s. The heating and cooling curved for the sample are

<table>
<thead>
<tr>
<th>Halogen Heat source</th>
<th>Manufacturer</th>
<th>Custom made</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Lamps</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Power of each Lamp</td>
<td>500 W</td>
<td></td>
</tr>
<tr>
<td>Total Power from system</td>
<td>4000 W</td>
<td></td>
</tr>
</tbody>
</table>
recorded using the thermal imaging system. The specifications of the lamps are shown in the table below.

![Figure 3.8 Cooled Camera with Flash setup](image)

<table>
<thead>
<tr>
<th>Flash heating source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
</tr>
<tr>
<td>Lamp shape</td>
</tr>
<tr>
<td>Power of each Lamp</td>
</tr>
<tr>
<td>Total Power from the system</td>
</tr>
</tbody>
</table>

Table 3.4 Flash source specifications

**Induction heating:**

As discussed in the previous chapters an induction heating system generates magnetic fields due to the currents through the coil and the magnetic flux lines generate eddy currents within the test sample. Joule heating is responsible for the heating of the sample. The induction system used is a product of Ameritherm Inc. The Induction unit essentially consists of a heating unit, a cooling unit and coils. Two coils were used each having a different shape, geometry, and heating area. The digital panel consists of on/off
buttons and has provisions for varying parameters like Amperage, time of operation etc. Power and frequency vary according to given Amperage.

![Figure 3.9 Induction Unit (heating source)](image1)

![Figure 3.10 Coils (Pancake and spring)](image2)

![Figure 3.11 Digital panel of Induction system](image3)

<table>
<thead>
<tr>
<th>Induction heat source</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong> :</td>
<td>Hot Shot 1 FF V4</td>
</tr>
<tr>
<td><strong>Power Output</strong> :</td>
<td>1 kW</td>
</tr>
<tr>
<td><strong>Power input</strong> :</td>
<td>105-140 Nominal Frequency(kHz)</td>
</tr>
<tr>
<td><strong>Volts(rms)</strong> :</td>
<td>115</td>
</tr>
<tr>
<td><strong>F.L.Amps(rms)</strong> :</td>
<td>15</td>
</tr>
<tr>
<td><strong>Water Input</strong> :</td>
<td>40-80 psi</td>
</tr>
</tbody>
</table>

**Table 3.5 Induction heat source specifications**
Limitations of Using Pulse Heating:

1. High power output in a short pulse creating a transient heating condition and exponential decay of heat.
2. The pulse mode of heating follows Gaussian profile, so it is difficult to have control over saturation and uniform heating of the entire sample.
3. Non-uniformities in light distribution due to the profile of the sources used.
4. Non-uniformities in heat distribution due to non-uniform surface properties that affect the thermal absorption and emission and non-uniformities related to surface geometry and roughness.
5. The lamps used for pulse heating have residual heat after the short pulse and this heat has an adverse effect on the thermal images being captured during cooling.

Advantages of Induction heating systems:

1. Internal mode of exciting a work specimen with low power output sufficient to create a substantial thermal contrast at the defect and non-defect regions.
2. Induction based heating provides uniform temperature distribution at optimal frequencies.
3. The induction mode of heating gives us control over frequency of heating.
4. Induction heating provides us with high repeatability in results having control over spatial and time domain of the capture.

3.5 Test results using cooled camera (Initial results)

The test samples are thermally excited using Halogen sources of heat (pulse heating) and the thermal images are recorded using the infrared measuring system. The
following thermal images are obtained after the test sample is allowed to cool after excitation.

Sample 1

Sample 2

Sample 3

Sample 4

Sample 5

Sample 6

Figure 3.12 Thermal images after heating the source with Halogen lamps

The results indicate that halogen source has heated the sample to a very high temperature and to extent saturated the pixels around the corners of the frame. Also the line defect in the sixth sample cannot be seen. Non-uniform heating of the surface can be clearly observed as one portion of the image is visible and the other appears to be highly reflective. Two point NUC has been performed before testing each sample and it cannot be accounted for the degraded images.
**Induction heating results:**

The test samples are now excited using Induction heater which is an internal mode of heating a work piece unlike other pulse techniques. The thermo grams are captured using the infrared imaging system. The following thermal images were captured after induction heater passed over the steel sheet.

![Sample 1](image1.png)

![Sample 2](image2.png)

![Sample 3](image3.png)

![Sample 4](image4.png)

![Sample 5](image5.png)

![Sample 6](image6.png)

**Figure 3.13 Thermal images after heating the source with Induction heater**

The thermal images obtained after induction heating show that the temperature distribution is uniform over the surface with no overheating. A good thermal contrast can be clearly observed between the defect and non-defect regions. Although the detect
ability (visibility of the defects) is good in induction heating the results must be quantified and are discussed in the next chapter.

3.6 Thermal contrast computation

The degree of detectable temperature difference between surrounding areas in a body having unequal temperatures at a particular moment is called as thermal contrast. The defect visibility and image quality are improved by having a good thermal contrast. Several definitions are used to calculate the absolute contrast or temperature rise with respect to a particular region at a particular moment [21].

\[ C^a(t) = T_{def}(t) - T_s(t) \]  \hspace{1cm} (3.1)

Where \( T \) is the temperature signal and the subscripts \( def, s \) refer to the signal over a suspected defective location (any pixel in the image) and over a sound area. \( C^a \) is a linear function of the energy absorbed and offers better visualization of defects with respect to the background. Standard contrast can be normalized by a behavior of a sound area,

\[ C^s(t) = \frac{T_{def}(t) - T_{def}(t_o)}{T_s(t) - T_s(t_o)} \] \hspace{1cm} (3.2)

In pulse phase thermography computation of the thermal contrast requires prior knowledge about the non-defect region within the field of view.

Thermography for Facial Defects [21]:

Contaminant detection on the paint films has been inspected and analytically formulated by Dr. M Omar. Lateral or facial heating scheme has been taken for this approach since it generates a lateral heating front to detect contaminants. Defects or seeds
can be modeled as thermal resistance to diffusion heat flow. The mathematical model that represents the solution to one dimensional conduction in two-layered solids with a defective interface is given by

\[ T(0, t) = C_c \sqrt{t} \left[ 1 + \sum_{n=1}^{\infty} \left( 2(-\Gamma)^n n \{ \exp(n^2d^2/\alpha t) - (n\sqrt{\pi}/\sqrt{\alpha t}) \cdot \text{erfc}(nd/\sqrt{\alpha t}) \} \right) \right] \] (3.3)

\[ C_c = \text{constant dependent on heating source.} \]

\[ t = \text{time} \]

\[ \Gamma = \text{thermal mismatch} \]

\[ d = \text{thickness of coat} \]

\[ \alpha = \text{thermal diffusivity} \]

By inspecting the above equation it is clear that the thermal mismatch at the interface controls the facial temperature map at same Fourier number. Modeling the seeded regions as regions with modified thermal properties results in a thermal mismatch, between the seed and the surrounding, and results in different temperatures in those areas. The modeling starts with converting the seeded spots into regions of modified thermal properties using a conversion factor such as \( \zeta \) that is related to seed geometry. Thermal mismatch is then computed between the seeds and the surrounding.

For the modeling, radius of the seed is used to represent the seed geometry. Based on the geometric factor the thermal properties were modified in the equation as

\[ \sqrt{(k \cdot \rho \cdot C_p_{\text{surr}})} \cdot \zeta + \sqrt{(k \cdot \rho \cdot C_p_{\text{air}})} \cdot (1 - \zeta) = \sqrt{(k \cdot \rho \cdot C_p_{\text{seed}})} \] (3.4)

\[ K = \text{thermal conductivity} \]

\[ \rho = \text{density} \]

\[ C_p = \text{specific heat.} \]
Various relations for $\zeta$ were tried to run the analytical model and compared with the experimental results and came up with an equation with a least error percentage of 18%.

$$\zeta = 1 - (r. \sqrt{\frac{\Pi}{\alpha}}) \quad (3.5)$$

The above equation was used to correlate the seed experimental temperature deviation with equation (3.6).

$$\frac{T_{seed}}{T_{surr}} = \frac{\varepsilon}{\varepsilon_{seed}} \times \frac{1 - \Gamma \cdot \exp (-2\pi \zeta)}{1 + \Gamma \cdot \exp (-2\pi \zeta)} \quad (3.6)$$

All the computations were made taking into account only the geometrical seeds and not the contaminant seeds which define $\zeta$ based on their material.
4.1 Quantitative Analysis for Detectability

This chapter gives the quantitative analysis for the detectability of defects when induction heating sources are used for excitation of the material. Two quantitative criteria can be used to describe the signal from defective surroundings.

a) Local signal-to-noise ratio computed across the defect and

b) Detectability based on contrast computation

Lee et al [22] proposed an approach to compute the signal-to-noise ratio. The uniformity of the thermal signal across the defect is computed using the equation

\[
\text{SNR} = \frac{\sum \sum [\text{Therm}(i,j)]^2}{\left(\frac{1}{2}\right)[\sigma(N(i,j))]^2}
\]  

(4.1)

Numerator gives the average power of the thermogram \(\text{Therm}\) and \((i, j)\) being the coordinates and \(n\text{col}\) and \(n\text{row}\) are the number of columns and rows respectively. The denominator gives the average power of noise and \(\sigma\) is the standard deviation of the noise \(N(i, j)\). This noise is calculated as the difference between two thermograms acquired for a single scene simultaneously. By using two intensity profiles on a single thermal image the above equation was modified as

\[
\text{SNR} = \frac{\sum_i^k [Pf(i)]^2/k}{[\sigma(N(i))]^2}
\]  

(4.2)

\(Pf(i, j)\) is the intensity profile along the defect, and the noise \(N(i)\) represents the difference between two profiles such as \(Pf(i)\) across the defect.
Second quantitative criteria for detecting defects uses contrast computation. In contrast computation, intensity or temperature profiles are drawn across the defect and the surrounding non-defect regions. Our experiments deal with creating temperature profile across the defective and non-defective regions. So, the results are based on contrast computation.

4.2 Camera Configuration and Experimental Setup

Camera Configuration:

• Camera – FLIR Phoenix DTS(Cooled Camera)
• NETD – 0.025K
• FPA Cooling – 74K
• Lens Used – Microscopic Lens
• Frame Size – 640x100
• Frame Rate – 407 (frames/s)
• Direction of heating – Front
• Ambient Temperature – 21°C

Experimental Setup:

The experimental setup consists of Steel sample to be tested, thermal imaging system mounted on a XYZ mechanism, induction heater with coil positioned within the slots, and a conveyor belt to move the test sample. Steel samples 1 and 2 are considered for the experiments. The speed of the conveyor belt can be set up to a maximum speed of 2000 rpm which converts to 36.75 m/min in linear motion.
The Steel sample is subjected to different experimental conditions. Let us now discuss the detectability using the second quantitative criterion which is based on contrast computation. A test condition in which the test sample is subjected to induction heating at a current supply of 50 Amps is taken into account. When the induction coil is moved over the surface of the Steel sheet at a constant separation of 1cm from the Steel sheet, the Steel sheet due electromagnetic coupling gets heated up. A defect present on the surface of the steel sheet also gets heated up but to a lower extent. The defect due to its geometry has an emissivity different from that of the Steel sheet and hence results in a completely different temperature profile.

The infrared system captures thermal images at a frame rate of 407Hz and at a resolution of 640x100 pixels for 2 seconds. Since the conveyor belt is moving at a set...
speed only a few frames which contain the defect can be noticed. This will not affect the
detect ability until and unless the conveyor speed is too high. The Region of Interest
(ROI) is selected on the defect using a line profile. Voxel plots for up to 20 frames are
generated. Ten frames before the defect frame and ten frames after the defect frame are
selected for the plots.

Figure 4.2 shows the temperature at the defect and temperature of the surrounding
area. The detect ability is quantified as a substantial temperature difference is observed
between and defect and non-defect region.

![Temperature vs. Time](image)

**Fig 4.2 Temperature Vs Time plot for the thermal image containing a defect**

Two main points can be concluded from the following graph:

- Temperature drop gives the anomaly or the actual difference between the defect
  and the non-defect regions on a sample.
- Time response of the defect can hold the information about the dimensions of the
defect.
Several experimental conditions were tried to check the detectability of defects. These conditions included changing the sample to coil distance, conveyor belt speed, and varying current supplies. The table below shows the different experimental conditions used for testing.

<table>
<thead>
<tr>
<th>Coil to sample distance (cm)</th>
<th>Conveyer Belt Speed(rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400</td>
</tr>
<tr>
<td>Amperage (Amps)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1.5</td>
<td>50</td>
</tr>
<tr>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2.5</td>
<td>50</td>
</tr>
<tr>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4.1 Experimental conditions

4.3 Temperature Dependence on Input current

Thermal Images:

Infrared thermal images for the defect and non-defect regions are shown below for a coil to sample distance of 1 cm at different speeds and Amperages.
Fig 4.3 Thermal images of the sample with a defect
The thermal images clearly show that the defect is visible for all testing conditions for a sample to coil distance of 1cm. But the degree to which the sample and defect get heated depends on the input Amperage supplied.

For an input supply of 100 Amps the temperature difference between the defect and its surroundings was found to be $6.45^0\text{C}$. Similarly the temperature difference between the defect and its surroundings for 75 Amps and 50 Amps was found to be $5.7^0\text{C}$ and $5.6^0\text{C}$ respectively (Fig 4.4). The differences clearly indicating that greater the input current higher the temperature difference between the defect and its surroundings for a constant sample to coil distance. One has to note that all these readings were taken at a constant conveyor belt speed of 400 rpm or 7.35 m/min. If the speed of the conveyor was increased twice to the original speed the temperature values varied greatly and are shown in figure 4.5.

![Temperature Vs Time plot for different Amperages for a sample to coil distance of 1cm and constant conveyor speed of 7.35m/min](image)

Fig 4.4 Temperature Vs Time plot for different Amperages for a sample to coil distance of 1cm and constant conveyor speed of 7.35m/min
In figure 4.5 the degree to which the sample is heated is decreased due to increased speed of the conveyor belt. Increasing the conveyor belt decreases the time of exposure of the sample with the induction coil and simultaneously the coupling time.

4.4 Coupling Efficiency

Coupling efficiency plays a key role in temperature distribution within the sample. The distance of the coil from the surface of the sample affects induction parameters like induced current at the coil and work piece, frequency and the power output at the coil. Close coupling increases the current flow within the work piece resulting in increased amount of heat produced within the body. Figure 4.6 below shows the temperature distribution in the sample with the defect for different sample to coil distances and a constant input current and conveyor speed.
Fig 4.6 Temperature Vs Time plot for different sample to coil distances at an input Amperage of 100Amps and a conveyor speed of 7.35 m/min

The maximum temperature to which the sample is being heated is very much dependent on the coil to sample to distance as it can be observed that closest coupling is found at a sample to coil distance of 1cm. The temperature values tend to decrease with an increase in the sample to coil distance. But at a distance of 2cm and 2.5cm the temperature values are almost same which indicates that temperature on the sample is very much dependent on the coupling efficiency.

4.5 Power, Amperage and Frequency

The power at the work piece and the frequency at the coil are purely dependent on the input current supplied, the distance between the sample and the coil, and the material properties. Table 4.2 shows the power and the frequency at the work piece for a given input of current.
<table>
<thead>
<tr>
<th>Coil to sample distance (cm)</th>
<th>Amperage (Amps)</th>
<th>Power (W)</th>
<th>Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>206.6</td>
<td>305</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>114.8</td>
<td>307.8</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>50.8</td>
<td>313.6</td>
</tr>
<tr>
<td>1.5</td>
<td>100</td>
<td>188.4</td>
<td>304.8</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>106</td>
<td>307.4</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>48</td>
<td>313.2</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>178.2</td>
<td>304</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>100.8</td>
<td>307</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>46</td>
<td>313</td>
</tr>
<tr>
<td>2.5</td>
<td>100</td>
<td>174.6</td>
<td>304.6</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>99</td>
<td>307</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>45.4</td>
<td>313</td>
</tr>
</tbody>
</table>

Table 4.2 Power, Amperage and Frequency requirements

Close coupling indicates higher induced power. As the distance between the sample and the coil increases the induced power increases resulting in higher temperature and increasing distances decreases induced power. Detectability is good for up to a sample to coil distance of 1.5cm. Although power requirements are low for 2cm and 2.5cm sample to coil distance the detectability is poor.

4.6 Image Processing

Images captured using an Infrared camera consists of many undesired signals and noise along with the actual information. The images are to be processed in order to clear any confusion between the actual defect signal and noise signal. Image processing technique like Principal component thermography is used to process IR images obtained from the thermal imaging camera to enhance the contrast of the image and extract the required information.
The Principal component analysis (PCA) applied to thermographic images are called as Principal component thermography (PCT) [22]. Undesired noise levels present in the thermal images captured are reduced by using PCT thus increasing the contrast of the processed images. In PCT the original data is projected on to a set of orthogonal statistical modes to enhance the contrast of the thermal images captured. Due to huge volumes of images captured in a sequence an SVD based PCA is used to actual PCT. In SVD based PCA normalization of the data obtained from the infrared images is done to reduce the effects of ambient conditions and reflections. PCT is then applied on the data after normalization and the first empirical orthogonal function is plotted to obtain the processed image. The first few orthogonal functions have up to 90% of the variability of image data and a clear distinction can be observed between the raw image and the processed image.

Fig 4.7 Raw and processed images for a current input of 100 Amps, a coil to sample distance of 1cm and different conveyor speeds (400 rpm, 800 rpm, 1200 rpm, 1600 rpm, and 2000 rpm)
Fig 4.8 Raw and processed images for a current input of 75 Amps, a coil to sample distance of 1cm and different conveyor speeds (400 rpm, 800 rpm, 1200 rpm, 1600 rpm, and 2000 rpm)

Fig 4.9 Raw and processed images for a current input of 50 Amps, a coil to sample distance of 1cm and different conveyor speeds (400 rpm, 800 rpm, 1200 rpm, 1600 rpm, and 2000 rpm)
The defects in the processed image appear as white spot in the center of the frame and a thermal contrast can be observed. The enhancement in the appearance of the defect is visible but limited due to minute geometry of the defect. Although the enhancement is limited the detectability of the defect is verified using PCT. In quality testing of sheet metals using thermography, processing plays a major role. It not only enhances the visibility of defect but also improves memory required to store huge volumes of thermographic data.

### 4.7 Testing on Sandwiched Samples

**Sandwich test specimen:**

The test specimen used in the experiments is a sandwich of steel and silicon rubber adhesively bonded to the steel. A defect with certain dimensions is induced in the silicon rubber layer. The shape of the defect is usually a square with dimensions varying from 5mmx5mm to 3mmx3mm and 1mmx1mm. Figure 4.7 shows the test specimen. Figure 4.9 shows the induced defect in silicon rubber.

![Fig 4.10 Steel sample of 5mm thickness](image1)

Fig 4.10 Steel sample of 5mm thickness

![Fig 4.11 Silicon rubber with induced defect](image2)

Fig 4.11 Silicon rubber with induced defect
The sandwiched samples were heated using two different sources of heat. One source is Induction heater and the other is Halogen heat source. Table 4.3 and 4.4 show the thermal images of the samples heated using the Induction heater and Halogen source respectively. The thermal images captured for induction heating clearly show the boundaries of the defect on the silicon rubber. The boundaries are captured distinctively because of the presence of air in the defect region. The rate of heat transfer varies in materials to that in air and hence the boundaries of the defect can be clearly seen.

<table>
<thead>
<tr>
<th>Steel thickness (mm)</th>
<th>Defect size (5mmx5mm)</th>
<th>Defect size (3mmx3mm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>1</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>3</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>5</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Table 4.3: Thermal Images after Induction heating

While the thermal images shown in table 4.4 do not show any signs of the defect. The pulse mode of excitation decays (conducts) too fast in steel and since the samples are small it is very hard to detect the defect using halogen heating. Also heat saturation in the
middle of the image can be observed due to the lamp Gaussian profile which hides the defect gap.

<table>
<thead>
<tr>
<th>Steel thickness (mm)</th>
<th>Defect size (5mm x 5mm)</th>
<th>Defect size (3mm x 3mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
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</tr>
<tr>
<td>5</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Table 4.4 Thermal images after Halogen heating
Chapter 5

Conclusions and Future Work

Induction heating as a source of excitation for thermographic analysis and the physics involved in Induction heating are discussed. Induction heating provides uniform temperature distribution on sheet metals compared to other sources of excitation. The thermographic images captured after exciting the samples using pulse sources show heat saturation. Moreover, the heat conduction equations when pulse sources are used cannot be relied on since they follow a Gaussian profile resulting in an uneven temperature distribution on the sample. A temperature contrast is established between the defect and non-defect areas using induction source of excitation. Orientation and geometry of the defect is responsible for uneven temperature distribution. Emissivity difference at the defect and non-defect regions give intensity (temperature) profiles. The difference in temperature at the defect and non-defect regions can be used to quantify the detectability of the defect. Detectability was found to be good for up to a sample to coil distance of 1.5 cm. Current input has a considerable effect on the temperature distribution. Low current inputs are sufficient for good detectability but for higher currents the images may saturate due to overheating of the sample.

Power requirements can be optimized using different coil shapes. Online inspection of sheet metals using infrared thermography under dynamic conditions where the conveyor speeds are very high. Increase frame rate to avoid information loss by optimizing frame size and integration time.
References

    http://www.ndt-ed.org/EducationResources/CommunityCollege/Other%20Methods/AE/AE_Intro.htm


[22] Principal Component Thermography for steady perturbation scenarios (Dec 2009). Rohit Parvataneni. Department of Mechanical Engineering, Clemson University.