ABSTRACT: The present study discusses potential of Eddy current thermography in detection of Edge defects in metal plates. The focus is on detecting the defect’s dimension and location for the defects available at the edge of metal plates. We have used a slab of SA 387 Gr12(Killed steel) for performing our study. SA 387 Gr12(Killed steel) possess tremendous tensile and yield strength, the combination of Chromium-Molybdenum provides corrosion-combating skills along with improved tensile strength at higher temperatures. It has wide applications in the field of power (especially thermal power plants), oil and chemical Industry, construction sector etc. as heat exchangers, pressure vessels, industrial boilers, piping industry and in piping support structures, Sour Service Environments etc. Small cracks in any component can cause catastrophic failures. So it becomes a necessity to detect the crack in the initial stage itself and specially to avoid stress concentration in processes like rolling of Steel plates. The study is performed on a SA 387 Gr12 sample with defects created at various angles. Similar cracks can also be found in rails, created because of Rolled Contact Fatigue. Hence the study is going to be useful for the detection of defects in rails also. ECT offers further possibilities in the area of automation and has various advantages in comparison to conventional methods and the same is also discussed in the work.

Keywords: Edge Defects Detection, Induction Thermography, Eddy Current Thermography (ECT), A387GR12 inspection.

1. Introduction

The Eddy Current Thermography (ECT) is an evolving non-destructive technique for contact-free testing of electrically conductive materials for crack testing. It is basically the amalgamation of two existing non-destructive testing techniques, eddy current testing which is depth sensitive [1,2] and thermography which is fast and contact-free [1,2]. It is a quick technique and prove useful for detection and characterization of degradation and failures like corrosion, defect, fatigue, and residual stress etc. This method can be used to detect hidden, subsurface defects even for components with complex geometry. The main requirement for the method is that the materials shall be electrically conductive. Here an induction coil is used to heat the parts to be tested by an inductively generated current flow and a thermographic camera is used to detect the temperature variation on the surface of the component being tested. Presence of cracks or structural degradation obstructs the path of eddy currents and causes localised heating and thus the thermal variation near the defect. This can be easily detected thermographically with a high-resolution Infrared Camera (IR camera). This technique can be used as a replacement dye penetrant inspection for subsurface defects like closed cracks. Also it can prove to be a good and quick alternate for its sister, Eddy Current technique which is slower comparatively.

Various efforts have been made in this direction to study the suitability of ECT for surface and subsurface detects. Yunze He [3] used phase analysis on a steel sample for detection of surface defects with slots perpendicular to the surface with varying depths. Results shown that phase can eliminate the effect of non-uniform heating and improve detectability of defect comparing with the conventional thermograms in Eddy current pulsed thermography. On the other hand, Zainal Abidin [4] et al used aluminium sample with on-surface angular slots for simulating the
quantitative analysis of angular surface defects. The author used experimental and simulation setup for detecting angles and length of slot/defect. Netzelmann and Walle [5] discussed the use of induction thermography to detect surface defects in forged components and ECT was found as a good alternative to Magnetic Particle testing. Vrana [6] studied an analytical model for the calculation of the current distribution along with finite-element calculations for two different crack models i.e. notch & slot. Oswald-Tranta and Wally [7] used FEM modelling and experimental study for exploring the thermal distribution around the crack with different penetration depths. The results disclosed that in magnetic materials, after a short heating period, cracks are made visible by higher temperatures and in nonmagnetic materials by lower temperatures. Wally and Oswald [8] did their study on the effect of crack shape and geometry on the result of thermo-inductive crack detection. The term Thermal contrast was introduced to demonstrate the influence of different shapes on the thermal behaviour of cracks, which is basically the ratio of the temperature at crack divided by the sample surface temperature.

But less focus has been given towards detection and quantification of Edge defects. Suixian Yang [9] et al carried the simulation work for detectability of edge defects. The study ascertained the defect detectability with varying defect sizes and it was found that the thermal contrast decreases with increase in heating time so the heating time shall be kept least. Wilson et al [10] did their work for imaging multiple cracks from rolling contact fatigue in the edges of rails for “Gauge Corner Cracking” (GCC) and “Head Checking (HC)”. These edge cracks will cause a temperature distribution along the edge which can be captured by the thermographic camera for defects detection. These studies basically focused upon finding the detectability of defects. In this work, detection of the defect’s depth and size will be presented using the Eddy current thermography. In this study, we have worked upon A387 GR12 plate (killed steel). It has wide area of applications in various industries. The experiment discusses the inspection and finding dimension and location of angular edge defects using Eddy Current Thermography.

2. Theory of Eddy Current Thermography (ECT)

2.1 ASTM SA387 or A387 GR12 CL2 Cr-Mo Steel

The ASME SA387 standard covers the availability of weldable chrome molybdenum alloy steel plates for pressure vessels applications at elevated temperature [ASTM standard]. Molybdenum and chromium are used as main alloying materials which provides excellent resistance against corrosion especially at high-temperature [ASME BPVC.II.A]. For this study, A387GR12CL2 sample is used. As per ASME standard, it is engineered for use at elevated temperature service with applications in weldable pressure vessels and industrial boilers. In power plants, high thickness plates (thickness varying from 100 mm to 220 mm) are needed for weldable pressure vessels while low thickness plates are utilized in supporting structures for superheater, reheater, DeSH etc. In the petrochemical industry, inside the reactor, drums etc., it is used as drum internals like internal support clips or brackets. Chromium as alloy material provides excellent resistance for corrosion and oxidation which makes it ideal for sour service applications in the oil and gas industry. ASME BPVC code [11] specify the Tensile requirements as:
**Table I:** Mechanical properties of A387GR12

<table>
<thead>
<tr>
<th>Designation</th>
<th>Nominal Chromium (Content (%))</th>
<th>Nominal Molybdenum (Content(%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A387 Grade 12</td>
<td>1.00%</td>
<td>0.50%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tensile Requirements for Class 2 Plates:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designation</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>A387 Grade 12</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
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</tbody>
</table>

### 2.2 Eddy Current Thermography (ECT)

ECT is based on the concept of heating the sample/component using eddy currents and noticing the thermal variation alongside the crack for defect detection. It uses a high power and frequency coil for induction heating of the component and using a high resolution Infrared camera for observing the thermal response. This technique can be used in line with other thermographic evaluation techniques such as laser spot thermography and sonic thermography. Any open or closed cracks or surface/subsurface flaws will respond with a thermal gradient around itself.

**Induction Heating:** Induction heating being an efficient, precise and fast non-contact method for heating electro conductive materials is largely employed in manufacturing industries especially for pre-heating and post-heating processes during welding. It depends on principle of electromagnetic induction and a coil, suitably dimensioned and conducting high or medium frequency alternated current, is placed near to the metal component to be heated. This induces eddy currents in the material which cause heating of the specimen. This heat is distributed to the rest of the material by conduction. Induction Heating thus doesn’t need any physical contact and is a very efficient way of heating without much loss of energy. Induction heating is a combination of the three principles:

(a) Electromagnetic induction
(b) Joule Heating
(c) Thermal conduction

(a) **Electromagnetic Induction:** Faraday’s law of electromagnetic induction states that an emf is induced in a coil when magnetic flux through the coil changes with time and the direction of induced emf is given by Lenz law. That is:

\[ \varepsilon = -d\Phi / dt \quad (1) \]

This change of flux may be because of various reasons like relative movement between the secondary and the primary coil (generating magnetic flux), or using a time-varying magnetic flux (Example induction heaters).

**Eddy currents:** When a bulk piece of the conductor is placed in the vicinity of changing magnetic flux, induced currents are produced in it. As, their flow patterns resemble swirling eddies in water so called Eddy currents. The effect was discovered by physicist Foucault and these currents are also called Foucault currents. The eddy currents intensity is specified as:

\[ i_{eddy} = i_{surface} * e^{-z/(coth)} \quad (2) \]
Here, \( i_{\text{surface}} \) is current at the surface, \( z \) is coordinate for depth, \( c \) is a constant, \( \mu \) is the magnetic permeability of the material and \( \sigma \) is the conductivity of the material.

As the magnetic field is penetrating the specimen so the eddy currents are going to be concentric circles perpendicular to the magnetic flux and as shown in fig2, the temperature distribution along the depth will also be a similar profile as on the surface of the specimen with intensity decreasing exponentially with depth. As the Current density depends on material properties like Magnetic permeability and Conductivity of material thus the temperature profile is going to be a signature profile for a particular material at a specific frequency and applied field for a given time. Presence of any flaw/crack/defect in the specimen will disturb the flow of eddy currents and thus the temperature profile will change for the specimen and thus the signature temperature profile is distorted. By analysing this distortion in temperature profile we’ll be able to locate the defect and find out its size, as explained in the subsequent portion of this chapter.

(b) Joule Heating: Joule heating or resistance heating is the generation of heat when electric current is passed through a conductor. Joule’s first law states that the heat generated by an electrical conductor is proportional to the product of its resistance, the square of the current and the time. Therefore, the eddy currents produced in a material encounter the resistance offered by the material of the specimen which causes heating. Now, there are other factors which shall be taken into consideration while discussing about eddy currents.

The depth of penetration and skin depth: Eddy currents are more concentrated on the surface and their intensity decrease exponentially with distance below the surface of the metal. The effect is known as "skin effect". Skin depth can be calculated from following relation:

\[
\delta = \sqrt{\frac{2}{\omega \mu_0 \mu_r \sigma}}
\]

Where, \( \delta \) = standard depth of penetration (mm), \( \omega \) = angular frequency (Hz), \( \mu_0 \) = permeability of free space and \( \mu_r \) = Relative permeability, \( \sigma \) = conductivity (m/Ωmm²).

As conductivity and permeability are going to be constant for a selected material, the standard depth of penetration will be inversely proportional to the square root of frequency applied. Skin depth is also used to design the thickness of current carrying wires.
(c) **Thermal Conduction:** Conduction and convection heat transfer modes depend on various material properties like density \( \rho \), thermal conductivity \( k \), specific heat \( c \), thermal diffusivity \( \alpha \), temperature \( T \). The differences in these properties for defect area and rest of the specimen creates the thermal gradient around defect area and thus becomes the base of the Thermal inspection.

**Infrared Thermography:** Infrared thermography based on detection of infrared energy emitted by an object, converting it to temperature, and displaying the image of temperature distribution. On the basis of the source for heating the specimen or the method of establishing the heat flow, thermography can be divided into two sections i.e. Passive Thermography & Active Thermography.

Active thermography requires an external stimulus to create the necessary temperature gradient between defective and non-defective zone. So, thermography can be further categorized on basis of the excitation mode and heat source. Source of stimulus can be:

- Optical Excitation
- Electromagnetic Excitation
- Mechanical Excitation

Electromagnetic excitation is being used in our experiment.

### 3. Experimental Setup of Eddy Current Thermography

#### 3.1 Specimen

A plate of Cr-Mo steel of grade SA387Gr12Cl2 is used as a specimen for the study. Three different samples having dimension 75mm x 60mm x 10 mm were cut from this plate. Now to make it similar with a real-time edge defect, angular slots with dimension 7 ± 0.2 mm x 1.25 ± 0.25 mm are created using saw-cutting throughout 60 mm width at angles of 90°, 60° and 30° with constant slot length & thickness, in all 3 samples respectively. Surface for all specimen was painted black to avoid reflection.

#### 3.2 Induction heating system

Indutech make Induction heater with a maximum power output of 1 kW is used for induction heating of the specimen. The electrical energy is applied through a copper coil which produces a precisely controlled magnetic field over the specimen. Operating frequency range of the system is 500 kHz.

**Coil design:** The coil used in the experiment is shown in Figure 5.

- Material: Copper
- Geometry: Helical (with constant base diameter & 4No of turns)
- Internal Diameter: 42±2 mm and OD: 50±2 mm
- Copper tube Radius used to make the coil:4mm
- Coil lift off: 4.5 mm.

![Fig. 5: Induction coil used for the experiment](image1)

![Fig. 4: Sample under testing](image2)
**IR Camera:** IR camera FLIR SC 7500 is used for this experiment. Camera sensor detects the thermal profile which is then converted to thermogram by using computer software. The camera with a sensitivity of 25mK and frame rate up to 380 Hz is used for the experiment. Frame rate basically determines the speed at which the camera can be operated. The thermograms recorded by IR camera can be evaluated and displayed using ALTAIR SOFTWARE. MS Excel and Origin 8 are used for plotting graphs.

### 3.3 Schematic Diagram

The schematic diagram for the experiment is shown in Fig 7 and the actual experimental setup is displayed in figure 6. The copper induction coil will induce eddy currents in the specimen. These eddy currents will try to take the shortest closed path which will create uneven heating around the flawed region. This uneven heating same will be captured by IR camera and this image can be processed further for defect detection.

![Figure 6: Schematic Diagram](image)

![Figure 7: Actual experimental setup](image)

### 4. Observation and Analysis

#### 4.1 Experiment Observations and Results

The coolant system was used for the coil to avoid overheating. IR camera was calibrated accordingly. Setting was done at full power of 1 kW for Induction Heater so as to deliver a current of 400A. Heating tripped after 1s and the sample was observed for a time of 10 sec. In theory, the excitation signal and the thermal response is supposed to be like as in figure 8.

![Figure 8.a: Left: Excitation signal](image)

![Figure 8.a: Right: temperature response](image)

Now the thermograms recorded for different angles are shown in figure 9. With the thermograms, it’s evident that where the eddy currents are rushed/trapped more, there the indication is strong enough to provide a thermo-visible indication of the defect. It can be easily seen that if the angle of trapment ($A_t$) or slot angle is less (like defect angle of 30°), the temperature rises at the marked area as indicated in figure 10, will be a sudden spike due to concentrated eddy currents. And for the larger slot angles like 60° and 90°, the entrapped area is shifted to bottom, as shown in figure 10, thus the thermal indication of a defect will be strong in transmission mode.
During the cooling phase, the heat generated in the entrapped zone is going to be diffused to the neighbouring area causing a temperature rise in the neighbouring area during the cooling phase as well. The heating zone will also vary with the frequency and standard depth of penetration [Oswald and Wally] [7]

Now an edge defect can be defined having dimensions ‘a’ and ‘b’ as shown in fig11. Now, if a is greater than b then it will be like a shallow defect and more eddy currents will rush under the defect and heating in this zone is going to be more [Suixian Yang] [9].

As for our experiment we have created a defect throughout the width of the sample, as shown in fig12, therefore all the eddy currents are being forcefully diverted under the defect. Because of this the defects deeper than Std. depth of penetration are also going to be visible from the side view. Same is evident from the thermograms shown in fig9.

Temperature Profiles for side face:
If the temperature profile is taken along a vertical line drawn on the side face of a defect-free sample, then this profile is going to act as a reference for defect detection which is explained in section 2.2.1 (a). Reason for this is that the presence of a defect/flaw in the specimen will distort the path of eddy currents and so the intensity of eddy current will get disturbed in the defective region causing a deviation in the temperature profile of the region from that of standard profile which will form basis of our defect detection.

As shown in figure 13, vertical lines are drawn to take the temperature profiles. The temperature data was taken at 0.70 seconds of heating. Temperature profile for the defect-free specimen will appear as shown in fig14. This temperature profile is going to be unique at a particular heating time and thus can be used as a Reference Profile for studying the specimen for defects.
Now for studying the specimen for edge defects, we are going to analyse the temperature profiles along the side face for all slot angles. For this vertical lines are drawn on the side face as shown in fig13 and temperature profile is recorded along these lines.

**Slot Angle 30°:** The temperature profile along the reference vertical lines is analysed. Due to the presence of any defect in the specimen, the thermal profile is going to be distorted as the path of eddy currents is disturbed. This will provide an indication about the presence of a defect. To study it, 5 vertical lines as L1, L2, L3, L4, L5 are drawn in the defective zone for 30° slot angle at 0mm, 1.5mm, 3mm, 5mm, 7mm distance from the tip of the left edge respectively. L0 denotes the vertical temperature profile for defect-free region. This is projected in fig13.

In fig15, the temperature profile along the reference line drawn in defect-free zone, which is going to act as Reference profile (i.e. along vertical line L0), indicates the decrease of temperature with depth which is supposed to be natural profile for as eddy current intensity decreases exponentially with depth. Now coming to temperatures profiles for defective zone (defect angle 30°), the temperature profile along line L5 shows that the temperature will be more in the zone where trapped eddy current is more comparatively to the temperature in defect-free zone. Further to this, as shown in fig9 (thermogram for 30°) the heat will diffuse from the tip of the defect to the neighbouring area, thus the temperature slope for point farther from defect mouth (i.e. Line L5 is leftmost and farthest from defect mouth) is relatively less in trapped zone as depicted by curve from O to A. We see a sudden drop in temperature at point A which shows deviation from the profile of a defect-free zone. This depicts the presence of a zone with material properties different than the parent material. i.e. a crack open to the surface in this case and point A marks the beginning of the crack opening. Later on we see a sudden spike in temperature to point B and this marks the other end of the crack opening. So the
horizontal/abscissa distance between the two points $A$ and $B$ defines the width of the crack and $O$ to $A$ distance will give us the depth of the defect from the surface.

Similarly, for line L1, as the line is drawn at the tip of the defect, the temperature is very much more at the surface than the temperature in defect-free zone. We see a sudden drop in temperature at point $A'$ indicating the beginning of the crack. Further to this, we again see a temperature rise to point $B'$ indicating the other end of the defect. Thus the distance from $A'$ to $B'$ denotes the width/depth of the defect. In the similar fashion, starting and end point for the defect can also be located along line L2, L3 & L4.

Surface temperature comparison for line L2, L3 & L4 is as temperature for L2>L3>L4 (Start point of curves (at points, $O$ & $O'$) indicates the surface temperature). This is due to the reason that for very steep slot angle, Current density will be more for the points nearer to the tip of the defect (i.e. inside edge).

For $60^\circ$: Similarly, 4 lines are drawn in the defective zone for $60^\circ$ slot angle also named L1, L2, L3, L4 at a distance of 0mm, 1.5mm, 3mm, 5mm from the inside tip of the edge defect respectively. L0 denotes the vertical temperature profile for defect-free zone.

It is evident from the figure 17 that, contrary to the case of $30^\circ$ slot angle as shown in figure 15, here it can be seen that the temperature difference at surface for line L1, L2 & L0 i.e. at starting point of profile at point $O$ is not meagre. Lesser trapped eddy currents due to slant slot angle in the zone can be a reason here.

In fig.18, temperature profile for line L3, L4 and L0 is almost the same up to point $A$. Here onwards to point $A$, the temperature rise is very gradual and not sudden for L3. This shows that the line L3 may not cross the defect but can be in the vicinity of the same and highlights the presence of a nearby defect. Also, as the temperature decrease initially and then we see a gradual increase later at a certain depth, this hints towards the presence of a nearby angular/horizontal defect. For line L4 in figure 18, profile traced is similar to the profile of L0 line with a little less slope and more temperature. This can be due to heat diffusion from a nearby trapped heat zone as shown in below fig19.

For $90^\circ$: Contradictory to the temperature profile for a defect free sample, for line L1 graph shows a very less temperature at the surface which indicates an open-to-surface defect. Temperature increases gradually with depth and reaches a point of maximum temperature and then decreases suddenly. This provides a hint that the defect may be a vertical open to surface defect.
defect, depth of which is measured by abscissa of OA. For line L2 & L3, the vertical temperature profile is similar up to point Z followed by gradual increase in temperature. This indicates the presence of a defect in the vicinity.

Some important points which can be drawn from above graphical comparisons are:
- In all above graphs: Points A, A’, A” marks the beginning of the crack.
- Points B, B’, B” marks the end of the crack opening.
- Distance AB, A’B’, A”B” shows the height of the crack.
- Distance OA, OA’, OA” shows the depth of the crack.
- If there’s no point B/B’ then it shows point A is just in the vicinity of crack.

A table as follows is made in accordance with above data, comparing the theoretical values with the experimental values for defect depth and height.

<table>
<thead>
<tr>
<th>Slot angle (degrees)</th>
<th>Location (line drawn for taking temp profile)</th>
<th>The distance of the line from defect tip (mm)</th>
<th>Geometrical value</th>
<th>Experimental value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Defect depth from surface (mm)</td>
<td>Defect Height/width of (mm)</td>
</tr>
<tr>
<td>30</td>
<td>L1 0.00</td>
<td></td>
<td>0.00</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td>L2 1.50</td>
<td></td>
<td>0.00</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>L3 3.00</td>
<td></td>
<td>0.00</td>
<td>1.25</td>
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<tr>
<td></td>
<td>L4 5.00</td>
<td></td>
<td>0.00</td>
<td>1.25</td>
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<tr>
<td></td>
<td>L5 7.00</td>
<td></td>
<td>0.00</td>
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<td>60</td>
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<td></td>
<td>L3 3.00</td>
<td></td>
<td>No defect</td>
<td>No defect</td>
</tr>
<tr>
<td></td>
<td>L4 5.00</td>
<td></td>
<td>No defect</td>
<td>No defect</td>
</tr>
<tr>
<td>90</td>
<td>L1 0.00</td>
<td></td>
<td>7.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>L2 1.50</td>
<td></td>
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<td>No defect</td>
</tr>
<tr>
<td></td>
<td>L3 3.00</td>
<td></td>
<td>No defect</td>
<td>No defect</td>
</tr>
</tbody>
</table>

Table 2: Experimental values vs Geometrical values of defect depth and defect height
Above table shows that the experimental values for defect height and depth are matching with the theoretical values with a tolerance of 0.25mm which can be rectified by different image processing tools or using Phase analysis [3].

5. Automated-ECT

The possibilities for automation of the steps involved in ECT inspection makes thermography an interesting alternative to other manual inspection techniques such as fluorescent penetration inspection (FPI) [12]. Automation of ECT by doing robotics in handling induction coils and component was discussed by Netzelmann and Walle [6,13]. Standardization of induction thermography and rails & train wheels’ automated inspection for surface defects was also discussed. Though, automation by doing the automated movements of components or induction coils is being discussed so far for the ease of inspection, but exploring the area of automated final decision making after inspection is going to be more interesting. A reference criterion similar to GO/NO-GO gauges can be set so as to establish an Accept-Reject criterion. Basically it is going to asks for a reference sample/charts/table similar to other NDE techniques. The theory in this direction can be explained as hereunder.

With the help of other NDE techniques and our own past experience, a Reference/Trueflaw sample-set can be prepared for a Specific product or a production line. This Trueflaw sample-set shall have all the possible defects for that production line based on our experience. Now, this Trueflaw-sample-set is going to act as limits for Accept-Reject criterion for our production line. Thermograms can be obtained by performing the Eddy current thermography study for this sample set. These thermograms are going to act as the reference sets for setting the accept-reject criterion. From these thermograms (as explained earlier in this paper) temperature graphs, amplitude & phase images can be generated. Accept-Reject criterion can be set for the production line on in accordance with amplitude and phase images [3]. With the current advancement in image processing and software development, maximum available readings with us can be linked/fed in the image processing software for the standard specimen. Now, all the components manufactured in the production line having the thermal readings, measured by thermal camera, is not within the set limits, those components can be marked for further evaluation or straightaway rejected. In this fashion, the complete production line including inspection decision, can also be automated.

6. Conclusion and Outlook

The experimental study presented here provides a good understanding of thermographic inspection for edge cracks in in-service components. ECT proves to be an effective and quick technique in inspection of edge defects. The location and dimension of defect can be measured easily with considerable accuracy. It is easy to inspect the materials and with the help of robotics, it is easy to automate the inspection process for suiting the production lines.

With the quickness similar to visible inspection, ECT is an emerging technique which can prove to be a good alternative to various other conventional NDE techniques and it shall be explored further. Also with use of automation, the inspection time and cost can be reduced by a considerable amount.
7. References


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