Eddy Current Thermography of Angular Slots in CrMo Steel Plate

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Abstract

ASTM A387 or SA387 Cr-Mo steel has wide applications in power plants sector, oil and chemical Industry as pressure vessels, heat exchangers, industrial boilers and piping works. A387 alloy undergoes fatigue cracks at high temperature environments. Infrared thermography is an important noncontact nondestructive testing method in the early detection of fatigue cracks. Nonhomogeneous stress field would result in crack propagation along curved paths. Eddy current thermography (ECT) has been found to be effective in determining angular cracks in aluminium. This technique is a combination of eddy current excitation and thermal imaging which proves to be a quick method for defect detection and characterisation over a larger area.

In the present study, we have examined simulated defects in GR12 plate of A387 (killed steel) which is commonly used in support structures for reheater and superheater coils of boilers in power plants. To simulate the real time long surface-cracks, samples are cut with the dimensions of 75 mm x 60 mm x 10 mm. Angular slots of dimension 7 ± 0.2 mm x 1.25 ± 0.25 mm are made throughout 60 mm width at angles of 30º, 45º, 60º and 90º with constant slot length and thickness. ECT experiments were performed using a 500 kHz induction generator as eddy current energy source and FLIR SC7000 thermal imaging camera under reflection and transmission modes. The study suggests that ECT could be carried out to determine angular cracks in service components. The validation of above experiment results by other methods suggest ECT as an alternative to conventional non-destructive examination techniques. ECT offers further prospects in extending into the area of automation and has specific advantages compared to conventional methods.

Keywords: Eddy current Thermography (ECT), Angular defects detection, A387GR12, Induction Thermography

1. Introduction

The Eddy Current Thermography (ECT) is an evolving contact-free, non-destructive method for crack testing of electroconductive materials and is a combination of two existing non-destructive testing methods, the depth sensitive eddy current testing and the fast and contact-free thermography [1,2]. It is quick inspection method and can be used for detection and characterization of structural degradation and failures such as defect, fatigue, corrosion, and residual stress etc. This technique is able to detect hidden, subsurface defects even in complex geometry components. In this, the parts to be tested are heated up by an inductively generated current flow and the temperature variation on the surface of the component is recorded with a thermographic camera. Cracks disturb the flow of the current in the component and thus change the temperature distribution as well which can be detected thermographically with a high resolution Infrared Camera (IR camera). This method has also a high application potential for closed cracks and cracks close under the surface where the dye penetrant inspection could not be used.

In the present study, we have examined simulated defects in GR12 plate of A387 (killed steel) which has wide applications in power plants sector, oil and chemical industry as pressure vessels, heat exchangers, industrial boilers etc. The experiment results for reflection as well as transmission modes could be undertaken by recording the images at an angle. The results on ECT in angular slots and its advantages are discussed.
2. Experimental techniques:

2.1 ASTM A387 or SA387 Cr-Mo Steel

The ASME SA387 standard covers the supply of weldable chrome molybdenum alloy steel plates for pressure vessels used in elevated temperature service. The added molybdenum and chromium provides excellent corrosion resistance and high temperature resistance respectively [ASME BPVC.II.A]. It is a low alloy steel due to its good oxidation and corrosion resistance, strength at elevated temperatures and has wide application area from power boilers to industry boilers, oil and chemical industries to piping sector. It is available in various grades and shall be killed and treated thermally and shall conform to the chemical composition requirements and also to undergo various tests like tensile strength, yield strength and elongation as specified by the code. A387 is available in grades 2, 5, 9, 11, 12, 21, 22, 91 as per the percentage content of Chromium & Molybdenum [ASME BPVC.II.A]. Each grade except Grades 21L, 22L, and 91 is available in two classes of tensile strength levels.

2.1.i Grade 12 Class 2:

For the present study we have used A387GR12CL2 sample. As per ASME standard, it is engineered for use in 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 used for weldable pressure vessels. Lesser thickness plates are used in supporting structures for reheater superheater coil etc. In petro-chemical industry inside reactor, column, drums etc., it is used as internal support clips or brackets. The material benefits from added chromium which provides excellent corrosion and oxidation resistance making it ideal for sour service applications in the oil and gas industry. Tensile requirements as specified in ASME BPVC code as [3]:

<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>

Tensile Requirements for Class 2 Plates:

<table>
<thead>
<tr>
<th>Designation</th>
<th>Requirement</th>
<th>Grade 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>A387 Grade 12</td>
<td>Tensile strength, ksi [MPA]</td>
<td>65 to 85 [450 to 585]</td>
</tr>
<tr>
<td></td>
<td>Yield strength, min, ksi [MPa]/(0.2% offset)</td>
<td>43 [310]</td>
</tr>
<tr>
<td></td>
<td>Elongation in 8 in. [200mm], min %</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Elongation in 2 in. [50mm], min %</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Reduction of area, min %</td>
<td>—</td>
</tr>
</tbody>
</table>

2.2 Eddy Current Thermography

ECT can be used in line with other thermographic non-destructive evaluation (NDE) techniques such as sonic and laser spot thermography [1]. It involves heating of component/sample using induced currents using a high power and high frequency coil and observing the thermal response of the component using an infrared camera. Any surface or subsurface flaws will respond with a temperature gradient around itself. It consists of:

2.2.i Induction heating

Induction heating is a fast, efficient, precise, non-contact method for heating metals or electrically-conductive materials by means of electromagnetic induction. In this, a coil, suitably dimensioned & conducting high or medium frequency alternated current, is placed close to the metal parts to be heated, which induces eddy currents in the material. These eddy currents cause heating of the specimen, further this heat is distributed to the nearby material by conduction. Heating occurs without any physical contact and very efficiently without any loss of energy. Induction heating is basically a combination of following three principles:

a) Electromagnetic induction.
b) Joule Heating

c) Thermal conduction

2.2.i.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. i.e.

\[ \varepsilon = -\frac{d\Phi}{dt} \quad \text{Eq 2.1} \]

This flux change may be because of several reasons like relative movement between the coil and the primary coil (generating magnetic flux); or using a time varying magnetic flux a (e.g. induction heaters).

**Eddy currents:** When bulk piece of conductor is subjected to changing magnetic flux, induced currents are produced in them. However, their flow patterns resemble swirling eddies in water. This effect was discovered by physicist Foucault and these currents are called eddy currents or Foucault currents. Eddy current intensity can be given as:

\[ i_{\text{eddy}} = i_{\text{surface}} \cdot e^{\frac{z}{(c \cdot \sigma)}} \quad \text{Eq 2.2} \]

where \( i_{\text{surface}} \) is the current at the surface, \( z \) is the depth coordinate, \( c \) is a constant, \( \sigma \) is the conductivity of the material and \( \mu \) is the magnetic permeability of the material.

2.2.i.b Joule Heating:

Joule heating or resistance heating is the generation of heat by passing an electric current through a conductor. Joule’s first law states that the of heat generated by an electrical conductor is proportional to the product of its resistance, the square of the current and the time. So the eddy currents produced by a high energy coil encounter the resistance offered by the material of the sample/specimen which causes heating. Now with eddy currents there are several other factors which shall be taken into consideration

**Edge Effect:** When the induction coil is near to the edge then there can be rushing of eddy currents near the edge as shown in fig.2.1, may cause extra heating near the edge and some extra thermal gradient may be shown on IR camera. This is called edge effect.

**Depth of penetration and skin depth:** Eddy currents are more concentrated at the surface and decrease in intensity with distance below the surface of the metal. This effect is known as the "skin effect.". The relation between them can be given as:

\[ \delta = \sqrt{\frac{2}{\omega \mu_0 \mu_r \sigma}} \quad \text{Eq 2.2} \]

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

Assuming conductivity and permeability to be constant for a selected material, standard depth of penetration will be inversely proportional to the square root of applied frequency. Skin depth is sometimes used to design the thickness of current carrying wires.

2.2.i.c Thermal Conduction:
The heat transfer by conduction and convection depend on various material characteristics like specific heat ‘c’, density ‘ρ’, thermal conductivity ‘k’, thermal diffusivity ‘α’, temperature ‘T’. Thermal inspection depends on differences in these material characteristics to establish a measurable, and usually localized, temperature differential.

2.2.ii Infrared Thermography:
As the name suggests, infrared thermography detects infrared energy emitted from an object, converts it to temperature, and displays image of temperature distribution. On the basis of source to heat the specimen or the way to establish the heat blow thermography can be divided into two basic sections i.e. Active Thermography & Passive Thermography.

Configuration Modes: There are two possible ways of conventional optical thermography:
- Reflection Mode, where the thermal excitation source heats the specimen and the IR camera records the temperature on the same side.
- Transmission mode, where the heat source is on one side while the IR camera records from other side. Generally, transmission mode yields more contrast compared to reflection mode.

3. Experimental setup of Eddy Current Thermography:

3.1 SPECIMEN:
A slab of SA387Gr12Cl2 (Cr-Mo steel) was used as a specimen for the study. Four samples with dimension 75mm x 60mm x 100 mm were cut from Cr-Mo steel plate. Now to make it similar with a real time defect, angular slots of dimension 6 ± 0.2 mm x 1.25 ± 0.25 mm are made throughout 60 mm width at angles of 30º, 45º, 60º and 90º with constant slot length and thickness in all 4 samples respectively. Angular defects were induced using saw-cutting. Every specimen surface was painted with black paint to avoid reflection.

3.2 INDUCTION HEATING SYSTEM
The induction heating system used is an Indutech make Induction heater with maximum power output of 1 kW. This energy is delivered to a copper coil and it produce a precisely controlled magnetic field over the work piece. The system operates in the frequency range of 500 kHz.

3.2.i Coil design: Figure 3.1 shows the coil used in the experiment.
- Material: Copper
- Geometry: Helical (with 4No of turns & constant base dia)
- ID: 42+-2 mm and OD: 50+-2 mm
- Copper tube Rad:4mm (used to make the coil)
- Coil lift off is 4.5 mm.

3.2.ii IR Camera:
The IR camera used for this experiment is FLIR SC 7500. The thermal profile detected by camera sensor is converted to thermogram by using computer software’s. The camera used has an accuracy of 25mK and frame rate can go up to 380 Hz which determines the speed at which the camera can be operated. The camera records thermograms which can be evaluated and displayed using ALTAIR SOFTWARE. Origin 8 and MS Excel are used for plotting graphs.

3.3 Schematic Diagram:
The schematic diagram for the process and the actual arrangement is shown in fig 3.2. Coil will induce eddy currents in the sample which will rush for the shortest close path creating uneven heating which will be captured by IR camera and the image can be processed further. This will cause uneven heating and the same will be observed using IR camera.
4. Observation & Analysis:

Experiment observations & results:

The experiment was performed with the coolant system for the coil and calibration of the IR camera. Induction Heater was set at full power of 1 kW so as to deliver a current of 400A. Power was tripped after 1s of heating. The sample thermal profile was recorded using camera for a total of 10 sec. The excitation signal and the thermal response is similar to the one shown in fig 4.1.

Now Various thermograms recorded for various angles are shown in fig4.2. The across the width slot created in the sample will act similar to a longer and shallow surface crack.

From the thermograms, it is clear that wherever the eddy currents are rushed/trapped more, the indication there is enough to give a strong thermo-visible indication for defect. It is clear that for lesser angle of trapment ($A_t$) or slot angle, defect angle like 30° or 45°, temperature rise at the area indicated in fig 4.3 will be sudden because of concentrated eddy currents. When the slot angles are large like 60° and 90°, the trapped area has shifted to
bottom as shown in fig 4.3 and the temperature indication of defect will be strong in transmission mode.

We also see the increased temperature along the top edge of the sample, depicts edge effect. During cooling phase, the heat generated in the trapped area will be diffused to the neighbouring area which may cause a temperature rise in neighbouring portion during cooling phase also.

To further study this, total 8 Points, as indicated in fig 4.4, were considered for taking the temperature data and plotting the graphs. The objective was to see the temperature gradient within the trapped area during heating phase and the temperature change due to diffusion during cooling phase.

![Figure 4.4: Sample layout indicating points for taking temperature profiles](image)

For each slot angle we have plotted the graphs as given below:

a. Comparison of temperature variations between points on bottom edge i.e. B1, B2, B3, B4.

b. Comparison of temperature variations between points on top line i.e. T1, T2, T3, T4.

**Graphs:**

Abscissa ordinate the frame number for the time and is a unit of time (2000 frames = 10 seconds). Ordinate indicates the temperature in °C. For the various slot/defect angles, our observations are:

**Slot angle 30°:**

1. For temperature profile in bottom edge, Temperature at point B1 (point just below the end of the defect) is found to be maximum. This is because of the change of path of eddy currents because of presence of the defect. Now, as the slot/defect is across the width of the specimen, so eddy currents are bound to be pushed under the defect. This simulates for longer and shallow surface defect.

2. The temperature is maximum at B1 and then decreases as we move from B1 to B4. This is because we are moving away from the zone of local heating. This difference in the transient temperature profile at various points highlight the presence of a defect in the vicinity.

3. For temperature profile along the top line, we observe the temperature at T3 is much much more than at the neighbouring points and then temperature drops suddenly during cooling phase. This indicates the presence of a surface defect at a steep angle. This is because of the more rushing of the eddy currents at the inside tip of the steep angular defect as shown in fig4.3.

4. We see a gradual increase in the temperature at point T1 with time. This is because of the diffusion of the heat from the localised heat zone, formed at the tip because of rushing of more eddy currents, to the neighbouring region as shown in fig 4.5
5. Temperature at T4 is minimum as the flow of eddy currents is disturbed to a minimal amount here.

**Slot angle 45° and 60°:**
1. In graph 4.2, for temperature profile at bottom edge, with the increase in the slot angle from 30° to 45°, the point of maximum temperature is shifted from B1 to B2 and temperatures at B1 & B3, B4 are lesser. Similarly, in case of 60°, the maximum temperature is now at B3.
2. In T-comparison graph of graph 4.2, the rise in temperature during heating at T3 is comparatively lesser than in case of 30° slot angle as the trapped area has increased causing a comparatively lesser current density.
3. Temperature rise at bottom point with maximum temperature (i.e. B2 in case of 45° slot angle and B3 in case of 60°), is more for 60° as trapped area for eddy currents is reduced because of more slant angle.

**Slot angle 90°**
1. In graph 4.4, Temperature rise at B4 is maximum compared to neighboring points. Also the temperature rises in case of 90° is maximum at bottom point of maximum temperature (B1 for 30°, B2 for 45°, B3 for 60°) as the trapped area is reducing causing more rushing of eddy currents in the zone.
2. Difference between temperatures at point T3, T2 & T1 is not much.
From the graphs and thermograms, the following comments can be made:

- For smaller slot or defect angles (i.e. 30° & 45°), temperature at point 3 (T3 & M3) is very much more than neighbouring points which means heating portion or defect-indication shall be clearly visible in reflection mode while for larger slot angles (i.e. 60° & 90°), temperature rises in the bottom portion and thus transmission mode will be more effective for detecting defects.

- There is some offset between location of high temperature zone in reflection and transmission zone. This offset is more for steeper angles and it decreases with increase of slot angle.

- Similar results can be expected with sub-surface defects and same can be detected.

- This offset can help us determine the orientation of the defect. If the high temperature zone is noticed on both sides of the sample and both are at an offset then it can be an angular defect.

- For lesser specimen thickness, if high temperature zones are detected on only one side then it can be a near surface or subsurface defect.

- Defects parallel to the plane of eddy currents may get undetected so defect detection probability can be increased using a moving coil with the help of robotics arm etc.
Various studies have carried out for simulation for similar Coil-Sample arrangement with angular defects created in materials other than that used in the present study. Zainal Abidin et al [4] carried the simulation work on samples with angular defects with plane of coil perpendicular to sample plane. C.He et al [5] carried the simulation on iron sample with angular edge and surface defects. The study results are similar to the results obtained in this work suggesting the suitability of the ECT in angular defect detection on various materials.

5. Automated-ECT

The automation possibilities of the different steps involved in an inspection makes thermography an interesting alternative to manual inspection methods such as fluorescent penetration inspection (FPI) [6]. Netzelmann & Walle [7,8] discussed about the automation of ECT using robotics for handling of component and induction coils and also about the standardization of induction thermography and inspection of rails and train wheels performed for surface defects. However, automated movements of components or induction coils is being discussed for the ease of inspection. But it is more interesting to even explore the area of final decision making after automated inspection. A reference can be set similar to GO/NO-GO gauges so as to set up an Accept-Reject criterion. It basically asks for a reference sample/table/charts similar to other NDE techniques.

Specific to a product or a production line, with our past experience and with the help of other NDE techniques, a Reference/Trueflaw sample-set can be prepared. This Trueflaw sample-set shall have the possible/desired defects for that production line. Now this Trueflaw-sample-set sets the limit of Accept-Reject criterion for our production line. Eddy current thermography study can be performed for this sample-set. With the help of these thermograms (as available in previous section of this paper) temperature graphs, amplitude & phase images can be generated. From the amplitude and phase images [9], the Accept-Reject criterion can be set for our production line. With the available advancement in software development and image processing, the maximum readings available with us can be linked/fed in the image processing software of our thermal camera. For all the components produced in the production line, for which the thermal readings as measured by thermal camera are higher than the set limits, those components can be rejected or marked for further evaluation. This way whole production line including inspection decision can also be automated.

Various valves industries, inspection of Hardfacing/Stelliting of valve seats is done using liquid penetration testing which is time consuming and involves various chemicals. Avoiding all these chemicals and their hazards to the operator, automated-ECT as explained above can be explored for future inspections.

6. ECT as an alternative to other NDT methods

Magnetic particle testing (MPT) involves magnetization of component, application of powdered magnetic particles, examining the powder patterns and last demagnetization of component. The powder patterns surface up the defects. Though the method has use in industry sector it has some shortcomings like difficult post cleaning for intricate jobs. It is difficult to test the components/welds in overhead or vertical positions. Also in the scenario where various agencies aim at reducing energy-intensive methods, energy consumption required for magnetization and demagnetization is quiet considerable. With its ease of operation and lesser inspection time, induction thermography can prove to be an emerging alternate for MPT. Especially for inspection for cracks after heat treatment in drive shafts, service induced cracks in splined & threaded shafts etc. can be looked into. As inspection in all directions i.e. in vertical and overhead positions also is comfortably possible, it can be used for inspection of crane hooks without removing them for in-service cracks. Various
studies have already been done for forged components also. Bouteille & Legros [10] performed the comparison of induction thermography and MPT for forged wheel hubs and induction thermography was found to be credible alternate of MPT.

Several studies were also performed for comparison of ECT to LPT and the results were quiet satisfactory. The comparison for inspection of gas turbine blades and techniques for inspection of artificial hip joints were reported. As explained in previous section, Automated-ECT can be explored as an alternate inspection technique for inspection of Hardfacing/Stelliting of valves seats.

Comparison of ECT with radiography testing (RT) is pretty untouched, may be because of the bigger portfolio of RT. But if factors like radiation hazard to operators, more time consuming nature of conventional RT, it is always better to explore other safe methods like induction thermography. Especially inspection of weld defects like hot cracks, cold cracks, cater cracking etc. can be explored using ECT.

7. Conclusion and outlook

The experimental model presented here gives a good understanding of the thermographic inspection of angular cracks in service components. ECT proves to be an effective technique for inspection of surface and sub-surface defects. Materials are easy to inspect and with the help of robotics it can be automated easily for suiting to production lines. A contact-free method, without use of chemicals and coupling media, ECT is an environment friendly and energy efficient method. With reduced risk to operator’s health, thermography complies with European directives regarding exposure to electromagnetic fields and solvent vapours.

With the quickness of visible inspection and accuracy, ECT is an emerging technique which can be explored to be a credible alternate to various other conventional NDE methods. With the use of automation, inspection time can be reduced to few seconds at low inspection costs.

References: