APPLICATION OF MICRO FOCAL X-RAY TECHNIQUE FOR RADIOGRAPHY OF TUBE TO TUBESHEET WELDS OF FBR STEAM GENERATOR

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ABSTRACT

Fast Breeder Reactor (FBR) steam generator assembly, is a shell and tube heat exchanger. In this equipment, steam is generated by the transfer of heat from sodium on shell side to water on tube side. Due to inherent dangers of sodium-water reaction, the integrity and leak tightness of weld joints separating sodium and water/steam is very important. The tube to tube sheet (TTS) welds in steam generators separate the sodium and water, are such critical weld joints. To ensure integrity of the TTS joint, suitable recordable NDT technique was required to be established. Due to the stringent acceptance criteria, intricate geometry and limited access; performing NDT with conventional techniques was not feasible. These limitations were overcome using rod-anode Micro Focal X-ray Radiography technique. The micro focal X-ray unit, with smaller focal spot size in the range of 15 to 50 µm, enables great detail to be recorded in the projection radiographs resulting through the object magnification and resolution. Sensitivity up to the order of 32 microns is achieved. This paper describes the basic principle of Micro Focal X-ray and its application on TTS joints of FBR. Nearly 25000 joints of TTS welds have been successfully radiographed using Micro Focal rod-anode X-ray technique.

INTRODUCTION

Fast Breeder Reactor is a sodium cooled pool type reactor. The heat generated in reactor core is removed by circulating primary sodium. The primary sodium then transfers its heat to the secondary sodium. This secondary sodium which is non-radioactive, heats up water to generate steam in steam generator. The steam generated in these steam generators run the turbine generator, generating the electricity. The steam generator is a vertical shell and tube type heat exchanger. The fluid on shell side is the secondary sodium and on tube side is water/steam. As sodium and water reaction is violent and can lead to an explosion, integrity of weld joints in the boundary separating these two fluids assumes maximum importance. The tube to tube sheet (TTS) welds in steam generators separate the sodium and water, are such critical weld joints. To ensure integrity of the TTS joint, suitable recordable NDT technique was required to be established. The acceptance criteria for various flaws in the TTS welds are shown in table below.

Major material of construction of steam generators is 9Cr 1Mo modified. Tubes are 2.3mm thick and tube sheets are 180 mm thick with integral machined spigots. Detail of joint configuration is shown in Figure 1 below. Welding of these TTS weld joints is being done by internal bore welding without filler wire using GTAW process.

The possible defects in this joint are cracks, lack of fusion, incomplete penetration, tungsten inclusion, undercut, porosities, and deviation in weld profile viz concavities and convexities.

<table>
<thead>
<tr>
<th>Total pore count in the entire weld - Sum of all visible pore diameters in the weld, to be less than the following</th>
<th>Local concentration of pores(thesfer) - Total pore count of all pores in a 3mm circle anywhere in the weld must be such that their diameter is less than the following</th>
<th>Max. diameter of individual acceptable pore to be less than</th>
<th>Lack of fusion</th>
<th>Convexity</th>
<th>Concavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7mm</td>
<td>0.6mm</td>
<td>0.46mm</td>
<td>Nil</td>
<td>0.35mm</td>
<td>0.20mm</td>
</tr>
</tbody>
</table>
These intricate TTS weld joints are required to be examined by recordable non-destructive examination to ensure that it is free from weld defects. The TTS joints being thin and the only joints in the steam generator separating water and sodium, the integrity of the weld joints required is of the highest order. Therefore detection of micro defects to the order of 50 microns and detectable wire Image Quality Indicator (IQI) wire diameter of 32 microns was required.

With artificial low energy source (Thulium 170) the sensitivity requirements achieved were not sufficient to establish integrity of these TTS joints, hence it was necessary to apply micro focal rod anode X-ray technique. Use of Micro Focal Radiography enhances radiographic sensitivity. Coupled with projection radiography it facilitates accurate measurement of flaw size due to magnification. It utilizes rod-anode and focal spot of 15 to 50 microns.

**THEORY**

The purpose of radiographic examination is to examine an object for flaws. A basic understanding of the underlying fundamental principles that affect the visibility of flaw in the radiographic image is important. The quality of a radiographic image can be described in terms of three factors.

- Contrast,
- Definition (unsharpness) and
- Image graininess

All three of these important factors mainly affect detectability.

Radiographic Contrast is the density difference between areas of a radiograph. Obviously an image becomes more discernible when contrast is increased. Contrast is dependent on X-ray energy, radiation scatter conditions, type of film used, film development and film density.

Definition refers to sharpness or unsharpness of the image. In general one can assume that a sharp image is of higher quality than a less sharp image. However, at the limit of detection the quality of the image depends on both contrast and unsharpness.

Graininess refers to visual impression created by coagulated minute silver grains. The image on an X-ray film is formed by these countless minute silver grains. All films exhibit graininess to a greater or lesser degree. In general, the slower films have lower graininess than the faster films and give better sensitivity compared to fast films.

Another qualitative term used by radiographers to describe radiographic quality is “sensitivity”. It is a general term used to describe the ability of a radiograph to show details in the image. It is a reference to the amount of information or detail in the image. For example, if very small flaws can be seen in the radiograph, it is said to have high or good sensitivity. Radiographic sensitivity depends on image contrast, definition and graininess.

**Radiographic Factors Affecting Image Quality**

The important geometry factors affecting image quality are:

1. X-ray source or focal spot size - F
2. Source to object distance - D1
3. Object to image plane distance - D2

The most important of these factors is the focal spot size, because it not only influences the geometry of the inspection but also the resolution and image definition limits. All three of these variables are tied together in the equation for geometrical unsharpness (Ug). Geometrical unsharpness is defined as the focal spot size as seen from the image plane multiplied by the ratio of object to image plane distance (D2) to source to object distance (D1).

\[ U_g = F \times D_2 / D_1 \] (1)

Since the X-ray source always has a finite size, geometric unsharpness or image blur will always occur. The only way to reduce the image blur for a fixed radiographic set-up is to use a machine with a smaller focal spot. This is well illustrated in Fig. 2 where the Image effect of different size focal spots and
source to film distances is shown. When the radiation emanates from a focal point a shadow occurs. This shadow or image blur is called the geometric unsharpness. The magnitude of the geometrical unsharpness is directly proportional to the X-ray source size and can vary widely depending on the industrial X-ray machine used.

**Projection Radiography**

Projection radiography (image magnification) occurs when the specimen is moved away from the image plane. Conventional industrial techniques generally make little or no use of direct image magnification. This is because the image unsharpness and potential contrast loss caused by the large focal spot of the X-ray source and graininess of the film or screen mottle limit the amount of additional information that can be obtained. However, the application of micro focal X-ray sources to critical industrial inspection problems has shown that considerable more details can be acquired by image projection magnification radiography without compromising on geometrical unsharpness and contrast.

**CHALLENGES**

**Density Variation**

While conical targets produce radial panoramic beam, due to limitations in its manufacturing a flat target which is easy to manufacture, is used in Micro Focal radiography. The flat target produces panoramic beam in the backward direction with the beam angles being $0^\circ \times 45^\circ \times 360^\circ$ (w.r.t vertical) which has inherent disadvantage of producing the beam with uneven intensity across the weld. Additionally, it is necessary to position the rod-anode on center line of the weld joints. Both these limitations contributed for density variations and uneven radiographic contrast.

Although processing method is one of the technique which can be used for overcoming the challenge of density variation, considering the productivity and quality requirements it was decided to overcome this challenge by developing a suitable device for compensating density variation and designing a mobile unit with cross slides which will facilitate easy centering of the rod-anode.

Table 1 below indicates density variation of radiographs with and without compensating device.

Introduction of the suitable device and properly aligning the rod-anode has resulted in reducing the density variations in the radiographic film. While in the case of uncompensated beam the density varies across the weld by more than 68%, this variation has been reduced to less than 25%.

It can also be observed from the table that the use of a suitable device has increased the latitude. Thus densities less than 1.8

![Figure 2](image-url)

**Table 1**

<table>
<thead>
<tr>
<th>Weld Joint Identification number</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>381 R7H33</td>
<td>1.38</td>
<td>2.84</td>
<td>3.47</td>
<td>1.06</td>
<td>1.94</td>
<td>3.71</td>
<td>1.62</td>
<td>2.67</td>
<td>2.68</td>
</tr>
<tr>
<td>381 R7H37</td>
<td>1.66</td>
<td>2.53</td>
<td>3.30</td>
<td>1.04</td>
<td>1.94</td>
<td>3.39</td>
<td>1.47</td>
<td>2.21</td>
<td>3.07</td>
</tr>
<tr>
<td>381 R7H15</td>
<td>2.12</td>
<td>3.10</td>
<td>3.45</td>
<td>1.20</td>
<td>1.96</td>
<td>3.57</td>
<td>1.55</td>
<td>2.30</td>
<td>3.16</td>
</tr>
</tbody>
</table>

**With Compensating Device**

<table>
<thead>
<tr>
<th>Weld Joint Identification number</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>381 R7H33</td>
<td>2.89</td>
<td>3.30</td>
<td>3.78</td>
<td>1.78</td>
<td>5.10</td>
<td>3.27</td>
<td>2.91</td>
<td>5.40</td>
<td>2.07</td>
</tr>
<tr>
<td>381 R7H37</td>
<td>3.25</td>
<td>3.39</td>
<td>2.66</td>
<td>1.96</td>
<td>2.78</td>
<td>2.61</td>
<td>2.45</td>
<td>2.95</td>
<td>2.26</td>
</tr>
<tr>
<td>381 R7H15</td>
<td>2.73</td>
<td>3.49</td>
<td>2.70</td>
<td>2.07</td>
<td>2.90</td>
<td>2.75</td>
<td>2.25</td>
<td>2.75</td>
<td>2.30</td>
</tr>
</tbody>
</table>
have improved and overall density on the radiographic film was within the acceptable range of 1.8 to 4.0 as stipulated in the standards.

Apart from reducing the density variations, it also improved radiographic contrast. It is well known that uneven radiographic contrasts make interpretation very difficult. The use of the device has made it possible to achieve even radiographic contrast thus making film interpretation convenient and easy.

**Magnetism**

The material used in construction of steam generators; 9 Cr 1Mo modified for tube-sheet, tubes and thermal shields which are in close vicinity of the weld joints had undergone in-process machining, eddy current testing and laser cutting respectively. It has been observed practically that these processes induce magnetism; material being very hard also has higher magnetic retentivity.

It is well known limitation of rod-anode x-ray technique that electron beam gets deflected by magnetism. Any deflection of electron beam causes misalignment of the electron beam w.r.t target location and leads to diversion in x-rays produced. In Micro Focal rod-anode the focal spot is in the range of 15 to 50 µm hence the fine electron beam hitting the Tungsten target needs to be perfectly aligned.

Insitu-demagnetization technique using coils was used. The tube-sheet, thermal shields which were integral part of the tube bundle were demagnetized in-situ and the tubes were demagnetized prior to use. The guide rod fixture was made of stainless steel, the rod anode was coated with “µ” material.

**Interpretation & evaluation of radiographs**

The quantified acceptance criteria for porosity necessitated use of projection radiography technique. The radiographs were produced with magnification of 2.76X and viewed with lens of 3X magnification. Measurement of porosities was accomplished with eye piece of 8X magnification.

**CONCLUSION**

Micro focal X-ray technique was successfully applied for radiographic examination of critical TTS welds of FBR steam generators.

**ACKNOWLEDGEMENTS**

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