VIDEO INSPECTION OF LATTICE TUBE ROLLED JOINT AREA WITH STRUCTURED LIGHTING FOR ENHANCED SURFACE PROFILING

P.A. Rochefort, M. Bouchard, P. Joynes, A. Kittmer, M. King

AECL – Chalk River Laboratories
Inspection, Monitoring and Dynamics Branch
Chalk River, Ontario, Canada, K0J 1J0

Abstract

Retube Tubesheet Bore Dressing is a series of operations being performed by the Bruce Retube Project between calandria tube removal and installation of the new calandria tubes. Specialized remotely-operated tooling has been designed and developed to perform the task to ensure proper tubesheet bore conditions prior to making the new calandria tube rolled joint. A key part of the tool is the video inspection module. During operation, the module scans the area to ensure proper tool location and to assess surface condition. The tool may then be used to perform either rotary brushing or milling to improve the groove profile. Following dressing, the system re-inspects the bore to verify the operation. The tool may also perform a video inspection of the inboard section of the lattice tube and verify the condition of the inboard bearing.

In order to enhance the operator's ability to evaluate the machined surface, structured lighting has been used, consisting of an axially projected laser light stripe. This was included in the design to better define the surface profile during scanning. Surface inspection images are shown to demonstrate the performance of the unit. By analysing a series of captured images from the surface scan, both a surface profile and diametral measurements of the tubesheet bore can be calculated, extending the technique from a qualitative to a quantitative method.

1. INTRODUCTION

Bruce A Unit #1 and #2 Retube project is performing a tubesheet bore dressing operation to ensure the replacement calandria rolled joints meet operational requirements. The dressing operation combines a detailed video inspection with either a rotary brushing of the tubesheet surface or a milling operation to recondition the tubesheet bore grooves. Qualification testing of the replacement calandria tube rolled joints has shown that for certain cases it is beneficial to perform a small amount of machining to provide new sharp corners. In other cases, only a brushing is required to ensure that the surface is clean of any small loose debris. This work is scheduled to commence the fall of 2008 beginning with Bruce Unit 2.

A specialized tool was designed by AECL's Mechanical Equipment Development group at Chalk River Laboratories to perform this lattice tube mechanical operation. In brief, the tool includes an orbiting head to which can be mounted either a profiled milling cutter or a rotary brush that extends onto the target surface. The tool rotates 360 degrees in order to dress the whole of the rolled joint surface. The dressing tool is a modular unit that is delivered and controlled by a general delivery tool system used for other fuel channel and calandria removal operations.

As part of the original design requirements, a visual inspection capability was specified in order to ensure proper tool location, to verify surface condition, and to inspect the rolled joint area before and after the dressing. The inspection capability is an integral part of the overall process to ensure the whole operation is performed properly. In order to maximize the efficiency of the surface dressing process, it was specified that the inspection capability was to be part of the mechanical dressing tool. Six tools were to be fabricated: two units for each face of the reactor, one unit as back up and one for training.

2. INSPECTION MODULE REQUIREMENTS

As mentioned in the previous section, it was decided that the visual inspection capability would be part of the dressing tool and be in the form of an inspection module that affixes to the main body of the tool. Within the given constraints (see below) this permitted the development of the inspection system in parallel with the main tool.

The inspection module had the following general requirements specifications:

- have an imaging field of view encompassing the full axial width of the tubesheet, approximately 40 mm,
- operate in an ionising radiation field of approximately 30 krad/h with an accumulated dose up to of 3 Mrad,
- be mechanically robust,
- have an integral lighting system, and
- fit within a semi-circular shell space having the approximate dimensions of 134 mm (5.2") outer diameter, 35 mm (1.4") thickness, and 500 mm (20") in length.

The limited space for the inspection system was due to it having to fit around the central drive shafts. The shafts deliver power and control the machining head that is located at the inboard end of tool. The inspection module is located outboard of the machining head.

The initial field of view specification was 30 mm, sufficient to cover the middle and inboard grooves targeted for the dressing operation. Later, after operational review and fabrication of the module components had commenced, the field of view specification was expanded to 40 mm in order to cover the whole tubesheet area. Additionally, it was desired that the inspection module should inspect the inboard lattice bearing to assess its condition and the bottom of the lattice tube to look for debris. Fortunately, there was just sufficient adjustment latitude to meet this requirement except in the case of the structured lighting component (see below).

3. MODULE DESIGN

One of major constraints on the design of the inspection module was the allocated space within the overall tool. As well, the tool development and fabrication time constraints did not allow for the fabrication of a prototype inspection module. Therefore, to make the system adaptable to inevitable adjustments, the camera, the lighting module, and the structured lighting module were all designed into cylindrical modules that could be individually axially and rotationally adjusted, and then clamped into place.

4. IMAGING DESIGN AND COMPONENTS

The other major design constraint was the ability of the camera to operate in the anticipated radiation field and accumulated dose. Standard CCD (Charge-Coupled Device) cameras can operate up to an accumulated dose of the order of 10 to 20 krad. With an anticipated radiation exposure of 30 krad for 15 minutes at each lattice tube location, a CCD camera would have to be changed out approximately every 2 to 4 dressing operations. Therefore, a radiation resistant camera and lens system was needed for the inspection module in order to minimize component replacements and maximize efficiency.

The chosen camera is a solid state CID (Charge Injection Device) OEM (original equipment manufacture) monochrome (black and white) camera that can operate in fields of 100 krad/h and tolerate at a minimum 3 Mrad of accumulated dose. An array of miniature silicone detectors makes up a CID's detector, similar to CCD detectors. CCD imagers transfer charges from one row of pixel charges to another to form the image data packet [1]. With the accumulated damage to the electronics, the charge transfer mechanism becomes less efficient and charges accumulate in each pixel with each pixel transfer. In contrast, CID imagers have integrated circuitry that reads each individual image-forming pixel to form the image packet [2]. Although prone to the same damage process as the CCDs, they do not accumulate charges in each pixel as the image is read. This electronic configuration makes image CIDs significantly more resistant to noise and degradation from radiation as compared to CCD detectors [3].

Vacuum-tube type imagers were considered since they can operate with up to 100 to 200 Mrad accumulated dose, but they produce a significantly inferior image and are about five times more expensive per camera system as compared to CID (or CCD) systems. As well, the available tube-type cameras are approximately 100 mm longer than the specified CID camera and size was a significant issue in the design of the inspection module.

A 25-mm-focal-length, F2.8 radiation resistant multi-element fused quartz lens (supplied by the camera manufacturer) is used with the camera. In order to produce a 40 mm field of view, a 17-mm extension tube is added to the rear of the lens to produce 0.32X optical magnification. With this configuration, the lens-to-object working distance is approximately 100 mm. To reduce chromatic aberrations of the lens and improve image quality, a long pass (red) filter with a 600 nm cut-off wavelength is mounted within the extension tube.

The camera is housed in a custom-mounting cylinder that is threaded into the back of the camera head. The lens/extension tube assembly is threaded to the front of the camera head while at the back-end, a two-part clamp is affixed to the camera's cable pig-tail. The cable exits the clamp at an offset-angled position to ease mounting of the inspection module and routing of the camera cable in the dressing tool. From clamp to lens hood, the camera is 320 mm (12.6") long. An assembled camera unit can be seen in Figure 1.

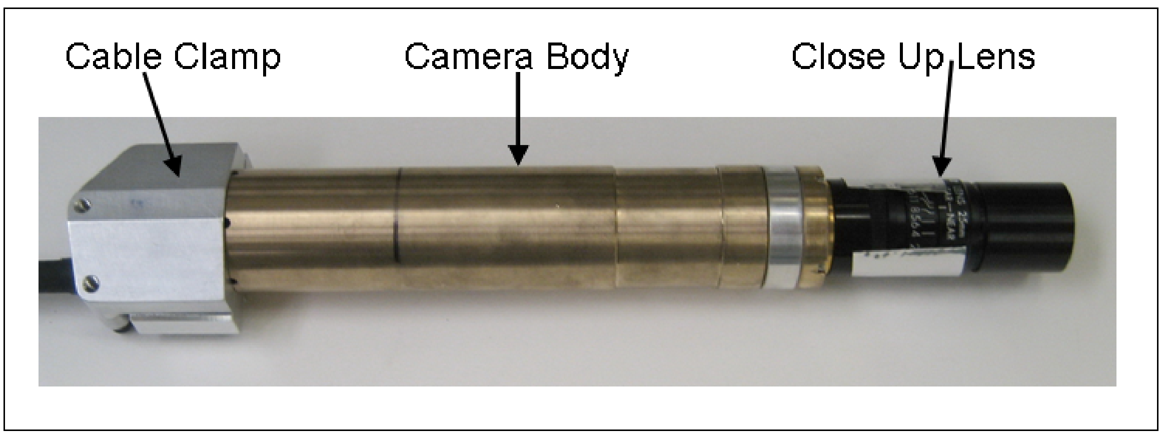

Figure 1 Camera body with offset-angled cable clamp and close-up lens.

In order for the camera to view the inspection surface, a 90-degree turning mirror is set approximately 50 mm in front of the lens. For robustness, the mirror is fabricated from a solid piece of stainless steel with a square mirror surface polished optically flat and over-coated with a hardened aluminium reflective surface. The back of the mirror is keyed with a threaded hole to affix to the mirror mount. The mirror mount is cylindrical in shape with a machined flat in order that it can move axially, but it is rotationally fixed. This configuration ensures that the mirror is square to the inspection surface; the image of the surface is aligned with the video system by rotating the camera.

5. LIGHTING DESIGN

Because a machined stainless surface is reflective, it is a challenge to illuminate for visual inspection systems. Diffused lighting is the standard method of lighting such a surface because it eliminates any direct light reflection into the camera system that would cause image “hot spots”. Because of space constraints, the use of diffuse light in the inspection module was not possible. As an alternative, the lighting system is configured to illuminate the surface at a low grazing angle to eliminate direct reflections into the camera’s optical system. This lighting configuration highlights edges and features but leaves the surface generally dark. The rolled joint surface is axially illuminated from both the front and rear to ensure full coverage and to reduce any shadowing within the tubesheet bore grooves.

High intensity, low-voltage quartz halogen reflector lamps are used as a lighting source. The 25 mm diameter lamps are housed in 32-mm (1.25”) diameter by 119-mm (4.7”) long cylinders. The light from lamps is reflected onto the inspection surface by an angled polished stainless steel mirror held in line with the lamp in the housing cylinder. The reflector has a wedge angle of 22.5 degrees so that the light is incident at a nominal 45 degrees from normal.

The two lamp modules are placed in-line facing each other, centered on the camera turning mirror, and 36 mm (1.4”) off-set from the imaging axis. To prevent any stray light from entering the camera system from the rear facing light module, a light baffle is placed between the two light modules.

6. STRUCTURED LIGHTING DESIGN

To improve the visibility of the surface elevation profile of the rolled joint area, a structured light stripe lighting system was included in the inspection module. The structured lighting was added because the lattice tube rolled joint surface profile is relatively featureless and the combination of near-grazing illumination and normal (to the surface) point of view produces a “flat” image. That is, the surface elevation changes cannot be evaluated from the information in the image; therefore, it would be difficult for an inspector to discern the difference between a properly machined surface and one with insufficient material removed. The structured lighting outlines the surface elevation profile, making it easier to evaluate the surface condition [4].

The basic principle of light stripe structured lighting is to profile surfaces as can be seen in Figure 2. Because the surface is viewed at an angle and the light stripe is projected normal to the surface, the vertical stripe is displaced in the image proportionally to the elevation of the surface. In the example of Figure 2, the higher the surface is, the higher the stripe is, as can be seen in the captured image.

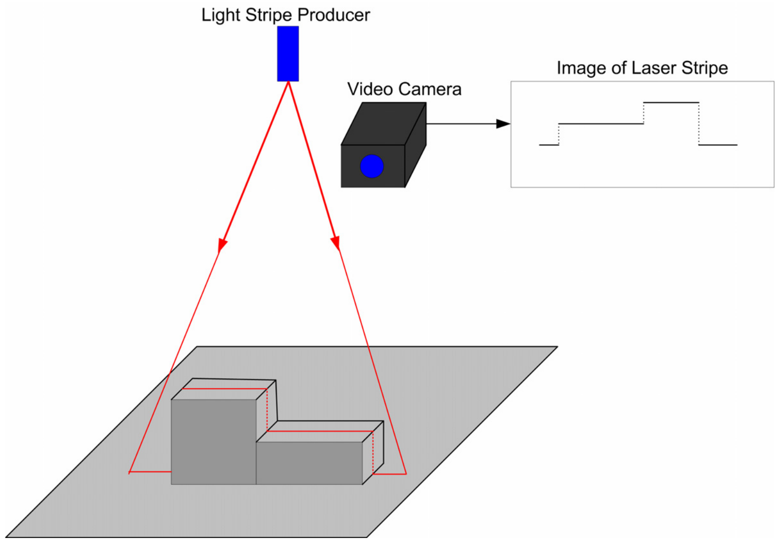

Figure 2 Typical light stripe configuration.

In the case of the inspection module, the camera and the light stripe generator are exchanged as compared to the example in Figure 2. That is, the camera is effectively pointing normal to the surface and light stripe is projected at approximately 60 degrees from the surface normal. The light stripe is produced by a 100-mW, 660-nm diode laser light stripe generator held in a cylindrical housing. The housing also holds a 90-degree turning mirror. The light stripe module is located in line with the camera system, on the opposite side from the lighting, and projects a 33-mm (1.3") long light stripe onto the inspection surface. A light stripe module mounted in a alignment jig can be seen in Figure 3.

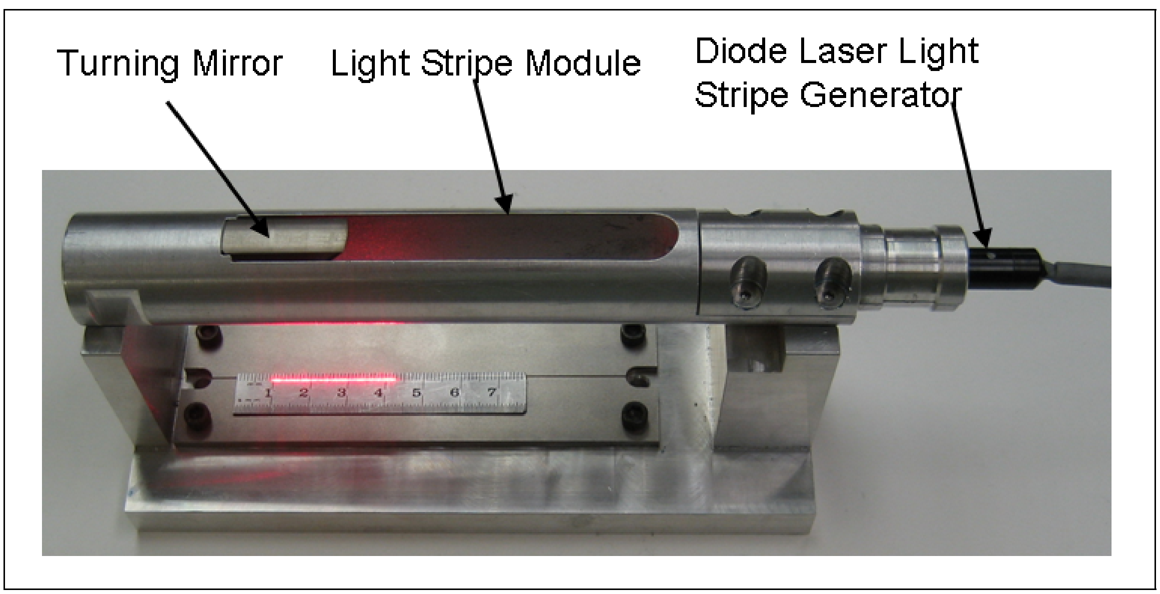

Figure 3 Light stripe module mounted on its alignment jig.

The laser power of the generator is 3 to 5 times stronger than what would be normally needed on a diffuse surface. However, as mentioned above with machined stainless surfaces reflecting most of the incident light, little is scattered into the imaging system. During mock-up testing, it was found that significant laser power was going to be needed to ensure visibility of the light stripe. To ensure that the light stripe and lighting system could be properly balanced, the light stripe generator was specified with an external voltage control that varies the light stripe intensity.

7. MODULE ASSEMBLY AND ALIGNMENT

The body of the inspection module is made of Ampco 18 aluminium–bronze and is a complex shell-like structure with set of axial apertures: one for the camera-mirror system, one for the lights, and one for the light stripe generator. Figure 4 illustrates the assembled inspection module with all the major sub-assemblies identified.

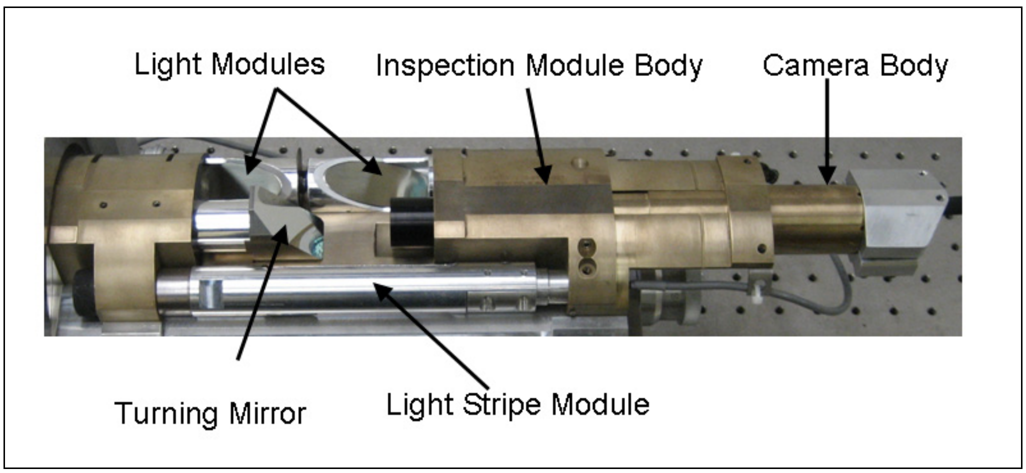

Figure 4 Assembled inspection module.

In order to align the components, a specialized alignment jig was fabricated which included a mock-up of the tubesheet bore. The jig is designed in such a manner that the module is at the same offset distance to the tubesheet bore as when mounted in the dressing tool. The tubesheet bore mock-up can be rotated to emulate the rotation of the tool. Figure 5 shows the inspection module in the jig with the turning mirror located at the tubesheet bore mock-up.

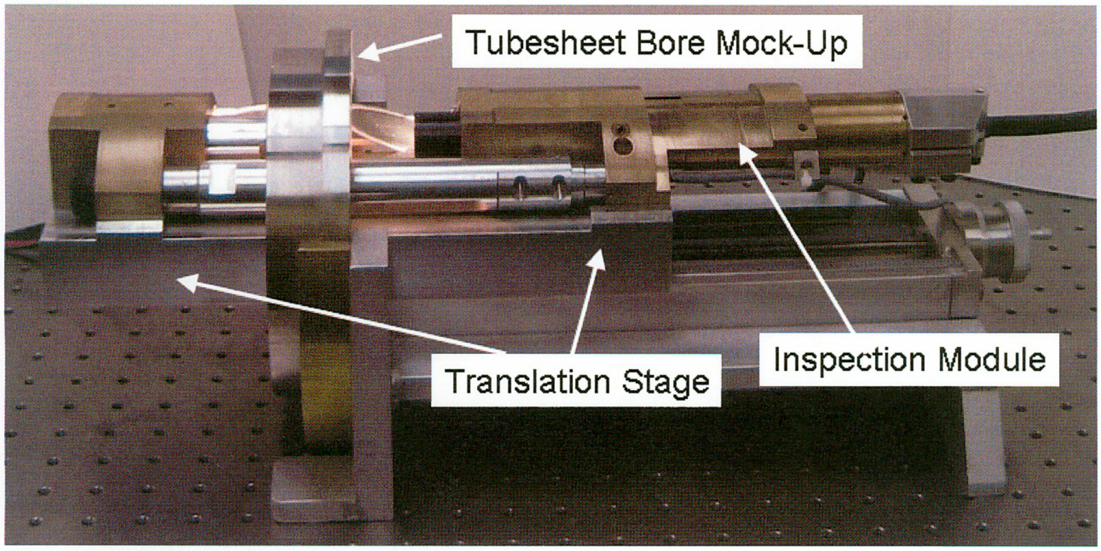

Figure 5 Inspection module in alignment jig set up under the tubesheet bore mock-up.

During the alignment process, the module is affixed to a linear translation stage, allowing it to move under the tubesheet area, but when withdrawn, access to various sub-assemblies is provided. A video monitor (not shown) is extensively used during the alignment. Typically, the camera is first focussed on the tubesheet surface, followed by the positioning and alignment of the light and baffle (the most difficult of the processes), and the final alignment is done with the light stripe module. Once a satisfactory image is produced of the rolled joint, all threaded fasteners (including the focussing lens barrel) are secured with a thread adhesive compound. A final confirmation of the image quality is done before the unit is released for integration into the tool.

8. INSPECTION PERFORMANCE

A typical image of the tubesheet bore area taken from the inspection module can be seen in Figure 6. The camera is set so that the top of mirror, closest to the surface, is to the right of the image. In this manner the full width of the tube sheet, approximately 40 mm (1.6”), is framed in the horizontal field of view; the vertical field of view captures approximately 30 mm (1.2”) of circumference of the area. The lattice tube axis runs from left to right of the image with the two outboard narrow, sharp-edge grooves on the left side of the image, while the inboard wider groove with the more tapered edges is on the right-hand side. With the standard video horizontal to vertical image ratio of 4:3, this configuration produces the maximum image resolution across the grooved area.

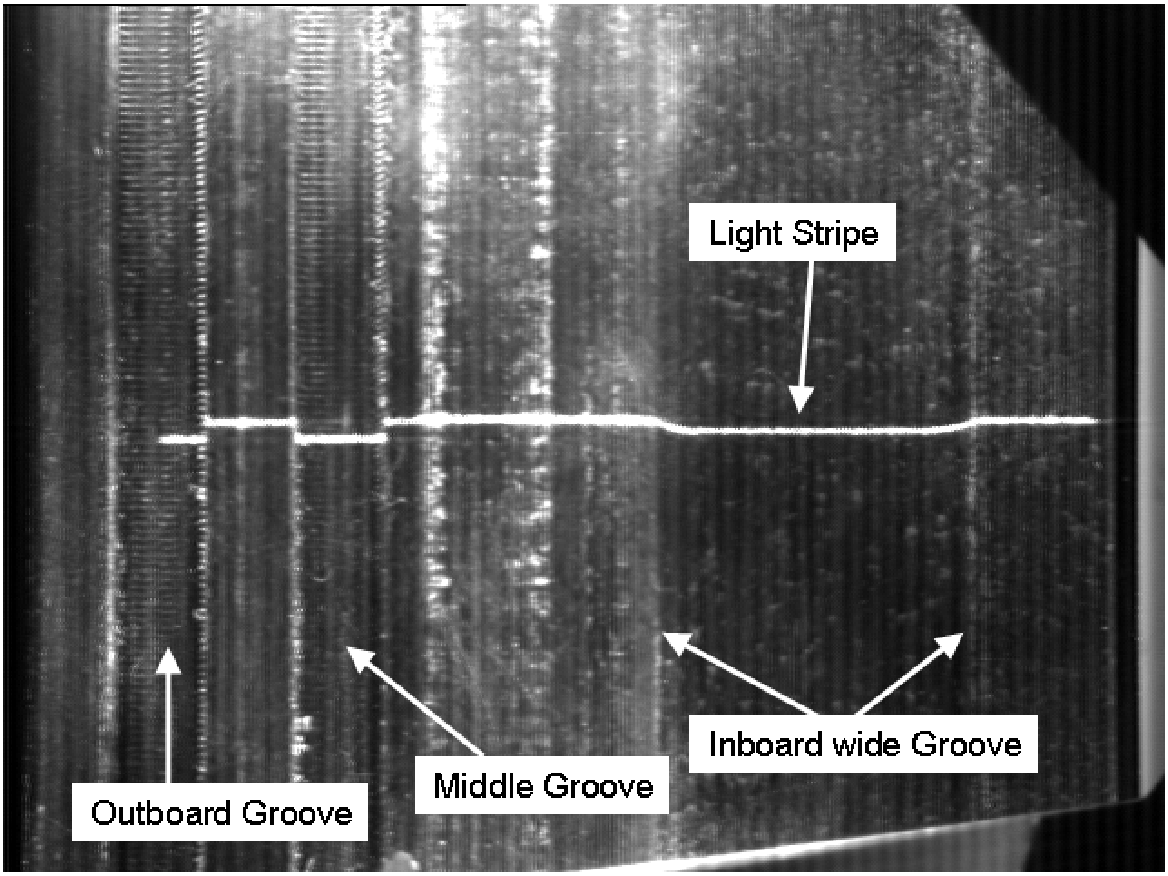

Figure 6 Captured image of lattice rolled joint area with inspection module.

In the upper right-hand corner of the image of Figure 6, a small corner of the surface image is lost. This is due to the mirror's cut corner that was required in order not to block part of the light stripe; the stripe is projected onto the surface from the top of the image. The image loss at the lower right hand corner is due to the mirror being slightly too narrow at top. However, the mirror could not be made any wider because of spatial constraints.

The general area lighting is from both the left and right side of the image at a relatively low grazing angle. As described above, the lighting is configured to eliminate specular reflections, but as a consequence, edges and corners are highlighted and flat even surfaces appear dark. As can be seen in the image of Figure 6, the edges of the grooves are highlighted as well as the machined surface markings. This grazing type of lighting enhances the appearance of surface features, which is appropriate for inspection but produces an overall relatively dark image.

The projected light stripe surface profile can be seen in the middle of the Figure 6 image. As mentioned above, the light stripe is projected from the top of the image on to the surface so that the stripe is vertically lower in the image for deeper surfaces and vice versa for elevated surfaces. This projection configuration is considered "natural" for an observer in that it equates a "deeper" surface with "lower" stripe location. The vertical stripe displacement to surface height ratio is approximately 1.2:1.

The light stripe is projected across approximately 33 mm (1.3”) of the inspection surface, centered over the inboard most narrow groove and wide groove that are to be dressed. The 33-mm coverage meets the original horizontal field of view specification but, as mentioned above, the field of view specification was expanded to 40 mm (1.6”) so that the full width of the tube sheet could be imaged. For the camera system, the image magnification was reduced by increasing the camera-to surface distance. Unfortunately, there was insufficient latitude in light stripe opto-mechanical design to extend the length of the stripe to 40 mm. In particular, the custom-built turning mirror was not long enough to project the stripe over the whole surface. The delivery deadline left insufficient time to re-design and fabricate new components so the stripe could be positioned over the target grooves of the dressing process.

During the inspection, an operator will observe the streaming video images as the tool rotates around the inspection surface. The video stream will be recorded for further review as required. Although not shown in Figure 6, date, time and lattice position will be overlaid in the corners of the recorded video feed image.

Although the imaging system does not have a remote focussing system, the camera system has a depth of focus field of approximately 15 mm, which is sufficient to inspect the inboard lattice site bearing and to identify possible debris of 0.5 mm size or larger at the bottom of the lattice tube. To create the large depth of field, the lens aperture is closed down to f11. In order to sufficiently illuminate the surface at such a large f-stop, the light and light stripe are operated at approximately 75% of full power. This configuration provides sufficient depth of field to the optical system while providing some margin to the illumination system.

9. INSPECTION PERFORMANCE EXTENSION

Although the inspection module is primarily used as qualitative inspection instrument, with the inclusion of structured lighting its use can be extended to a quantitative instrument. By recording the images and their location as the tool is rotated, then computer analysing the relative location of the light stripe, an elevation profile of the inspected surface can be generated. The surface profile of the tubesheet in the mock up is shown in Figure 7. As discussed above, due to the length of the light stripe, only the middle and inboard groove are profiled.

The surface profile in Figure 7 was generated from the analysis of 12 captured images of the mock-up surface as it was rotated in 30-degree steps around the inspection module. Using an automated image capturing system, this spacing could be reduced to the order 1 degree or less. Although this is not be discussed in detail here, both the image capture system and automated analysis have already been developed.

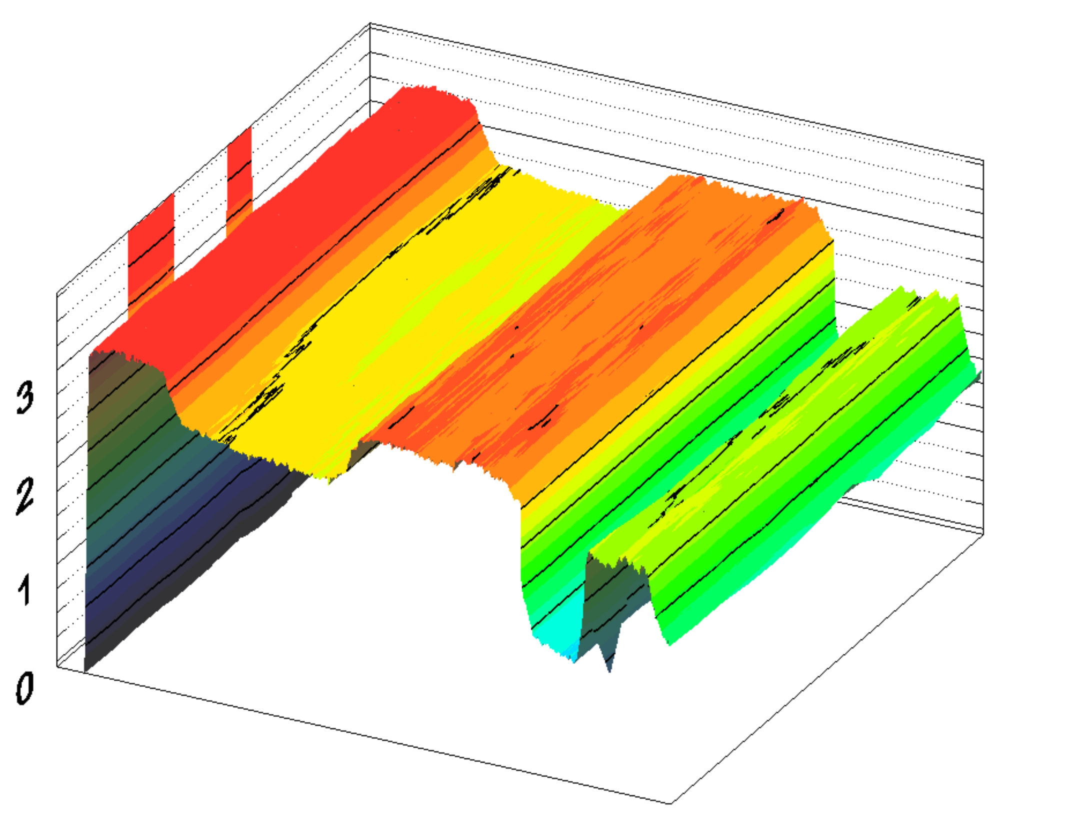

Figure 7 Surface profile of mock-up rolled joint surface.

Further analysis of the surface profile can produce a diametral measurement of the inspected area. By adding a constant radial offset distance to the surface profile and analysing the resulting radial information, the diameter at each axial position of the surface can be calculated.

Both light stripe analysis and the diameter calculation computer analysis modules have been developed and tested. Both can provide sub-millimetre measurement results. However, they still require testing against a calibrated system to fully evaluate the actual accuracy and resolution of the measurement methods. This evaluation and further developments of the inspection method are presently ongoing.

10. CONCLUSION

A specially-designed visual inspection module was designed and built as an integral part of the Bruce Retube Tubesheet Bore Dressing Tool. The combination of high magnification, radiation resistant camera system with grazing illumination, and structured light stripe lighting produces a high quality image with sufficient information for an inspector to evaluate the tubesheet bore condition. The module is compact to fit within the limited allocated space of the dressing and is robust to withstand the dressing operation.

As well, it has been shown that analysis of the recorded images could produce both a quantitative surface profile and diametrical measurements of the inspected area.

11. REFERENCES

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