Measurement of Air Gap of 30 to 50 Micron Width by Conventional X-Ray Machine

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Abstract

Detection of very fine defects in the width range of a few microns is very difficult by using conventional radiographic equipment, due to three limiting factors- contrast, definition and image graininess. Variables, such as X-ray energy, scattered radiation, type of film, processing parameters, film density, focal spot size, source to object distance etc, if controlled properly, can lead to radiographic image with improved quality and better flaw detection sensitivity. Image quality can be enhanced further by using microfocus X-ray tube having focal spot size from 1 to 50 micron. Microfocus X-ray machine when employed with projection radiography and real time radiography can result in ease of viewing a magnified image instantaneously. It becomes a very powerful tool for detecting microvoids and fine cracks in different materials and components having simple as well as complex geometry. However, due to high capital cost and requirement of dynamic vacuum for X-ray tube, microfocus equipments are used only in R&D sector and are rather less popular among common users. Considering the basic principles of image quality enhancement, potential of conventional X-ray machine was explored to detect the air gap of 30 to 50 micron width in a component called as "Diaphragm Type Self-Shorting Sensors". Sensor is a tiny component having brass tube of 2mm diameter and length between 12mm to 30mm. Air gap between end cap and centrally fixed copper wire is very critical, as it controls the time lag of the measurement. Dimensional gauging of the air gap detected on the radiograph was carried out using profile projector under 20x magnification. During validation of the measuring-technique it was observed that the total un-sharpness of the radiographic image had negligible effect on the accuracy of the measurement. Till now more than 200 sensors have been radiographed and results are quite encouraging. This paper presents the complete details of the technique developed at Centre for Design and Manufacture (CDM) for dimensional gauging of the air gap in Self-Shorting Sensors, using conventional X-ray machine.

Key words: *Radiography, air gap, micron size, sensor, shock wave*

1. Introduction

Radiography is a volumetric non-destructive testing method, which reveals internal details of any part, material and structural component. Besides detection of discontinuity, its potential is exploited for various applications useful for industrial products. Though seldom in use but one of the important applications of radiography method is in the field of thickness gauging, especially when other methods fail either due to non-accessibility or technique Tangential technique is one of the most popular techniques used for determining the wall thickness of a pipe. In this technique, the large attenuation offered by metal path, as compared to the surrounding air, gives a sharp and clear image and therefore width of the image directly measured on the film gives the wall thickness of the pipe with accuracy comparable with any other technique. However, gauging of narrow air gap within a metal path, simulating a crack, poses many challenges because its detection as well as direct measurement is difficult. Further, it may be even more problematic if the component, in which air gap is to be detected, is itself small in the range of 1 to 2 mm and conventional X ray machine having focal spot of the same order is to be used as a source of radiation.

Since unsharpness associated with microfocal X-ray source is very small, direct image magnification i.e. recording of magnified image on the film, provides a viable solution for such problems. Nevertheless, conventional X-ray machine can also offer a competitive solution provided high sensitivity radiography technique is used and recorded image is magnified (indirect magnification) for the purpose of measurement. Using similar course of action it was possible to detect

limitation.
and measure an air gap up to 25 µm width in a tiny component- `Diaphragm Type Self Shorting Shock Arrival Sensor' with an accuracy of ±5µm.

In the shock wave experiments, the velocity of the shock wave is calculated by the time intervals, which are obtained from electrical signals generated from self-shorting shock arrival sensors, mounted at the predetermined positions. Sensor consists of machined end cap of Brass, a Copper or SS guide tube and a central conductor of Copper wire with surface insulation (Figure 1). End cap with one end closed, is machined out of Brass rod to obtain dimensions of 2 mm outer diameter, 1.7 mm inner diameter and 5 mm length. Closed end with wall thickness of 0.15 (±0.005) mm acts like a diaphragm, which deforms due to shock wave. Guide tube containing centrally fixed Copper wire is inserted in the end cap and positioned in such a way that the distance between the diaphragm inner face and the central wire is maintained at 0.050/0.055 mm. To prevent the variations in the measured time lag it is important to control the gap between the deforming element and fixed element within the specified value. Acceptance and rejection of the sensor is based on the precise measurement of the

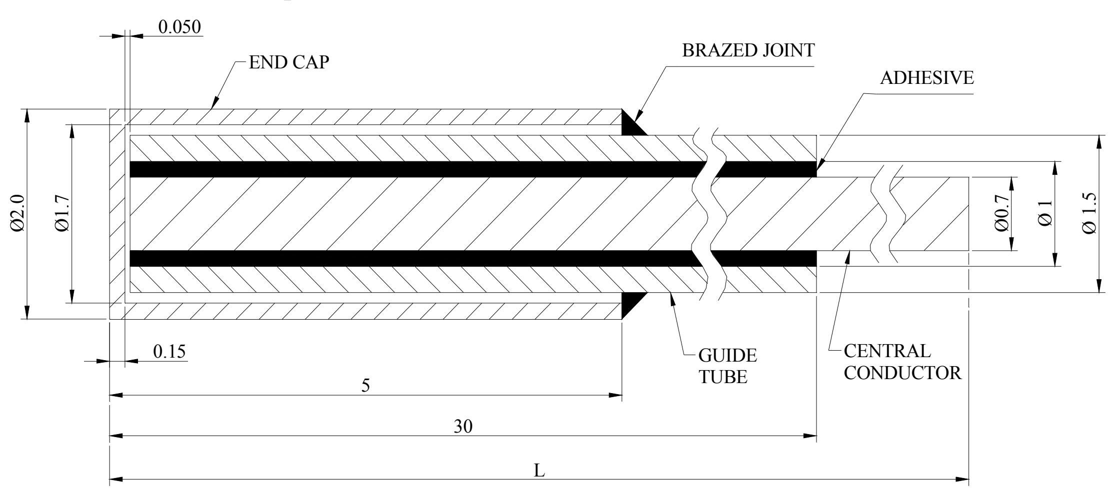

Figure 1: Sensor (Old Design)

air gap between the diaphragm and the central wire. [1]

Manufacturing of sensor, consists of following three basic processes a) Machining b) Gluing and c) Brazing. Brass end cap, Brass tube and Copper wire are cut and machined as per the required dimensions. Copper wire is inserted in the guide tube and fixed inside with the help of fevicol adhesive. End face of this sub assembly is machined on the lathe before inserting it in the end cap. Short circuit test is carried out between the end cap and the central conductor to confirm that they are touching each other and then guide tube along with the central wire is moved out by a distance of 0.050 mm. Finally end cap and guide tube are brazed together without disturbing their relative position. Once again short circuit test is carried out and then acceptable sensors are sent for radiography. Radiographic image of each sensor is viewed on a profile projector and the air gap between the end cap and copper wire is measured under the magnification of 20x or 50x depending upon the sharpness and clarity of the image. Based on this measurement, sensors not meeting the specifications for air gap are rejected and acceptable sensors are used in shock wave experiments.

2. Theoretical Considerations

Air gap can be considered as a crack having shape of circular disc with 1.7 mm diameter and 50 µm width (x). As far as detectability of the gap is concerned it mainly depends upon the contrast, where as definition is affected by the geometrical unsharpness U_g and grain size of the film. Out of all these, geometrical unsharpness is the most important factor because it affects contrast as well as definition in case of a small defect. The effect of U_g on the image of a crack is to (a) increase the width of the image on the film, compared with the real width of the defect and (b) reduce the contrast, when the width of the defect is smaller than the source of radiation ($x<f$). Reduction in contrast is governed by the equation:

$$C = C_0 \frac{x}{U_g}$$

(Valid for $U_g > x$). -----(1)

Where, C_o = Original image contrast

C = Reduced contrast

x = Width of the crack

U_g = Unsharpness.

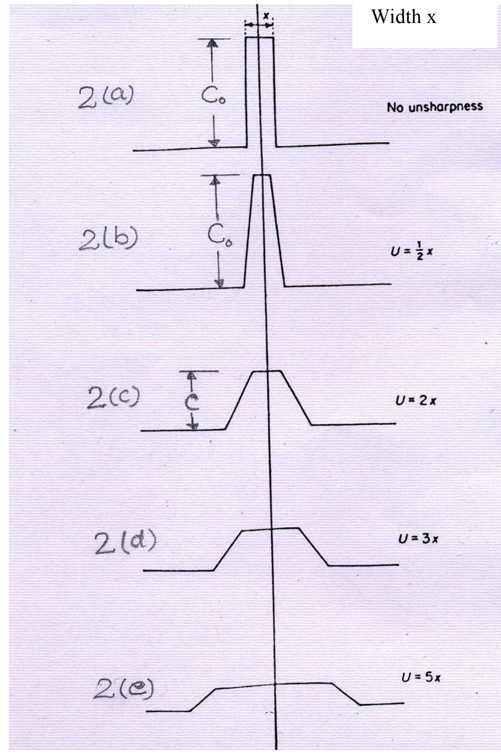

Figure 2: Density distribution in the image of crack width ***x***, with different unsharpness

Contrast is nothing but the density difference (ΔD) on a film and the minimum discernible density difference ΔD_{min} which a human eye can detect is 0.006 at a brightness of about 10 mL (mL– millilambert, 1 mL is the luminance of uniform diffusion emitting 1 millilumen/cm^2). Therefore, $C > D_{min}$ (0.006) is the condition which must be satisfied if any crack or air gap is to be detected. [2]

Density distribution across the width of the image of a crack, with different values of unsharpness is shown in Figure 2. For an idealized crack where there is no unsharpness, the distribution is assumed to be as shown in Figure 2(a). The effect of a total unsharpness less than the gap width x is, to broaden the image, but not to alter the contrast as shown in the Figure 2(b).

As soon as the total unsharpness is made greater than 'x' a reduction of contrast commences until a broad low-contrast image results, as shown in Figure 2 (c), (d) and (e). [2]

In a limiting condition when $x = U_g$, $C = Co$ and there is no reduction in the contrast, however when $U_g > x$ the actual contrast C reduces and if $C < D_{min}$ (0.006) crack will not be visible. It is matter of experience that a coarse grained image conveys less detail than one of finer grain, thus influence of graininess must be considered while recording any fine detail on a radiograph. The statistical fluctuation of density which the eye sees as it scans the film is known as graininess and is given by $(N \pm N^{1/2}).a$

where, N = Number of grains in a scanning area 'A', and

a = Area of each grain

Fluctuation of density can be reduced by increasing the scanning area 'A' or by increasing the viewing distance. Further lowering the voltage (kV) of X-Ray tube reduces the graininess effect.

2.1 Performance of the Eye

Besides the capability of a radiographic technique, to reveal a small defect, the ability of the eye to perceive the finer detail is also important due to the following limitations:

a) The ability of the eye to appreciate small, sharp details.
b) The influence of blurred outlines on the ability to discern detail of given contrast.
c) The ability of the eye to recognize detail in the presence of an irregular background, such as film grains.

Combined effect of all the three factors can be evaluated by judging the performance of the eye for its ability to detect a fine detail and the ability to separate i.e. resolve, details of the image (for example, to recognize two parallel lines, as such, and not as an unresolved images). Further, performance of the eye is influenced by: image contrast, image size, image shape, intensity of the viewing illuminator and viewing distance. From experimental point of view following conclusions regarding the performance of the eye remain valid for all practical purposes:

a) The value of minimum discernible contrast (ΔD_{min}) for a long narrow line is 0.006, however for a very small spot a slightly higher value such as 0.008, would be more suitable.
b) The ability of the eye to discern a small difference in density i.e. ΔD_{min} does not seem to be affected by blurring of the outline of the image if the width of the unsharpness is less than 0.5 mm (assuming a viewing distance of 250mm).
c) The smallest image size, which the human eye can detect, is 0.015 mm diameter at 250 mm distance and this is therefore, the limiting size below which all single objects such as bright spots appear to be of constant size.
d) At high contrasts the eye can resolve two images 0.05 mm apart seen at the normal viewing distance of 250 mm.
e) By standing further from the film a greater area of film is subtended by the effective scanning area of the eye and the impression of graininess is reduced. [2]

3. Experimental Details

Since direct measurement of air gap in case of sensor was not possible an indirect technique was developed for the measurement. Broadly, technique can be divided into two parts (a) recording the image of the air gap with proper contrast and definition and (b) accurate measurement of the air gap by magnifying the image on a profile projector.

Adequacy of the technique depends on the following:

a) Ability to detect the air gap,
b) Ability to record the image without blurring of boundaries,
c) Enlargement or reduction of the image size during radiography,
d) Density of the image suitable for viewing it with the light source available on the profile projector,
e) Overall measuring accuracy shall be within ± 5μm.

Since geometrical unsharpness (U_g) is one of the most important factors as it affects definition, contrast and size of the image, it was necessary to establish the value of U_g first. Using formula

$$U_g = \frac{f \times t}{SOD} \qquad \text{----------(2)}$$

Where,
f = focal spot size = 1.5 mm
t = thickness/diameter of sensor = 1.976 mm
SOD = Source to object distance = 1000 mm

$$U_g = \frac{1.5 \times 1.9}{1000} \approx 0.003 \text{ mm}$$

(a) Effect of U_g on the image contrast: Since the unsharpness U_g (0.003 mm) is less than the gap width, x (0.05 mm), there is no reduction in the contrast even though f > x.

b) Effect of U_g on the gap size: Image width -W = x + U_g ---------(3)

or W = 0.05 + 0.003 = 0.053 mm.

Since increase in the gap size (3 μm) is less than the required accuracy of ±5 μm, U_g = 0.003 is within acceptable limit.

Table 1 Contrast versus Gap Width

S. No.	**Location**	**Gap Width (x)**	**Background Density (D_b)**	**Image Density (D_i)**	**Contrast ($\Delta D = D_i - D_b$)**
1	L1	60 μm	0.4649	0.4934	0.0285
2	L2	62 μm	0.4500	0.5349	0.0849
3	L3	66 μm	0.4440	0.5655	0.1215

To study the effect of U_g on the contrast 'C', when gap width 'x' is less than the focal spot size, a variable gap was created by keeping 2 mm thick two slip gauges close to each other. Density profile was generated by scanning the densities across the gap at three places using microdensitometer with an aperture of size 3 mm x 0.02 mm (Refer Figure 3). Both, width and peak density of the gap were calculated from the density curves and values are given in the Table 1. It clearly indicates that contrast for air gap decreases as its width decreases.

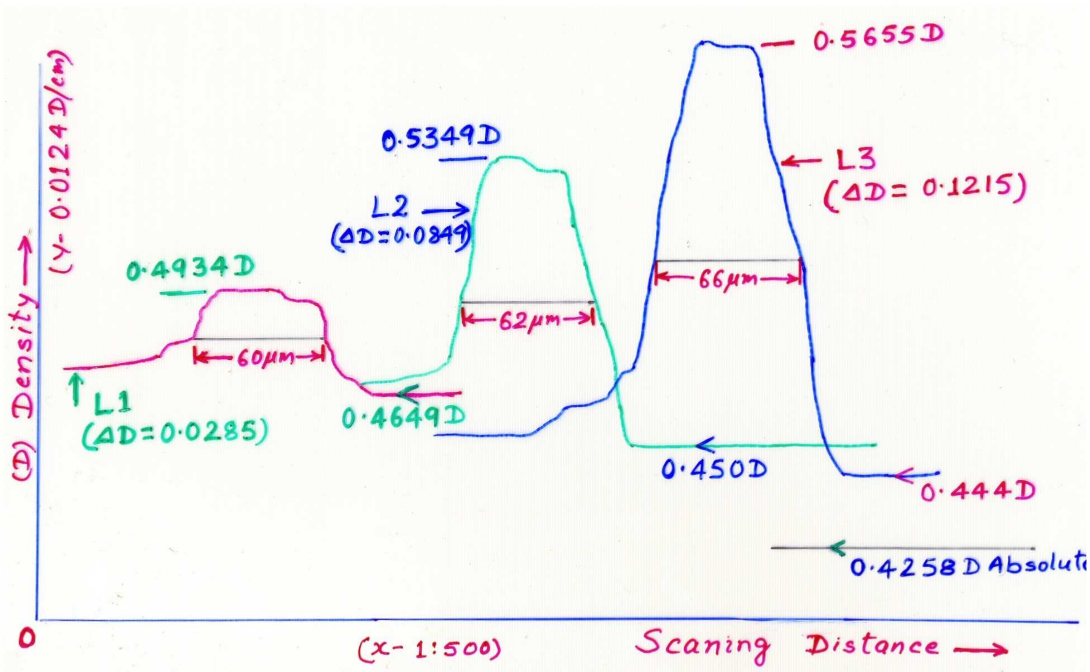

Figure 3: Microdensitometer scan across the image of air gap having variable width

In the same experimental set up gap was maintained by keeping a plastic foil between two slip gauges. Plastic foil, in comparison to air, offers more attenuation to the X-ray, which results in the reduction of the contrast. In fact, contrast was so poor that neither microdensitometer nor profile projector could measure the air gap.

Figure 4: Good contrast radiograph of sensor without any masking

3.1 Selection of Film

Agfa Structurix D2 film was selected as it offers highest contrast and resolution than any other film when used with X-Ray. It consists of very slow and very fine grains giving highest contrast of 6.0 between densities 1.5 and 3.5.

3.2 Voltage of X-ray Tube

Since lower the kV higher the subject contrast and lower the film graininess, 110 kV was found optimum for the radiography of the sensor

3.3 Protection from Scattered Radiation

Being a very small specimen, internal scatter from the object itself was negligible (Refer Figure 4). Backscatter protection was provided by keeping the film on 6 mm thick lead sheet. In addition, 0.1 mm thick front and back lead screens were also useful for scattered radiation protection. In another experiment, masking of sensor, on the three sides was done by using equal size of slip gauges. However, in this case contrast was poor because of internal scatter from the masking slip gauges (Figure 5).

Figure 5: Poor contrast radiograph with masking

4. Technique

First of all to check the adequacy of the technique, using the parameters (Table 2) based on theoretical calculation and practical experience, a radiograph of 50 μm air gap, created between the jaws of a digital vernier caliper was prepared. Gap width was measured by microdensitometer as well as by profile projector. The actual gap was also measured by the profile projector and its value was found to be between 51 μm and 54 μm. Higher thickness of the jaws and unsharpness value of 3 μm are responsible for the higher values of the air gap recorded by both the instruments (Table 3). Once the technique was established, sensors, five at a time were radiographed using the same parameters.

Table 2: Exposure Detail

S. No.	Parameter	Value/Detail
1	Type of Source	X-Ray
2	Focal Spot	1.5 x 1.5 mm
3	Tube Voltage	110 kV
4	Tube Current	4 mA
5	SFD	1000 mm
6	Exposure Time	60 second
7	Film	Agfa D2
8	Lead Screen	0.1 mm front & back
9	Developing Time	5 minute
10	Developing Temp.	20 degree C
11	Developer	Agfa NDI 230
12	Fixing Time	10 minute
13	Fixer	Agfa NDI 305

Table 3: Measurement of gap between jaws of caliper

Actual Gap Width (μm)	Densitometer Reading (μm)	Projector Reading (μm)	Remark
54	60	58	Maximum
51	52	53	Minimum

Though tube is of very small size, still technique can be called as double wall single image technique. To avoid the heel effect, width of the gap was kept perpendicular to the axis of the X-ray machine. Proper care was taken to maintain the alignment of sensors with focal spot, parallelism between X-ray machine head and plane of the film and scattered radiation protection.

Measurement of the air gap was carried out on profile projector having following specifications: Least count- 0.001 mm, Repeatability- 0.005 mm, Accuracy- 0.002 mm up to 5 mm, Magnification- 5, 10, 20, 50, 100, 200 and Working Mode – Discopic and Episcopic. For measurement, film is kept on a transparent horizontal X-Y table and it is illuminated by a light source from the bottom side (discopic mode) of the film. Transmitted light is collected by a system of lenses fixed above the film, which magnifies and projects the image on a vertical screen. A pair of cross wires, 90^0 to each other, is used to measure the gap width at any location by matching the wire with one edge of the gap and then displacing the horizontal table either in X or Y direction as the case may be, to match the other edge of the gap with the same wire. Displacement of the X or Y table (displayed on digital read out) gives the width of the gap and it can be printed directly on a chart paper. Measurement skill to match the edge of an image with the cross wire can influence the accuracy of the measurement and in case of the blurred image error may be as high as 10 μm. In case of sensor, the gap width could not be maintained at constant value due to manufacturing limitations, therefore minimum and maximum air gap width were recorded for each sensor.

5. Validation

Before carrying out the measurement of the air gap readings on profile projector for tube OD and wire diameter were compared with their actual values (Table 4). It is observed that errors in readings are +28μm and -19μm in the range of 2.0 mm and 0.7 mm respectively, which indicates that lower the range lower the error.

Table 4: Micrometer versus Profile Projector

Dimensions ↓	Identification →	L1-A	L1-B	L1-C	L1-D	L1-E	Error (Max)
Wire Diameter (mm)	Micrometer	0.710	0.720	0.720	**0.720**	0.720	-0.019
	PP	0.708	0.705	0.708	**0.701**	0.720	
Brass Tube OD (mm)	Micrometer	**1.953**	1.964	1.948	1.944	1.951	+0.028
	PP	**1.981**	1.960	1.955	1.958	1.954	
Air Gap by PP (mm)	Maximum	0.045	0.051	0.049	0.047	0.047	NA
	Minimum	0.032	0.043	0.043	0.026	0.047	

One of the sensors, after measurement, was cut by wire cutting machine along the plane parallel to the longitudinal axis. Air gap measurement carried out directly on the microscope at higher magnification recorded the width as 34 μm against the value of 39 μm recorded by the profile projector. From this measurement it was clear that reading obtained from the profile projector on a radiograph is very close to the actual value.

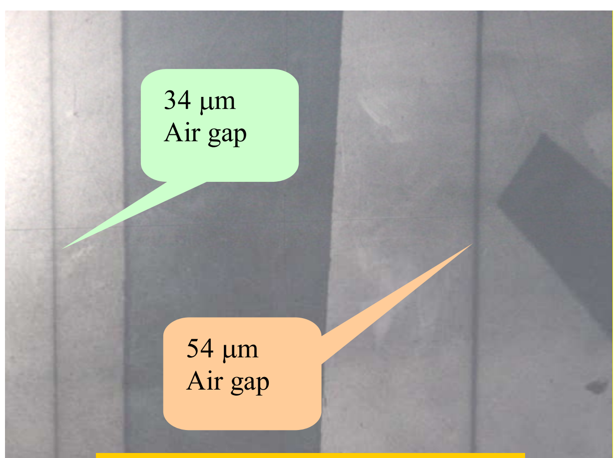

Figure 6: Thick and thin air gap

Various gap sizes were created to study the limitation of the technique and it was found that up to 25 μm there was absolutely no problem in the measurement as far as definition and contrast are concerned. For gap smaller than the 25 μm because of blurring and poor contrast matching the cross wire with the edge was difficult even at higher magnification of 50x. However, as compared to microdensitometer this is a superior technique, because microdensitometer reading was not accurate for air gap less than 50 μm. In Figure 6 air gaps of 34 μm and 54 μm projected at 20x magnification can be easily differentiated by the eye, where as microdensitometer scan could report approximately 60 μm for both the air gaps.

6. Design Modification

Based on the feedback and the confidence level gained in the measurement technique, the design of the sensor was modified because the adjustment of the 50 μm air gap was difficult as well as time consuming. In the new design a step with a 50 μm counter bore was formed on the inner face of the diaphragm (Figure 7). If all dimensions are maintained properly then

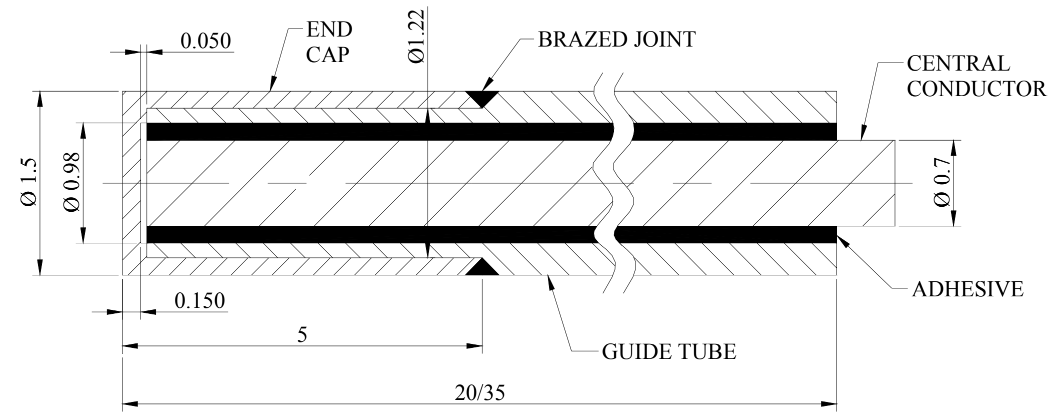

Figure 7 : Sensor (Modified Design)

a minimum gap of 50 μm can be assured when guide tube rests on the machined step. Since the total volume of the air gap as compared to the old design is less, exposure time has been increased to 70 second from 60 second to get the proper contrast in case of the new sensor. Radiograph of the modified version is shown in the Figure 8.

7. Conclusion

`Diaphragm Type Self Shorting Shock Arrival Sensor' is a tiny component used for measuring the velocity of shock wave by short circuiting the air gap of 50 μm between the end cap (diaphragm) and central conductor when the diaphragm ruptures due to arrival of the shock wave. Air gap being critical, it was required to develop a NDT technique for precise measurement of its width. Theoretical analysis and experiments were carried out to record the image of air gap with proper contrast and definition using conventional X-ray machine having 1.5 mm focal spot. Measurement of the

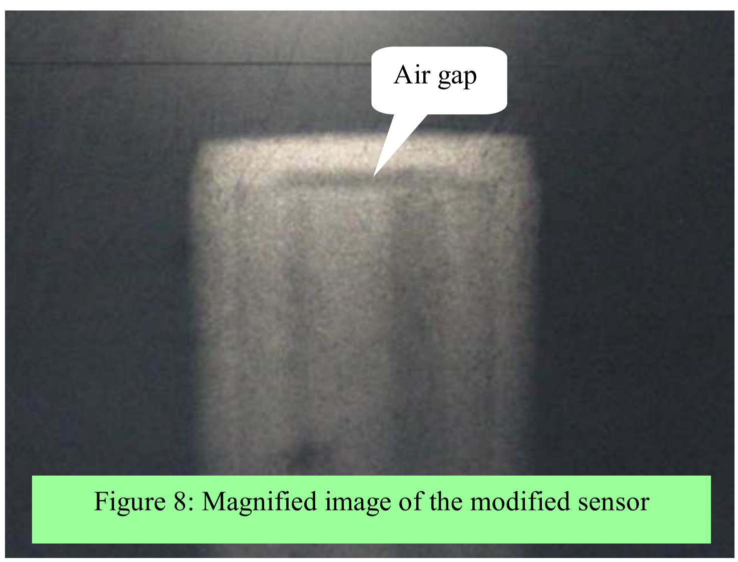

Figure 8: Magnified image of the modified sensor

gap width was carried out by profile projector at a magnification of 20x. Results were compared with those of microdensitometer's scan and technique was validated by measuring the actual gap by using microscope (on a sensor in which gap was exposed by cutting it). Considering the known value of unsharpness (3 μm) the overall accuracy of the technique is found to be within 5 μm. The lower limit of measurement is 25 μm, below which the blurring of edges and poor contrast makes the measurement rather difficult. Small size of the object reduces the contrast but at the same time it is advantageous because internal scatter is negligible during radiography. Therefore, in spite of several limitations the actual contrast obtained is higher than the minimum discernible value of the contrast. Though it is very simple and precise technique but measurement below 25 μm may require the use of micro focal X-ray machine.

8. Acknowledgement

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