Fundamentals of Microfocus Radiography

Introduction

Microfocus radiography or the use of fine focus X-ray tubes is assuming an expanding and important role in industrial radiography. The reason for this is that microfocus X-ray machines with focal spots as small as 1 mm (0.001 mm) can provide an enhanced flaw detection capability with greater reliability than it is attainable with conventional radiographic equipment. The source size contributes to the radiographic quality, influences the geometry of the inspection and sets radiographic image definition and resolution limits. Significantly reducing the size of the focal spot in an X-ray tube results in an enhanced flaw detection sensitivity. Microfocus radiography can meet the inspection requirements of today's quality standards for tighter material and structural integrity.

New concepts such as projection magnification radiographs where the object is moved away from the film and toward the source to enhance flaw detectability run counter to most radiographers basic upbringing. To alleviate these problems and to make both the user and the NDT customers aware of the full potential of microfocus radiography and its techniques, we have prepared this report.

Microfocus X-ray Equipment

Until a few years ago X-ray sources with focal spot sizes less than 50 mm (0.050 mm) were commercially unavailable. However, today there are several microfocus X-ray machines on the market that one can choose from. Microfocus X-ray machines with focal spots as small as 1 mm (0.001 mm) and capable of delivering the required electron current (8 mA) over an energy range of 0-160 kV are commercially available. The focal spots are usually continually adjustable up to 0.5 mm or more. The tube head should be water cooled in order to remove the heat generated at these high power densities. All of these “new” systems are continuously pumped which gives them a certain technical modular flexibility. The tube head can be opened, allowing to replace the X-ray target (anode) by another metal in order to modify the X-ray spectrum to meet special inspection requirements, change the tube head window, and even remove the target module itself and replace it with a rod-anode tube. These rod anode tube heads range in diameters from 18 mm down to as small as 4 mm and come in various lengths up to 1500 mm. With rod anode tubes this small one can often perform inside out single wall radiography on components with a flaw detection sensitivity that was previously unattainable.

Another important consideration in selecting a microfocus X-ray source is the field diameter of the X-ray beam or exit cone angle of the beam. The beam exit cone angle or field coverage is important when one needs to perform microfocus radiography at short source to film distances. For example, a tube head with a 40° exit cone will require considerable fewer exposure to inspect the same area than if one were to use a tube head with a 20° exit cone angle.
One should also consider the minimum distance between the focal spot and the tube head face which determines just how close one can place an object to the X-ray source. This parameter is important because it determines the maximum magnification that is attainable for a microfocus system. Since facility limitations and/or the radiation inverse square law \((I/R^2)\) prevent one from placing the detector at extremely long distances from the source the minimum object to X-ray source distance determines the upper limit of magnification. For example, a minimum source to object distance of 0.5" (12.7 mm) and the X-ray imaging system placed at 6' (1.8 m) limits one to maximum geometrical enlargement of 142.

**Focal Spot Size of Microfocus X-ray Tubes**

The advertised minimum focal spot sizes of microfocus X-ray tubes vary from 1 m to 50 m and questions arise on how to measure them. The commonly used pinhole imaging techniques employed with larger sized sources do not work because the pinhole has to be at least 1/10 the size of the focal spot one wants to measure. The smallest commercially available pinhole camera is 0.030 mm in diameter and can be used to measure focal spots as small as 0.3 mm accurately. Alternate techniques such as converging lead star patterns or parallel resolution test grids often used in the medical profession fail to work with focal spots 0.05 mm or smaller.

A method that has been developed to subjectively measure the focal spots of microfocus X-ray tubes is to radiograph an X-ray lithography mask on film at a high magnification (20-200 X) and determine the smallest line pairs still visible. The mask consists of various sized etched gold parallel line pairs down to 2 m (0.002 mm). Experience has shown that this simple method will measure the focal spot with a 30% accuracy. If a more accurate measurement is desired these patterns can be scanned with a scanning microdensitometer and the data analyzed by means of Fourier Transforms.

In practice, the real proof of fine focus X-ray tubes is in the quality of the image (contrast and definition. A quick way of checking the performance of a focal spot is to radiograph a fine wire mesh (i.e. 500 mesh) at high magnification or a covering star pattern placed on top of an absorber. This will show up any asymmetries in the focal spot. By nature of the tube head design many of the microfocal spots provide a better spatial resolution in one direction than in the other. These "resolution" test patterns are also very helpful in adjusting the focus to minimum size prior to radiography.

**Radiographic Principles**

Since the purpose of most radiographic inspections is to examine an object for flaws, a basic understanding of the underlying fundamental principles that affect the visibility of details in the radiographic image is important. The quality of a radiographic image can be described in terms of three factors. These are contrast, definition (unsharpness) and image graininess. All three of these important factors affect defect 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, and on the type of film used, processing 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. Definition is dependent on the geometric condition of the radiographic set-up, the focal spot size, radiographic energy, the film and its development or radiation imaging system used.

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**

A successful radiograph depends on the control of many factors. These factors can be usefully classified into several general areas geometry, X-ray machine, image detector and specimen, and exposure factors.

**Geometry Factors**

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 detector distance (D2) divided by the source to object distance (D1).

\[ Ug = F \times \frac{D2}{D1} \]  

Since the X-ray source always has a finite size, geometric unsharpness or image blur will always occur. And 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 figure 1 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.
Now, when the radiographic specimen, for a fixed source to detector plane distance, is moved closer to the source its image becomes magnified (Figure 2). The size of the radiographic image varies with its position relative to the source and the detector. This is known as geometrical image magnification \( M \). The magnification due to the geometry of the radiographic set-up (figure 3) is expressed by

\[
M = \frac{O_2}{O_1} = \frac{D_1 + D_2}{D_1} \quad (2)
\]

Where \( O_1 \) is the object diameter and \( O_2 \) is the image diameter and \( D_1, D_2 \) are the same as defined above. The magnification \( M \) is simply the source to image distance divided by the source to object distance.

Combining equations (1) and (2) one can arrive at another simple formula that relates the image blur \( U_g \) to the magnification \( M \) and the focal spot size \( F \). That is

\[
U_g = F (M-1) \quad (3)
\]
This relationship is more clearly illustrated in figure 4 where the image blur is plotted as a function of radiographic magnification for various sized focal spots. Conventional industrial X-ray machines have focal spots 1-4 mm in size, so called minifocus X-ray tube focal spots are 0.2-0.5 mm in size, while industrial microfocus X-ray tube focal range in size from 0.050 mm (50μm) to as small as 0.001 mm (1μm).

Positive advantages of radiographing with very small X-ray sources are less image blur and that one can use higher image magnification than what is attainable with conventional radiographic sources.

The importance of radiographing with microfocus X-ray sources becomes obvious when one considers the effect geometric unsharpness has on the radiographic image of small but often critical defects. The effects are:

To increase the width of the image due to blurring
When the geometrical unsharpness is greater in size than the flaw to be detected there is a loss of image contrast.
When the defect is smaller in size than the focal spot there is also a reduction in image contrast.
All three of these effects can easily result in a flaw not being imaged at all! Consider the case of a defect which, under ideal conditions, would just be imaged with a minimum detectable contrast, any factor producing radiographic unsharpness can also cause the image of such a defect to disappear.

Although the contrast and resolution effects on defect detection have been discussed for geometric unsharpness, it is obvious that they are also produced by any other source of radiographic unsharpness. These are the film unsharpness, fluorescent screen unsharpness, and motion unsharpness. According to Klasens the total radiographic unsharpness can be expressed as the cube root of the sum of the cubed values of unsharpness due to each source of unsharpness:

\[ U_{\text{total}} = \left( (U_{\text{film}})^3 + (U_{\text{screen}})^3 + (U_{\text{motion}})^3 + (U_g)^3 \right)^{1/3} \]  

(4)

Representative values of X-ray film unsharpness are 0.02 mm to 0.65 mm for X-ray at 10 keV and 10 MeV respectively. The fluorescent screen unsharpness depends on both energy and screen construction and can vary from 0.2 to 1.6 mm. The motion unsharpness is the distance the object moved during the exposure interval. And the geometric unsharpness was already discussed above (equation 1). Typically one of the unsharpness sources predominates in any given factors very small unless the other factors can be reduced to comparable values.

**Projection Radiography**

Projection radiography (image magnification) occurs when the specimen is moved away from the image plane (figure 3). 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 fine focus X-ray sources to difficult or critical industrial inspection problems has shown that considerable more details can be image projection magnification radiography.

By significantly reducing the size of the focal spot in an X-ray tube a number of advantages can
be identified. These are:

The sample does not have to be close to the film. By positioning the radiographic object close to the source and away from the film, an enlarged primary image is obtained on the film or X-ray imaging system. This facilitates the detection of fine structural detail. It also increases the size of the original detail that is lost in the background image noise produced by screen mottles or film granularity and grain clumping. The enlargement of fine detail makes it easier to detect and interpret by the radiographer and also reduces inspection fatigue.

The use of geometrical enlargement radiography also results in an increased signal (image carrying radiation) to noise ratio reaching the detector. This results in a very desirable increase in image contrast. By moving the radiographic object away from the film, most of the forward scattered radiation (noise) misses the detector due to the geometry of the setup and is also attenuated in the air (figure 4). The forward scattered radiation reaching the image detector is called “build-up”

Figure 4.

Faster films of film / fluorescent screen combination can be used with this technique. The use of faster film results in shorter exposure times without jeopardizing image quality.

Therefore, geometric magnification improves image contrast, resolution and reduces operator fatigue. All of which translates directly into enhanced defect detection. The ability of Microfocus X-ray machines to magnify image with an improved spatial resolution and a reduction in radiation build-up makes them ideal sources for industrial computerized tomography systems.

Other Benefits of Microfocus Radiography

If primary magnification is not required, the source to film distance can be significantly reduced without a loss of image definition. This means that the exposure time can be reduced and also that radiographs can be obtained in cases where access to the area to be inspected is limited. Small diameter (4 mm) microfocus rod anode tubes may be very helpful in these cases.
A very small focal spot also provides a better "depth of focus" (see figure 5) and hence gives a more uniform definition of object details through the thickness of the radiographic object. In conventional radiography, indications near the source side of the object are more blurred (reduced flaw sensitivity) than indications nearer to the image plane. Because of this, thicker samples can be radiographed with better "throughout" flaw detection sensitivity than it is possible with conventional radiography with the same energy. This greater "depth of focus" also makes it easier to fix thick or irregular shaped objects and moving or rotating objects for radiography because they do not have to be placed right next to the film.

Figure 5.

**Other Radiography Factors**

The primary film factors that affect radiography are speed and grain size. Microfocus radiography permits the use of fast films or film-fluorescent screen combination that are many times faster than conventional X-ray films. These fast films are not normally effective with conventional contact radiography because of poor definition and high quantum mottle. The anticipated increase in "quantum mottle" or noise is reduced proportional to the second power of the magnification (~M^2).

X-ray source factors that affect radiography are focal spot size, the X-ray energy spectrum and the source intensity. The advantages of fine focal spots were discussed above. Microfocus X-ray machines with finely focussed beam currents as high as 8 mA over a wide energy range are commercially available. Unlike conventional X-ray machines, the energy spectrum of feinfocus X-ray machines is easily modified by either changing the tube head window (i.e 0.1 mm Be) and / or the anode material (i.e. Ti, Cu, Mo). This may be advantageous for very low energy radiography, or for special techniques such as K-edge subtraction radiography. Specimen factors such as size, shape, composition and density dictate the radiographic energy and technique to be used. While the exposure time controls the film density and hence the contrast of the radiographic image.

**Microfocus Real-Time Radiography**

Microfocus real-time radiography utilizes a microfocus radiation source, a multi-axis part positioner holding the radiographic object and an X-ray image intensifier coupled to a Microfocul real-time radiography are:
- Instantaneous image
- The ability to see motion
- Improved crack / gap detection
- Better flaw sensitivity when compared to conventional realtime radiography
- 100% inspection is possible
- Save processing and film costs
- The possibility of computerized automatic defect recognition and instantaneous accept / reject decisions

With all these desirable advantages going for it is surprising that not everybody uses real-time radiography. One of the main drawbacks of real time radiography with conventional large focus X-ray machines is the relatively low flaw detections sensitivity that can be obtained. In general with film a 2% thickness sensitivity is normal and 1% sensitivity can be obtained with optimized radiographic techniques over wide material thickness range. In comparison with conventional real-time radiography, a 2% sensitivity is achieved over a limited thickness and energy range. Flaw detection sensitivities of 4% - 10% are more typical.

For example, using a typical modern 9" X-ray image intensifier with a 2.5 line pairs/mm resolution capability and no geometric magnification, a 2% sensitivity can be achieved in aluminium form 1.75" to 6" with radiographic energies ranging from 80 320 kV, a 3% sensitivity at 1" and a 5% sensitivity at 0.5". For steel things look worse. A 2% sensitivity can be achieved approximately over a thickness range of 0.65" to 0.9" of steel a 3% sensitivity from 0.5" to 1.5". Image processing techniques such as recursive filtering (frame averaging) can only improve these numbers very slightly (< 0.5%) although it makes the "real time" image easier to interpret.

With conventional radiography the flaw detection sensitivity gets dramatically worse when the material thickness fall out of the ranges quoted. It should also be noted that these sensitivity numbers and thickness ranges quoted will vary slightly for different intensifiers and different radiographic techniques. With real time, radiography just like in film radiography one should always use good radiographic practice like tight beam collimation, fixturing, beam filters, and even anti-scatter girds.

The poor sensitivity of conventional real time radiography is primarily caused by two reasons. The first is the poor inherent spatial resolution of X-ray imaging system (0.5 to 4 line pairs / mm), while the other reason is caused by the physics of radiography.

It is not possible to electronically image the 0.010" hole in a 2% ASTM penetrameter (IQI) in 0.5" of aluminium when it is radiographed with conventional radiographic techniques (magnification < 1.2). With a standard TV line rate 525 on a 12" monitor the width between the horizontal lines is already 0.020" which implies that the penetrameter hole will probably not be imaged. Doubling the TV-line rate does not help much. To be barely detectable under ideal conditions the hole must intercept at least one TV-line. However, it is unlikely that the NDT inspector in a production environment will see this.

With a feinfocus X-ray system one can considerably improve the flaw detection sensitivity of a real-time radiographic image by employing the projection magnification techniques discussed previously. Image magnification results in an improved spatial resolution and an increase in image contrast as a result of less object scattered radiation being detected. By spreading the hole image across 5 or more TV-lines, the image is not fuzzy but well defined. A penetrameter sensitivity of 1% can be achieved at a 15 or more diameter enlargement under well controlled conditions.

It is good radiographic practice to magnify the image in microfocus real-time radiography. One
an keep on increasing the image size until the geometric sharpness (equation 1) is almost equal to the inherent unsharpness of the real time imaging system. Then the total effective unsharpness is calculated with equation (4). This value is then substituted for the geometric unsharpness in equation (3) and solved for the near optimum magnification.

\[ M = \left( \frac{U_{\text{total}}}{F} \right) + 1 \]  

(5)

This equation yields the geometric magnification where the geometric unsharpness is equal to the unsharpness of the imaging system. This method of setting \( U_g \) equal to \( U_{\text{Screen}} \) is somewhat of an over simplification. A more accurate formula for the optimum magnification where the total effective unsharpness is a minimum is derived with differential calculus:

\[ M_{\text{opt.}} = 1 + \left( \frac{U_{\text{screen}}}{F} \right)^{3/2} \]  

(6)

It is evident from equation (6) that the focal spot size (F) is an important parameter in defining the optimum magnification as well as the unsharpness.

**Manipulators**

To realize the full potential of microfocal real-time radiography one should employ a 5-aixs manipulator. Movement of the object through the X-ray beam enhances the detectability of defects. A manipulator can also be used to optimize part position for real time inspection (i.e to align a crack with the radiation beam). In some applications merely rotating the object will give the desired effect. The image of such a moving object on a TV-monitor will give a 3-dimensional impression which can be very helpful in interpretation. Further on, the manipulator can be used to dynamically zoom in and out on small indications to assist the interpreter in identifying the radiographic indication. In all cases the image remains sharp and well defined whether it is close to the image plane or far away because of the great depth of focus of feinfocus X-ray equipment.

**Applications of Microfocus Radiography**

The applications for microfocus radiography are fairly self evident form the above discussions. Microfocus radiography can be used wherever conventional radiography is employed provided that the application falls within the kV range of the microfoucs tube. The application of microfocus radiography is also obvious for areas where conventional radiography cannot be applied because of access problems. The include geometrics such as jet engines, weapon components, complex assemblies, and castings and forgings. Inside-out radiography (e.g, single wall radiography) often results in more than doubling the flaw detection sensitivity attainable with previously used conventional radiographic techniques.

Feinfocus radiography should also be used to radiographically inspect components where even a small chance of failure is unacceptable. Most of these applications fall within the realm of the aircraft, aerospace, electronic industries.

Some applications where microfocus radiography has been successfully used include the detection of microvoids in ceramics, critical castings (e.g, turbine blades), stress corrosion cracking and fatigue cracks in aircraft structures, and the detection of voids, cracks and porosity in all types of other metal components. Another area where microfocus radiography is being applied is or the inspection of composites, plastics, and light metals. Of course the electronic industry with its critical inspection requirements of many small parts and assemblies is also a growing user of microfocus radiography.

Another unique application of microfocal projection radiography is the accurate dimensional
gauging of tubes, gaps, drilled holes, and other components that are inaccessible, fragile, or too small (e.g. laser fusion targets) for mechanical gauges. The technique is also being successfully applied to the inspection of radioactive components.

There is also a wide variety of applications, besides the ones mentioned above, where microfocus real-time radiography is being used. Some of these are the real time observation of dynamic component functioning, powder mixing studies, liquid flow in tubes or passages, dynamic material studies, and precision part alignment prior to film radiography. The number of applications of Microfocus Radiography is still growing.

Conclusions

Microfocus radiography offers a new dimension in industrial radiography. It extends the flaw detectability of film radiographic techniques and brings real time radiographic inspection into both the NDT laboratory and the factory for continuous on-line inspection. It is a powerful new NDT tool that can be successfully used to meet many of today's critical inspection requirements. Its application to radiographic inspection problems will result in an enhanced flaw detection sensitivity and reliability for the user and his customer.