Strategies for Film Replacement in Radiography - Approaches Used in the New Standards

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Abstract. Several standards were published by CEN, ASTM and ASME to support the application of phosphor imaging plates in lieu of X-ray film in the year 2005 and a set of standards for DDA application was published by ASTM in 2010. The new EN ISO/FDIS 17636-2 was proposed as result of the project “FilmFree” and further tests at BAM. One of the key concepts is the usage of signal-to-noise (SNR) measurements as equivalent to the optical density of film. The Image quality in digital radiography is typically measured with wire IQIs (Europe) or plate hole IQIs (USA). Studies were performed with Computed Radiography (CR) and Digital Detector Arrays (DDA) in comparison to film radiography (FR). Computed radiographs, taken with imaging plates, achieve similar IQI visibility than film radiographs. In many cases they achieve only class A (basic) of European standard EN 1435 and fulfill completely the requirements of ASME section V article 2. Radiography with DDAs achieves typically much better IQI visibility than FR and CR, even at short exposure time, but most DDAs are limited by the low basic spatial resolution of the detector. This basic spatial resolution is measured with the duplex wire IQI (see EN 462-5 or ISO 19232-5). The contrast sensitivity, measured by IQI visibility, depends on three essential parameters: The achieved signal-to-noise ratio (SNR), the basic spatial resolution (SRbimage) of the radiographic image and the specific contrast (μeff - effective attenuation coefficient). Knowing these 3 parameters for the given exposure condition, inspected material and monitor viewing condition permits the calculation of the just visible IQI element. Furthermore, this enables the optimization of exposure conditions. The new EN ISO/FDIS 17636-2 describes the practice for digital radiography with CR and DDAs. It considers first time compensation principles, derived from the three essential parameters (SNR, SRb, μeff). Compensation principle I enables the compensation of exposures with higher kV (reduced μeff) by exposure with higher SNR. In consequence the limitation of maximum permitted tube voltage as function of penetrated material thickness (EN 444, EN 1435) is given up in EN ISO/FDIS 17636-2. Compensation principle II allows the application of less sharp detectors if compensated by exposure with higher SNR. This requires e.g. the increase of the visible wire number, if the DDA or CR system does not qualify with its basic spatial resolution.

Introduction

The NDT community discusses about effective film replacement by Computed Radiography (CR) and Digital Detector Arrays (DDA), also known as flat panel detectors, since about 15 years. Several standards were published by CEN, ASTM and ASME to support the application of phosphor imaging plates in lieu of X-ray film in the year 2005 and a set of standards for DDA application was published by ASTM in 2010. The European Community funded the project “FilmFree” (www.filmfree.eu.com), which supported film replacement by digital techniques in analogy to the success story of digital photography. Thirty three companies and institutes tested the ability of the new technologies and developed guidelines and standards (2005-2009). The new EN ISO/FDIS 17636-2 was proposed as result of the project and further tests at BAM. This final draft was developed by a joined working group of CEN/TC121 and ISO/TC44 for replacement of the EN 1435. The content of EN 1435 was transferred into EN ISO 17636-1 (radiographic testing of welds with films) and a new part EN ISO 17636-2 (radiographic testing of welds with digital detectors) was added for new digital film replacement methods. One of the key concepts is the usage of signal-to-noise (SNR) measurements as equivalent to the optical density of film. The Image quality in digital radiography is typically measured with wire IQIs (Europe) or plate hole IQIs (USA). Studies were performed with Computed Radiography (CR) and Digital Detector Arrays (DDA) in comparison to film radiography (FR). Digital radiographs are typically characterized by lower spatial resolution than film radiographs. This basic spatial resolution is measured by the duplex wire IQI (see EN 462-5, ASTM E 2002 or ISO 19232-5). Computed radiographs, taken with imaging plates, achieve similar IQI visibility than film radiographs. In many cases they achieve only class A (basic) of European standard EN 1435 and fulfill completely the requirements of ASME section V article 2. Radiography with DDAs achieves typically much better IQI visibility than FR and CR, even at short exposure time, but most DDAs are limited by the low basic spatial resolution of the detector [1-9].

Differences and similarities between digital radiology and film radiography

Film replacement in radiographic testing (RT) will introduce new aspects to be considered by the inspection personnel:

- The Digital Industrial Radiology (DIR) procedure is different from the film radiography procedure.
- But: The optical impression of digital radiographic images is not different from film images in its structure (if no digital image processing is applied, except brightness AND contrast control).
- RT-trained personal can interpret digital images in analogy to film.
- Digital images need a computer and monitor for presentation and may be altered by specialized image processing.
- A basic training in image processing is essential to avoid miss interpretation.
- Quantitative assessment of flaw sizes is improved by digital measuring tools but the results may differ from those ones of film interpretation.
- New electronic reference catalogues may support correct image assessment.

Image quality in digital Radiology

The contrast sensitivity in Digital Industrial Radiology depends on the product of effective attenuation coefficient μ_{eff}, also called specific contrast, and the signal-to-noise ratio (SNR), normalized to the basic spatial resolution SR_b. This applies for CR, DDAs and X-ray film. Fig. 1 illustrates the effect of noise on flaw detection.

The contrast-to-noise ratio (CNR) per wall thickness difference Δt ($CNR^{Specific}$), which is the essential parameter for the visibility of flaws and IQIs of a given size, can be calculated from the detector response (SNR) as a function of exposure dose as follows (small flaws only, see Fig. 1):

$$CNR/\Delta t = SNR \cdot \mu_{eff} \qquad (1)$$

The perception threshold (PT) for the visibility of a hole (visibility of small details) by the human operator on the image display can be formulated as follows [10-13]:

$$PT = d_{visible} \cdot CNR \qquad (2)$$

PT - perception threshold
$d_{visible}$ - hole diameter of the just visible hole in the image

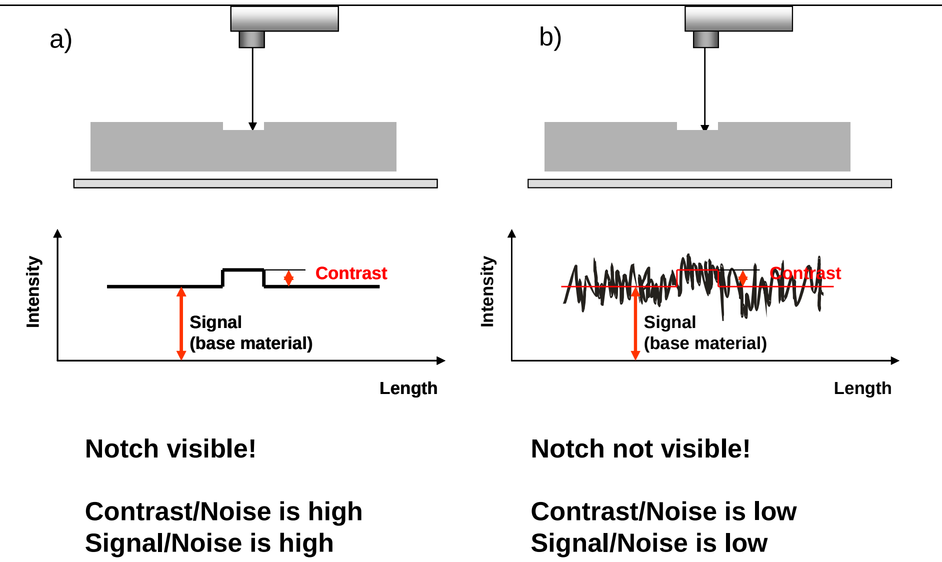

Fig. 1. The influence of noise on the visibility of a notch in radiography
a) the notch is visible if the noise contribution can be neglected,
b) the notch is not visible if the noise is just higher than the contrast.

Now it is assumed that the hole diameter d is equal to the IQI thickness T = Δt (1T hole with d = T = Δt). The just visible 1T hole diameter and IQI thickness can be calculated from eq. 2 and 3, if PT is known.

Additionally, the number of presented pixel at the monitor has to be considered for correct IQI perception [8]. Since the acquired image size depends on the pixel size and number, the presentation on the image display monitor depends also on the pixel size (one acquired pixel shall be presented at one separate monitor pixel). That means that the real diameter d can be presented with different scaling factors at the monitor. Following the Shannon sampling theorem, the information content of an unsharp image („bandlimited“) is sampled with the size of the unsharpness kernel and therefore, the basic spatial resolution is used instead of the pixel size. In consequence, the effective pixel size SR_b for scaling correction is also considered for calculation of the just visible IQI hole diameter:

$$d_{visible} = PT^* \cdot \sqrt{\frac{SR_b^{image}}{\mu_{eff} \cdot SNR}} = PT^* \cdot \sqrt{1 / CNR_N^{specific}} \qquad (3)$$

The basic spatial resolution SR_b corresponds to the effective pixel size (square root of effective pixel area, called sampling aperture in the medical literature) in a digital image. SR_b can be measured in different ways, but the standard committees recommend to use the duplex wire method due to its simplicity (EN 462-5, ISO 19232-5 and ASTM E 2002). The measurement with the duplex wire IQI provides a total image unsharpness value (u_T) in µm. The basic spatial resolution SR_b in the image is calculated by:

$$SR_b^{image} = u_T / 2 \qquad (4)$$

and u_T is calculated

$$u_T = \sqrt{u_I^2 + u_G^2} \qquad (5)$$

u_I is the inherent unsharpness of the detector ($u_I = 2 * SR_b^{detector}$) and u_G is the geometric unsharpness due to the radiographic set up and focal spot size (see EN ISO/FDIS 17636-2 and ASTM E 1000).

SR_b or $SR_b^{detector}$ is considered as basic spatial resolution of the detector (effective detector pixel size, magnification = 1), measured with the duplex wire IQI directly on the detector (see also ASTM E 2597, E 2445, E 2446). SR_b^{image} is considered here as the basic spatial image resolution, measured with the duplex wire IQI on the source side of the object in the digital image with magnification and unsharpness contributions from the object, which is also a source of scattered radiation.

$SR_b^{detector}$ corresponds typically to the pixel size (pixel limited unsharpness) of direct converting systems (e.g. α-Se-DDA or CdTe-DDA). It is greater than the pixel size (or laser spot size) for CR and larger than the pixel size (photo diode array elements) of DDA's with thicker scintillators. The basic spatial resolution parameter is an essential part of EN 14784, ASTM E 2445, E2446, E 2597and EN ISO/FDIS 17636-2.

The term $\mu_{eff} \cdot SNR/SR_b^{image}$ is considered as normalized specific contrast-to noise ratio ($CNR_N^{specific}$) per mm thickness difference and normalized by SR_b^{image} (see below for definition of SR_b^{image}). PT* depends also on operator and viewing conditions. If the hole diameter is much larger than the unsharpness, the equivalent IQI sensitivity (EPS in %) changes for a given material thickness as follows (see ASTM E 746 and E 1025 for 2T sensitivity):

$$EPS = \frac{PT'}{t_{testplate}} \sqrt{\frac{SR_b^{image}}{\mu_{eff} \cdot SNR}} \qquad (6)$$

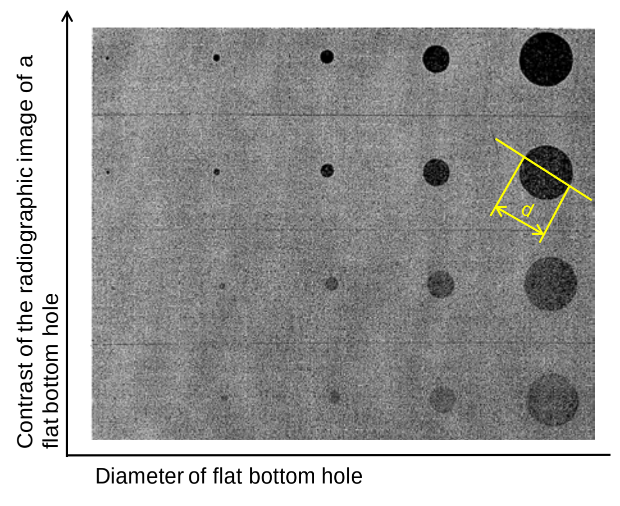

Fig. 2. Grey value image of holes with different contrast, CNR and diameter. The CNR is constant in each line and the diameter is constant in each column.

with PT' ≈ 200, determined from practical trials for clear visibility of holes on a monitor. The calculated EPS (procedure see ASTM E746 and [8]) by eq. (6) is equivalent to the visually measured EPS values as defined by the procedure of ASTM E 746. It is also equivalent to the requirements and definitions of ASTM E 1742 and E 1025.

Since the gray values of the pixels in the digital images (assuming signal is proportional to dose) depend on noise and signal intensity independent of the contrast and brightness processing for image viewing, the SNR has been proposed and accepted as an equivalence value to the optical density and a certain film system in film radiography (EN 14784-1, -2 and ASTM E 2445, E2446 and EN ISO/FDIS 17636-2).

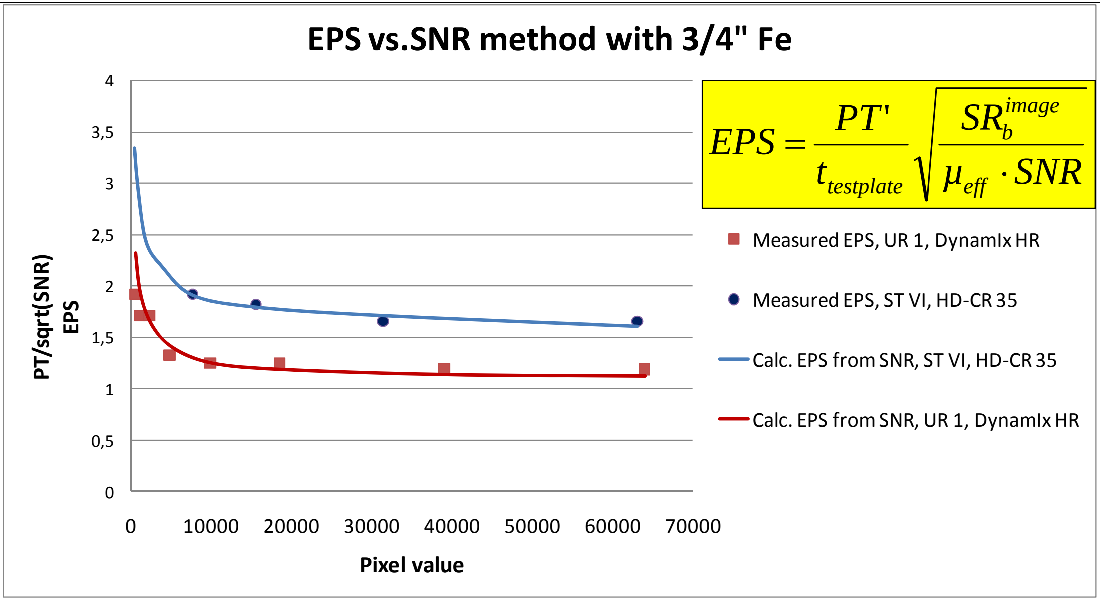

Fig. 3. Comparison of EPS measurements (200 kV) vs. PT*/sqrt(SNR) measurements. The curves fit accurately. The SNR method provides more accurate results. Different PT values were used for the SNR method since the Imaging Plates (IP) and the CR scanners used achieve different SR_b qualifications (see equation 6). PT* is calculated by 1.5▪sqrt(SR_b^{image} in µm) for both curves. Measured SR_b^{image} for IP UR 1 was 70 µm and SR_b^{image} for IP ST VI was 145 µm. The type of imaging plate and the scanner resolution dominate the EPS results here. No EPS values were obtained for IP ST VI with HD-CR 35 scanner for pixel value PV < 7000, meaning no EPS holes were visible in these radiographs.

Equation (6) was verified with modeling results [13] and experiments. The SNR and the grey values were measured with the software ISee! [14]. Independent operators determined the just visible 1T hole of EN 462-2 IQIs and wire number of EN 462-1 IQIs from modeled images [13]. Wires with 2.5 times smaller diameter than the diameter of the holes were seen with same perception.

Experiments were performed with different CR scanners and imaging plate types with a polished 19 mm (3/4”) Fe-plate at 200 kV to compare visually measured EPS values (strict application of ASTM E 746, 50% method) with calculated data, based on eq. (6). Fig. 3 shows that the visually determined EPS values fit well with the calculated ones (eq. (6)), with PT’ ≈ 2▪100% and $\mu_{eff} = 0.05\ mm^{-1}$.

This result allows the determination of EPS delectability of digital detectors at different energies and for different materials from SNR measurements without object.

Different noise sources have to be considered in digital radiography which have its origin in:

- Exposure conditions: photon noise depending on exposure dose (e.g. mA▪s or GBq▪min). This is the main factor, the SNR increases with higher exposure dose.
- Limitations for the maximum achievable SNR:
- Detector: structure noise of DDAs and imaging plates also called fixed pattern noise (due to variations in pixel response and inhomogeneities in the phosphor layer).

➢ Object:

  - Crystalline structure of material (e.g. nickel based steel, mottling)
  - Surface roughness of the test object

The first two noise sources can be influenced by the exposure conditions and detector se-lection. The achieved signal-to-noise ratio (SNR) of images depends on the exposure dose (low dose application). The SNR increases with the square root of mA▪minutes or GBq▪minutes, due to the improved quantum statistics of the X-ray photons. The structure noise of films and imaging plates depends on its manufacturing process and can be influenced basically by the selection of the specific detector type (e.g. like fine or coarse grained film). Film development and IP scanner properties contribute also to the final noise figure. The structure noise of detectors and all noise sources depending on the object properties determine the maximum achievable SNR and limit, therefore, the image quality independently on the exposure dose (high dose application). Only with DDAs the structure noise (due to different properties of the detector elements) can be corrected by a calibration procedure, since the characteristic of each element can be measured quite accurately. Fig. 4 shows the effect of SNR increase (equivalent to CNR increase) on the visibility of fine flaw indications [1, 2]. The digitized fine grained film provides a SNR of 265 in the base material region. The DDA image was measured with a SNR of about 1500 and magnification of 3.5. It shows significantly more fine flaw indications.

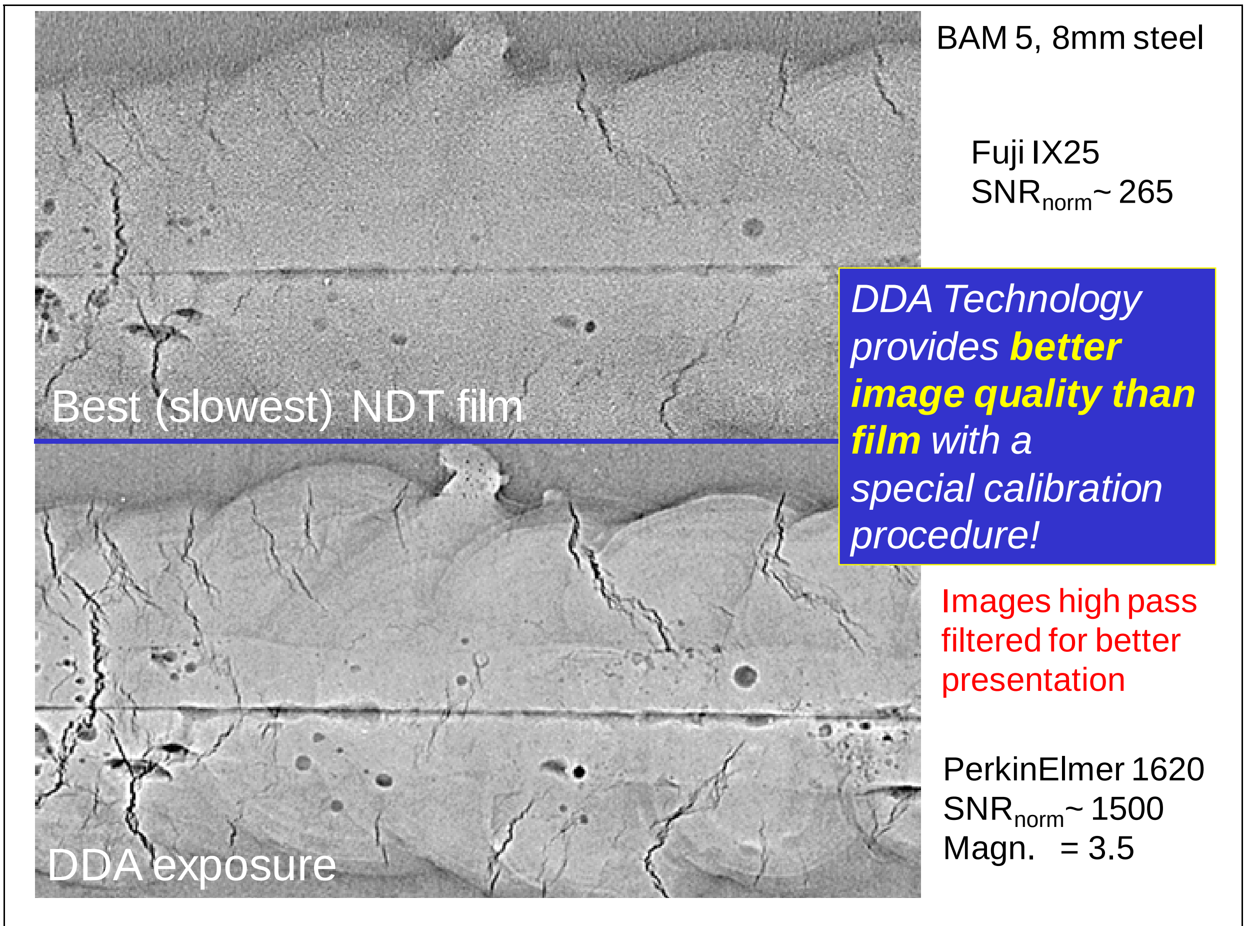

Fig. 4. Better detail visibility of flaws by increased SNR of DDA image in comparison to digitized film image of weld sample BAM 5.

The detail visibility in equation (3) and also the EPS in equation (6) depend on the same relation between the essential parameters (SNR, SR_b and μ_{eff}). This opens the way to the new compensation principles for digital radiology as introduced in EN ISO/FDIS 17636-2.

Compensation Principle I:

Compensation of reduced contrast (μ_{eff}) by increased signal-to-noise ratio (SNR)

In film radiography, it is well understood that the image quality increases if the tube voltage is reduced. In DIR, it can also be observed that the image quality increases in a certain range if the tube voltage is increased. The higher photon flow (X-ray intensity behind object) increases the SNR in the detected image faster than the reduction of the contrast by the decreased transmission contrast (also known as specific contrast or effective attenuation coefficient μ_{eff}). This effect depends on the ratio of attenuation decrease to SNR increase (see also equations 1 and 3) since the product of SNR and μ_{eff} controls the contrast sensitivity in the digital radiograph. The effect has been observed if DDAs are used for film replacement. Well calibrated DDAs can be exposed typically at higher tube voltages than films. However, too high tube voltage may even reduce the attenuation faster than the SNR increases. The maximum achievable SNR is the limiting parameter for the described compensation. It depends on the detector efficiency and the detector calibration of DDAs or the structure noise of imaging plates. It also depends on the noise of the material's structure and the material roughness. Therefore, the compensation by increase of the tube voltage is restricted depending on the detector and material properties and especially on the maximum achievable SNR in the radiograph.

Fig. 5a shows a typical example for the compensation of decreased contrast (μ_{eff}) by increased SNR. A step wedge with ASTM E 1025 IQIs (2%) was exposed at different X-ray energies and mA minutes with a constant source to detector distance. The visibility of the 2T hole (denoted with 2 in Fig. 5b) was achieved with increasing kV of the tube at shorter exposure time. This cannot be achieved with X-ray films, since they will always be exposed to an optical density between 2 and 4. In this case, the films of a given class always have the same SNR in a small range due to its specific manufacturing process. The increase of the tube voltage from 80 kV to 150 kV allows finally the reduction of exposure time down to 20% for digital radiology in the example of Fig. 5. All thickness steps of the test object can be inspected with one exposure at 150 kV. The steps with the smallest thickness are even radiographed with 2-1T quality. Here, the tube voltage increase yields a higher efficiency and an increased thickness range based on the digital "high contrast sensitivity" technique.

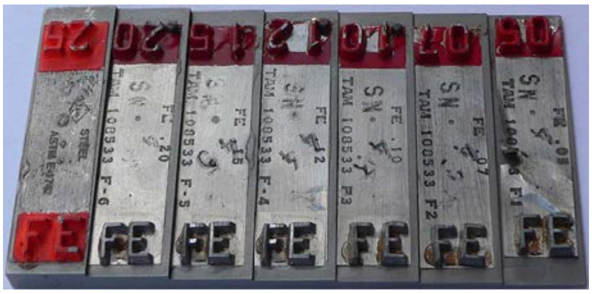

Fig. 5a. Step wedge of steel with ASTM E 1025 IQIs for determination of image quality.

80kV	1 mA min	2 mA min	5 mA min	10 mA min	20 mA min
0,05 in	1	2	1	1	1
0,07 in	4	2	2	2	1
0,10 in	-	2	2	2	1
0,12 in	4	4	2	2	1
0,15 in	-	-	2	2	2
0,20 in	-	-	-	2	2
0,25 in	-	-	-	-	4

100kV	1 mA min	2 mA min	5 mA min	10 mA min	20 mA min
0,05 in	2	1	1	1	1
0,07 in	2	2	1	1	1
0,10 in	2	2	1	1	1
0,12 in	2	2	1	1	1
0,15 in	4	2	2	1	1
0,20 in	-	4	2	1	1
0,25 in	-	-	1	?	1

150kV	1 mA min	2 mA min	5 mA min	10 mA min	20 mA min
0,05 in	2	1	1	?	?
0,07 in	2	1	1	?	?
0,10 in	2	2	1	?	?
0,12 in	2	2	2	1	?
0,15 in	2	2	2	1	1
0,20 in	4	2	2	1	1
0,25 in	4	2	2	1	2

Fig. 5b. Achieved IQI quality (smallest visible hole of 2% IQI. It means: 1: 1T hole, 2: 2T hole, 4: 4T hole) as function of kV, mAmin and wall thickness in inch for the test object shown in Fig. 3a.

As consequence the requirements for film radiography in relation to the maximum tube voltage (EN 1435, EN 444, ISO 17636:2003) are not valid anymore for digital radiography. In EN ISO/FDIS 17636-2 this is modified as follows:

- To maintain a good flaw sensitivity, the X-ray tube voltage should be as low as possible. The recommended maximum values of tube voltage versus thickness (see Fig. 6) are given in Fig. 20 of EN ISO/FDIS 17636-2.
- These maximum values are best practice values for film radiography.
- DDAs provide sufficient image quality at significant higher voltages too.
- Highly sensitive imaging plates with high structure noise of plate crystals (coarse grained) should be applied with about 20 % less X-ray energy as indicated in Fig. 20 of EN ISO/FDIS 17636-2.
- High definition imaging plates, which are exposed similar to X-ray films and having low structure noise (fine grained) can be exposed with X-ray energies of Fig. 20 of EN ISO/FDIS 17636-2 or significantly higher, if the SNR is sufficiently increased.

Fig. 20 of EN ISO/FDIS 17636-2 is given here in Fig. 6.

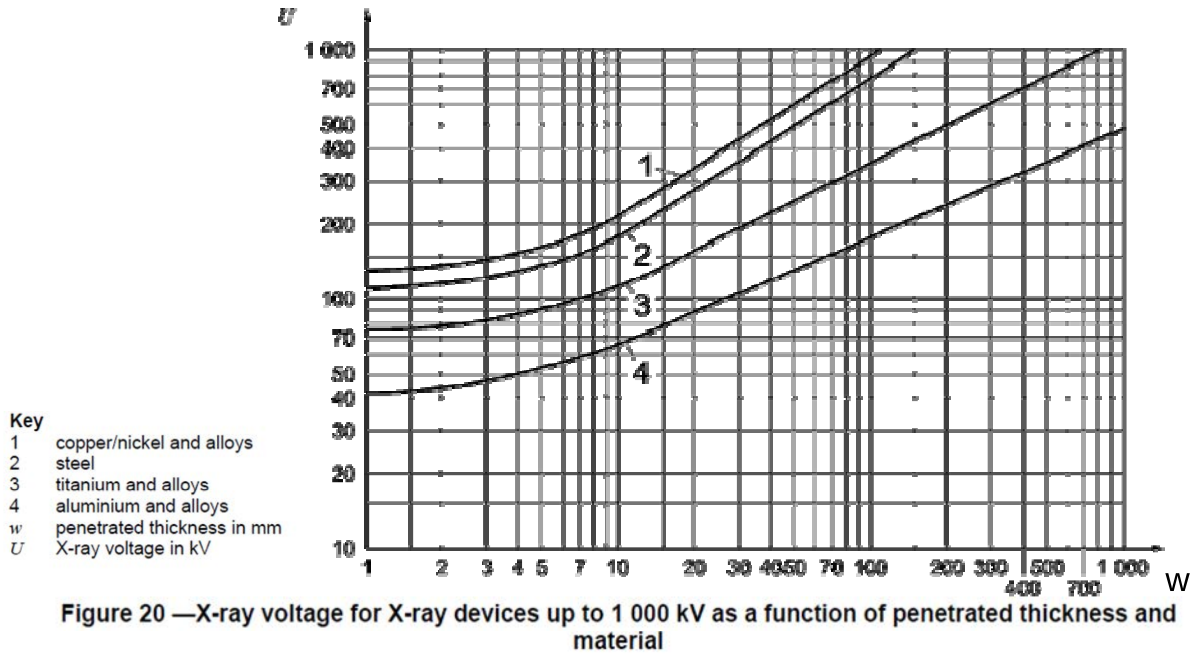

Fig. 6. The selection of X-ray tube voltage becomes a recommendation for digital detectors (see EN ISO/FDIS 17636-1 and -2).

Compensation Principle II:

Compensation of insufficient detector sharpness (higher unsharpness) by increased SNR

The European standard EN 14784-2 requires the application of high definition CR systems for X-ray inspection with pixel sizes of less than 50µm for class B inspection (for wall thickness <12 mm and tube voltages <150 kV). Most available systems do not allow a resolution below 50µm pixel size and are excluded for industrial X-ray applications at thin wall thicknesses according to this standard in Europe. Recent trials have shown that DDAs provide a better image quality and IQI visibility than industrial X-ray films [1, 2]. In a high contrast sensitivity mode the DDAs achieve better IQI reading than film exposures. This effect is observed when sub-pixel contrast resolution is achieved. This is the case, if the SNR at the detector is increased considerably. If a wire or crack is smaller than a pixel, it still influences the contrast for that pixel and can be seen in the image if the contrast is sufficiently higher than the noise. Therefore, systems with insufficient spatial resolution can be applied if their higher unsharpness is compensated by increased SNR.

Table 1 shows the revised table for hardware selection of EN ISO/FDIS 17636-2 (class B) which is widely conform to the ISO 10893-7:2010. No DDA or CR system shall be used, which does not provide the required basic spatial resolution, as defined in tables B.13, B. 14 of EN ISO/FDIS 17636-2. If the available digital system has not sufficient spatial resolution, it may be used on basis of the compensation (II) principle.

Table 14 — Maximum image unsharpness for all techniques Class B

Image Quality Class B: Duplex wire ISO 19232-5		
Penetrated thickness *w* [a] mm	Minimum IQI value and maximum unsharpness (ISO 19232-5) [b] mm	Maximum basic spatial resolution (equivalent to wire thickness and spacing) [b] mm
w ≤ 1,5	D 13+ 0,08	0,04
1,5 < *w* ≤ 4	D 13 0,10	0,05
4 < *w* ≤ 8	D 12 0,125	0,063
8 < *w* ≤ 12	D 11 0,16	0,08
12 < *w* ≤ 40	D 10 0,20	0,10
40 < *w* ≤ 120	D 9 0,26	0,13
120 < *w* ≤ 200	D 8 0,32	0,16
w > 200	D 7 0,40	0,20

[a] For double wall technique, single image, the nominal thickness *t* shall be used instead of the penetrated thickness *w*.

[b] The IQI reading for system selection (see Annex C) applies for contact radiography. If geometric magnification technique (see 7.7) is used, the IQI reading shall be performed in the corresponding reference radiographs.

Tab. 1. Minimum requirement to digital detection systems for class B testing as function of wall thickness in EN ISO/FDIS 17636-2 (see table B.13 for class A).

It is proposed to permit the application of unsharp systems, if the visibility of the required wire or step hole IQI is increased by compensation of missing duplex wire resolution (caused by too high basic spatial resolution values of the detection system) through SNR enhancement (see EN 462-5, ASTM E 2002 and requirements of EN 14784-2). Several new standards define minimum duplex wire values for specific applications (e.g. ISO 10893-7 or EN ISO/FDIS 17636-2). Typically, one higher (smaller diameter, see EN 462-1) single wire (resulting in higher contrast sensitivity) shall be seen through adjustment of parameters that increase the SNR if an additional duplex wire of spatial resolution is required in the system qualification for a given material thickness and application. This compensation is limited to maximum 2 wire vs. wire pair compensations in EN ISO 17636-2, by agreement of the contracting parties it could be extended to 3 wires vs. wire pairs. The compensation should also be applicable to plate hole IQIs too.

Example: Is a digital detection system used (DDA or CR), which achieves the duplex wire pair D11 (first unsharp wire pair) for inspection of a 5 mm thick object and class B testing as defined in EN ISO/FDIS 17636-2 (required is D12 and W16), single wire W17 shall be clearly visible in the image for acceptable quality.

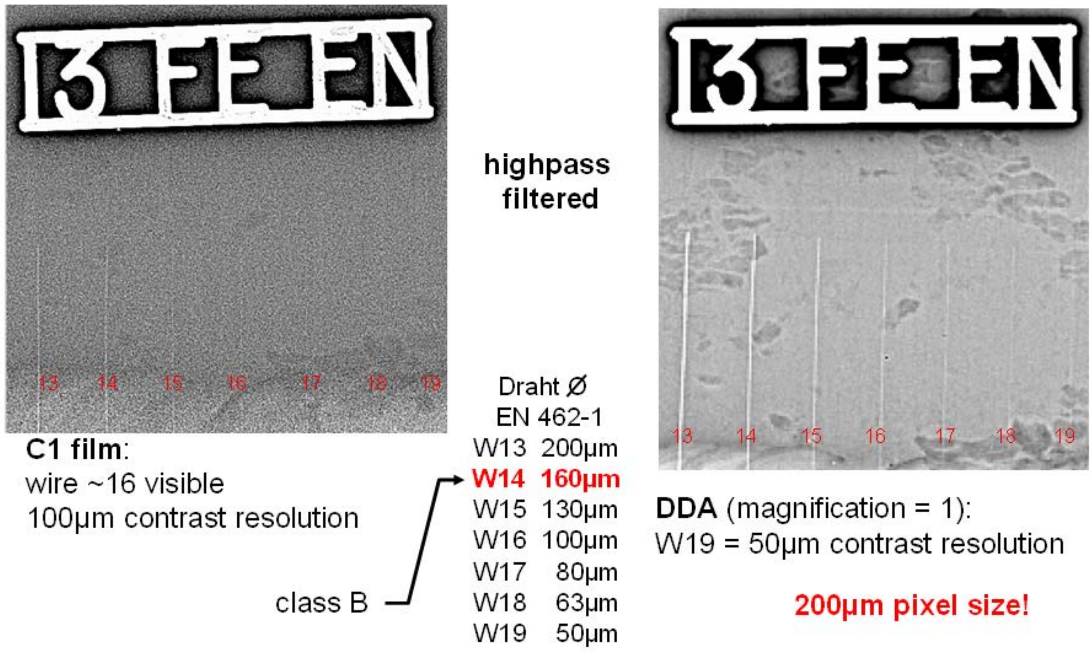

Fig. 7. Comparison of visibility of wire type IQIs according to EN 462-1 for film (left) and DDA (right) at 8mm wall thickness (images high pass filtered for better visualization). The improved SNR of the DDA allows to detect the wire W19 (50 µm diameter) at a detector pixel size of 200µm without magnification technique!

The compensation effect has been proven with commercially available DDAs. Even at a magnification of 1 and a basic spatial resolution of 200µm (pixel size), the significantly increased SNR of the DDA allows the detection of crack indications which are hidden by noise in the film image with its much better basic spatial resolution SR_b of 40µm. Fig. 7 shows the radiograph of an # 13 wire IQI on a 8 mm steel plate. The radiographs were high pass filtered for better graphical presentation. The digitized film (50 µm pixel size) shows wire number 16 (100 µm diameter) and the DDA image shows wire number 19 being visible, which has a diameter of 50 µm. Therefore, the detector shows the wire 19 indication with a sub-pixel resolution.

Inspection of pipe welds with DDAs and cassettes

In EN 1435 and EN ISO/FDIS 17636-1 flexible films are required, which are wrapped around the pipe in close contact to minimize the required SDD and achieve sharp radiographs. For digital detectors, which are mostly not flexible or sensitive against pressure to the surface, a flat detector geometry was considered for radiography of circumferential pipe welds. Fig. 8 (Fig. 2 of EN ISO/FDIS 17636-2) shows a typical example for recommended detector geometries of flexible (film, flexible IP) and rigid (DDA, CR cassette) detectors. The usage of rigid detectors increases the distance to the test object. The increase of b has to be considered and the SDD has to be increased to avoid an increasing geometric unsharpness. The corresponding equations for calculation of the object source distance f are given in Fig. 8.

Fig. 8. Testing with flat Detectors and flat Cassettes is required for effective testing with DDAs and Imaging Plates

Presently valid standards on digital radiology

In 2005 Europe and USA published the first complete set of CR standards. Table 2 provides an overview about the most important standards on digital industrial radiology (DIR). Especially, at ASTM the standardization is pushed ahead over the last 10 years. The next set of standards of DIR with DDAs was published in 2010. Now the revision of the CR standards is under discussion. CEN and ISO prepared a common standard (EN ISO/FDIS 17636) which is ready for final vote and following publication in 2012. It will substitute the EN 1435 for radiographic weld inspection and considers film (part 1) and CR and DDAs (part 2).

Tab. 2. Overview on presently valid DIR standards of CEN, ISO, ASME and ASTM without standards on Computed Tomography.

Conclusions

Digital radiography with CR and DDAs will substitute film radiography similar to digital photography. The contrast sensitivity, measured by IQI visibility, depends on three essential parameters:

- The achieved signal-to-noise ratio (SNR),
- the basic spatial resolution (SR_b^{image}) of the radiographic image and
- the specific contrast (= effective attenuation coefficient, μ_{eff}).

Knowing these 3 parameters for the given exposure condition, inspected material and monitor viewing condition permits the calculation of the just visible IQI element. Furthermore, this enables the optimization of exposure conditions. SR_b is limited by the design of DDAs and for CR by the imaging plate and scanner (laser focus) and its settings. SNR increases with exposure time but it does not exceed a SNR_{max} value which is limited by DDA calibration or by the design of the imaging plate (fixed pattern noise). The operator can increase the contrast sensitivity by increasing the exposure time and tube current. DDAs achieve a significant higher contrast sensitivity than film radiographs with correct detector calibration.

The new EN ISO/FDIS 17636-2 describes the practice for digital radiography with CR and DDAs in one document. Normalized SNR or grey values (only CR) are used as equivalent value for film system class and opt. density. The usage of duplex wire IQIs is required for system qualification and system selection. The mandatory usage of duplex wire IQIs in all radiographs is required for magnification technique. The usage of flat cassettes and DDAs for curved objects is accepted with a new formula for calculation of SDD. New revised unsharpness tables enable the correct hardware selection. EN ISO/FDIS 17636-2 considers first time compensation principles, derived from the three essential parameters (SNR, SR_b, μ_{eff}):

- Compensation principle I enables the compensation for reduced contrast (e.g. by increased tube voltage) by increased SNR (e.g. by increased tube current or exposure time). In consequence the limitation of maximum permitted tube voltage as function of penetrated material thickness (EN 444, EN 1435) will be given up in EN ISO/FDIS 17636-2.
- Compensation principle II allows the compensation for insufficient detector sharpness (the value of SR_b higher than specified) by increased SNR. This requires the increase in the single IQI wire or step hole value for each missing duplex wire pair value, if the DDA or CR system does not qualify with its basic spatial resolution.
- Compensation principle III allows the compensation for increased local interpolation unsharpness, due to bad pixel correction for DDAs, by increased SNR.

Digital radiography can be applied to a broad range of X-ray applications, including inspection of pipeline welds, castings, electronic assemblies, wheels, rails, bridges and many other industrial uses for technical, environmental, safety and economic advantages. Increased emphasis on environmental safety, including concerns for the effects of radiation on workers and the requirement for disposal of the chemicals used to process film, have contributed to the growing need to replace conventional X-ray inspections involving long film exposures. The relatively low operational cost of digital radiography and the possibility for online inspection are other major advantages of digital radiography.

Acknowledgments

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