Possibilities and Limits of Digital Industrial Radiology: - The new high contrast sensitivity technique - Examples and system theoretical analysis

Uwe Zscherpel [1], Uwe Ewert [1], Klaus Bavendiek [2]

[1] Division VIII.3, Federal Institute for Materials Research and Testing (BAM),
D-12200 Berlin, Germany, Phone: +49 30 8104 3677 / 1830, Fax +49 30 8104 1837 e-mail:
uwe.zscherpel@bam.de, uwe.ewert@bam.de
[2] YXLON International X-Ray GmbH, Essener Bogen 15,
D-22419 Hamburg, Germany, e-mail: kaus.bavendiek@hbg.yxlon.com

Abstract

During the last years more and more reports about film replacement techniques are published using different ways to prove the required and obtained image quality. The motivation is usually cost reduction due to shorter exposure times and lower storage costs, smaller space requirements and elimination of chemical processing inclusive associated waste handling and disposal. There are no other publications known, which explore the upper limits of image quality achievable by the new digital techniques. This is important for inspection of safety relevant and high risk parts, as e.g. in nuclear or aerospace industries. A new calibration and measurement procedure for digital detector arrays (DDA) was explored to obtain the maximum signal/noise ratio achievable with DDAs. This procedure yields a contrast sensitivity which allows distinguishing wall thickness changes of up to 1/1000 of the penetrated material thickness. Standard film radiography using NDT film systems (with and without lead screens) achieves a wall thickness contrast which is not better than 1/100 even with the best film system class (class "C1" according to EN 584-1 or "special" according to ASTM E 1815). Computed Radiography (CR) using phosphor imaging plates is a true film replacement technique without enhancement of the image quality compared to NDT film systems.

The comparison is based on parameter studies which measure signal/noise ratios and determine the basic spatial resolution as well as a comparison of radiological images with fine flaws.

Keywords: digital radiology, high contrast sensitivity technique, digital detector arrays, NDT film systems, Computed Radiography (CR) with imaging plates, film replacement, image quality, basic spatial resolution, signal/noise ratio, contrast sensitivity

1. Introduction

For more than 100 years industrial radiology has been based on X-ray film. Special film systems have been developed for applications in non-destructive testing (NDT), which have better image quality than medical film systems but lower speed. High spatial resolution is obtained by combination of these films with lead screens instead of fluorescence screens. Medical film systems have been developed under other requirements than NDT film systems because it is necessary in medicine to find a compromise between minimum patient dose and suitable image quality.

Computed Radiography (CR) with phosphor storage imaging plates (IP) is available since 20 years for film replacement in medicine too. The image quality is comparable with medical film systems with fluorescent screens, because the IP is designed similar to a fluorescent screen. Problems arise for CR applications in NDT. Fluorescent intensifying screens are usually not allowed in combination with films in NDT, because of its poor spatial resolution. Therefore, lead screen film systems are used. To compete with these NDT film systems new high definition CR systems have been developed in the last years, which yield comparable spatial resolution and signal-to-noise ratios (SNR) at comparable exposure dosage to NDT film systems.

New **d**igital **d**etectors **a**rray (DDA) systems were developed for medical applications, which have the potential to replace the X-ray film and revolutionize the radiological technique. These detectors enable new computer based applications with new intelligent computer based methods. These technological and algorithmic developments are also applicable to new NDT procedures.

But there exist also risks. Because the technology was developed primarily for medical applications, its weakest point is the low spatial resolution of most of the new DDA systems in comparison to NDT film. Additionally the application range of most DDAs is limited to lower X-ray energies (< 250 keV).

DDAs can be calibrated with new multi gain procedures which eliminate their structural noise almost completely. These techniques are not applicable for film based or CR techniques. Therefore, DDA systems permit low noise imaging in radiography and pave the way for new applications which require extra high contrast, sensitivity and wall thickness dynamics in the images.

An extraordinary economical advantage also exists where the classical film technique is replaced by digital detection and processing systems. Shorter processing and interpretation (P+I) cycles and the high image quality imply better product quality in a shorter time in comparison to the film technique and/or other NDT methods. The elimination of consumables in digital radiology is an additional monetary and a considerable ecological advantage.

2. Comparison of Image Quality

2.1 Essential Image Quality Parameters

In fig. 1 the basic relationships are shown between the image quality parameters of any radiographic image detector. The detection sensitivity (contrast sensitivity $C_S = 1/CNR$) for small wall thickness changes Δw (arising from a flaw inside the object) is defined by the ratio of contrast (signal intensity change ΔI) to the image noise (standard deviation of I). The CNR for a given Δw can be calculated from the SNR in the image considering the attenuation coefficient μ and the scatter ratio k between scattered and primary radiation. A radiographic image is described by the following major image quality parameters:

1. **Image unsharpness** consisting of the geometric unsharpness divided by the magnification (projected unsharpness) and the detector unsharpness described by the basic spatial resolution SR_b (half value of detector unsharpness or effective pixel size).
2. **Contrast to noise ratio** or contrast sensitivity (smallest detectable difference of material thickness) which is the inverse CNR. The specific CNR depends on the detector SNR and the effective material attenuation coefficient. The detector is characterized by the normalized signal-to-noise ratio SNR_{Norm} as function of exposure conditions (exposed dosage and radiation quality).

Considering practical aspects of radiographic applications an additional parameter is the **Material thickness range** (image dynamic based on the extent of material thicknesses evaluable in the same image). Since this value is fixed for films (limited by density range of 2 – 4.5 and μ_{eff}) it is usually not considered for film radiography in text books and standards. Since modern DDAs can be used even for replacement of double film technique this parameter is added here.

The normalization of the measured SNR by the basic spatial resolution of the image detector is essential, because the measured SNR at equal dosage increases with the square root of the area of the detector pixel element (result of Poisson statistics for the X-ray photons). The basic spatial resolution is measured by a duplex wire according to EN 462-5 and equal to the half value of the indicated image unsharpness. Details can be found in /1/ - /5/ and in the therein cited standards.

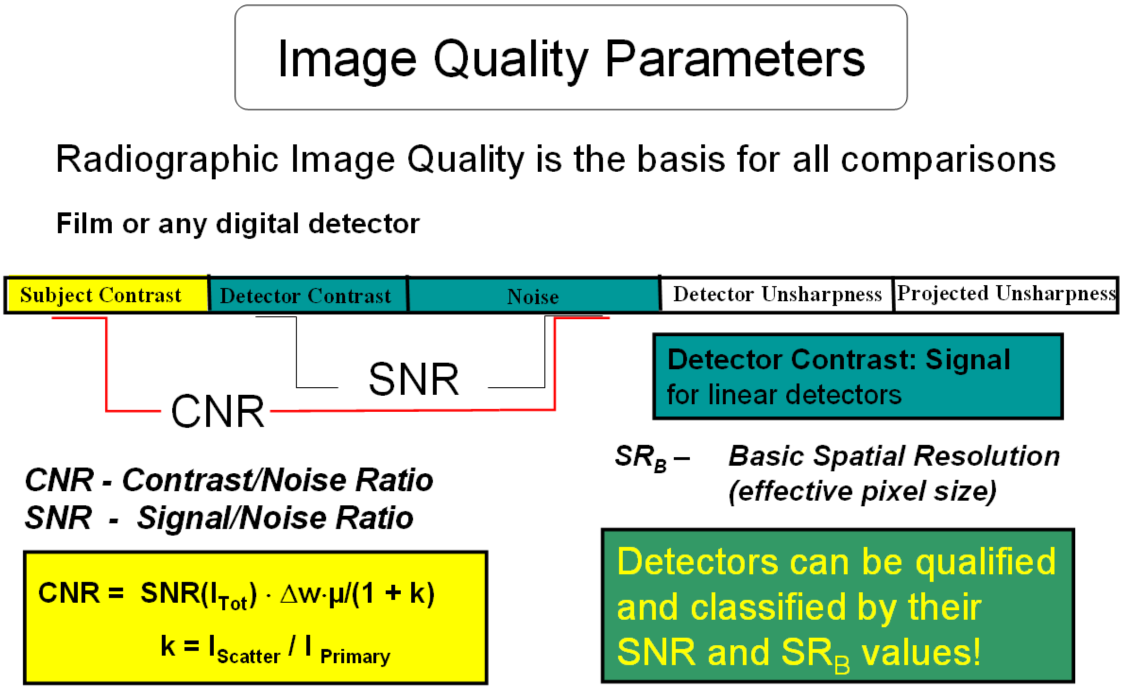


Fig. 1: Relationships between image quality parameters of radiographic image detectors (from [7])

2.2 Achievable Image Quality with NDT Film Systems

In fig. 2 the essential relationships are shown, which determine the image quality of NDT film systems. As follows, the SNR_{Norm} depends on the film system class. The minimum value is 43 (class C6 at $D\text{-}D_0$=2, dose ca. 2 mGy) the maximum 250 (best class C1, $D\text{-}D_0$= 4.5, dose ca. 60 mGy). Higher SNR_{Norm} values are not achievable with film systems according to EN584-1, because an increased dosage generates optical densities of D > 5, which are practically not readable from the films. The basic spatial resolution of a film system is determined by the radiation quality, because this determines the thickness of the lead screens to be used (see EN 444) and the spread of electrons generated by the lead screens to expose the film. Table 2 in EN ISO 14096-2

provides values similar to SR_b for correct film digitization to convert analogue films into digital image data.
The test weldment "BAM5" was selected to demonstrate the obtainable image quality with the different image detectors. This 8 mm steel plate with 2mm weld reinforcement contains all typical flaws. Additionally, typical image quality indicators (IQI) have been attached.
Fig. 4 describes the exposure conditions used for the film exposure. Caused by the dynamic range in the image originating from the wall thickness range no noise is visible for the human operator in the raw data. Therefore, a 2D-FFT high pass filter is used for better visual representation and image comparison, which suppresses the strong image background originating from the wall thickness changes (see fig. 7, 9 and 10).

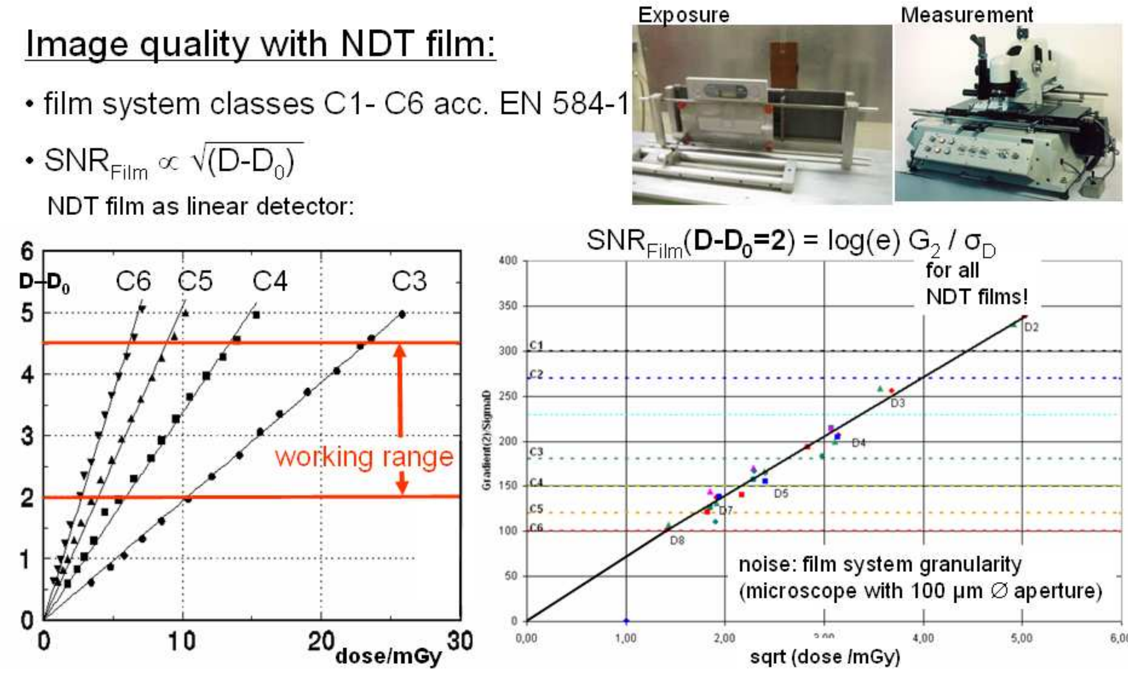


Fig. 2: Determination of image quality parameter SNR_N by NDT film system classification according to EN 584-1 (radiation quality 220 kV, 8mm Cu filter).
Left side – the NDT film as linear detector is used only in a limited dose range (working range with $2 \leq D \leq 4.5$)
Right side – gradient-over-noise ratio (G_2/σ_D) as function of square root of dose. The image noise of the film is measured as film granularity (σ_D) by an aperture (SR_b = 88,6 µm) of a microphoto-densitometer. The SNR of film can be calculated from the gradient-over-noise ratio by $SNR = 0.434 \cdot G_2/\sigma_D$ and is given by the limits of the film system class according to EN 584-1. All film system classes (independent on the manufacturer) are distributed along a linear line in the graph G_2/σ_D over square root of dose, which reflects the Poisson-statistics for X-ray quanta too.

Film System Classes are the Basis for CR Classification and Comparison to all Digital Detectors

Overview about the **film system classes** in different standards and the corresponding SNR values and G_2/s_D values:

$SNR_{Norm} = \log(e) \cdot (G_2/\sigma_D)$ **for linear detectors only**

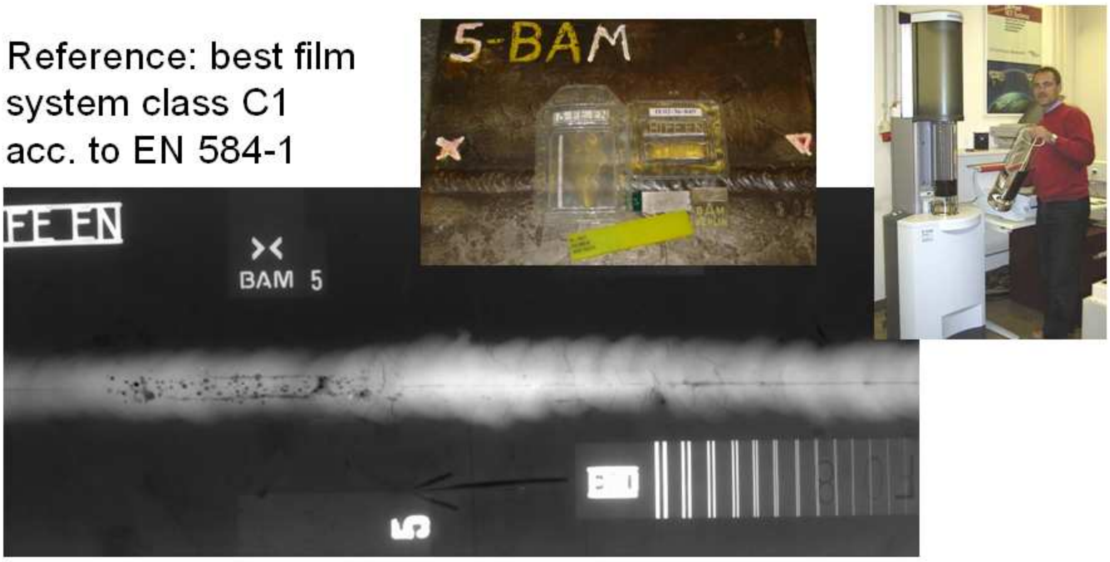
Film System Class				minimum Gradient to Noise Ratio at	normalized Signal to Noise Ratio	IP System Class	
World ISO 11699-1	Europe EN 584-1	USA ASTM E1815-01	Japan K7627-97	D=2 above D_0 G_2/σ_D	D=2 above D_0 SNR_{Norm}	Europe EN 14784-1	USA ASTM E2446-05
T1	C1	Special		300	130	IP-1	IP-Special
	C2		T1	270	117	IP-2	
T2	C3	I		180	78	IP-3	IP-I
	C4		T2	150	65	IP-4	
T3	C5	II	T3	120	52	IP-5	IP-II
T4	C6	III	T4	100	43	IP-6	IP-III
		W-A	W-A	135			
		W-B	W-B	110			
		W-C	W-C	80			

EN 14784-1: CR - Classification of Systems

CR Classification by
- SNR_{Norm} and
- Basic Spatial Resolution e.g.: IP-3/200

Fig. 3: Parameters for classification of NDT film systems and CR systems by the normalized SNR_{Norm}. Classes with different names in different standards still use the same limits.

Reference: best film system class C1 acc. to EN 584-1



parameters:
150kV, 5 mA, 2*0.027 Pb filter, 1000mm FDD, exposure time 330s [342mGy Dose],
digitized with 10µm pixel distance on Primescan 7100; aperture 21µm, averaged down to 50µm pixel size acc. to EN ISO 14096; 16 bit gray values, calibrated optical densities

Fig. 4: Reference for image quality comparison: Radiograph of BAM 5 test weldment taken with best film system class C1, digitized with a film digitizer with digitization class DS-10 according to EN ISO 14096.

2.3 Image Quality of Computed Radiography

The image quality of CR systems is classified in accordance with the NDT film system classes (see fig. 3). The limiting SNR_{Norm} values correspond to the limits of the similar film system class. Additionally to film classification, the basic spatial resolution of the CR system has to be provided (SR_b value in micrometer, for measurement see EN 14784-1). This considers the limited spatial resolution of CR systems in comparison to films.

The major development for applications of CR in NDT film replacement was the introduction of the High Definition CR last year (see fig.5). HD-CR paves the way for film replacement in weld and fine casting inspection.

The requirements on CR systems for industrial radiography are defined in EN 14784-1 and EN 14784-2. Table 4 of 14784-2 defines the minimum spatial resolution in dependence of testing class, radiation energy and wall thickness of the object under investigation. Whereas most of the contents of EN 14784-2 is similar to EN 444 (general principles for radiographic testing with NDT film), Table 4 in EN 14784-2 is new and limits the basic spatial resolution of the used CR system.

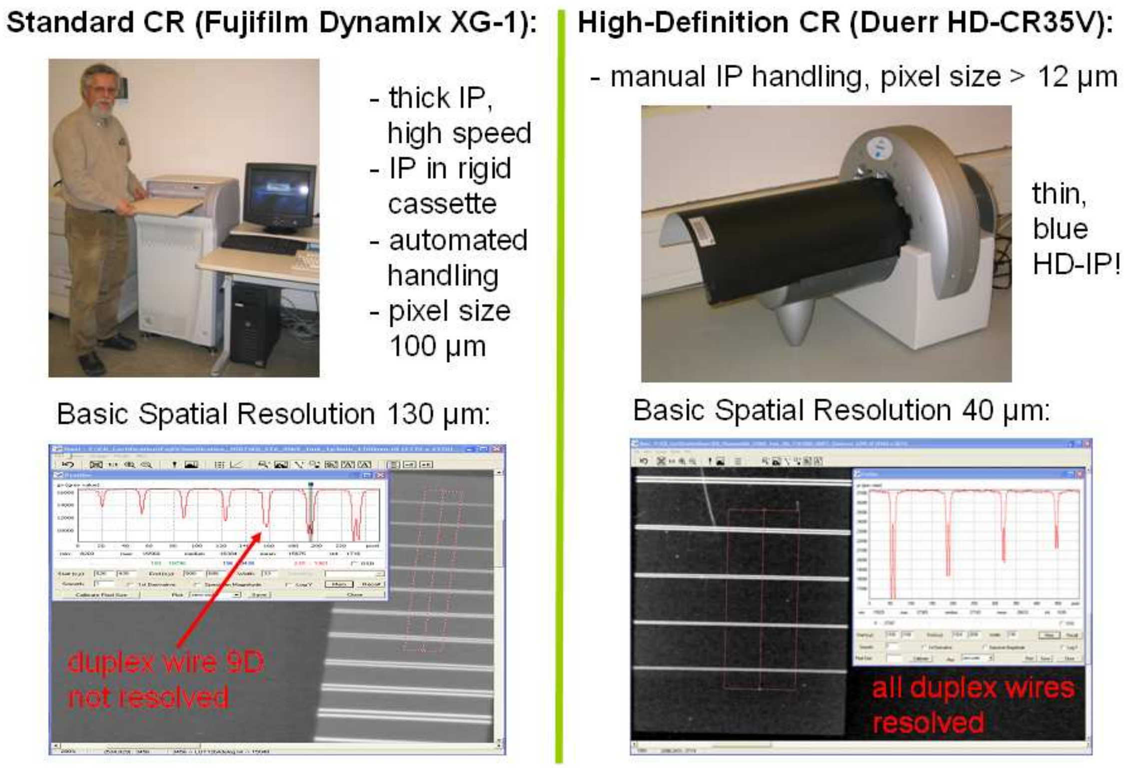


Fig. 5: Examples of CR systems and their measured basic spatial resolution:
Left side - DynamIx XG-1 of Fujifilm, SR_b=130µm as standard CR system with limited spatial resolution,
Right side - High-Definition system HD-CR 35V of Duerr, SR_b=40µm.

But there exist another limiting effect in the image quality for CR systems, which is shown in fig. 6. With increasing exposure dosage the maximum achievable SNR_{Norm} value is limited. This is caused by structure noise of the used imaging plate. Scanner effects may cause additional noise as e.g. line ripple. The structure noise of the IP is a side effect of production inhomogeneities of the phosphor layer. This effect is also known from fluorescent screens. At high exposure dosage the contribution of quantum noise of the X-rays is low compared to these image structures, and as result the image quality is finally limited.

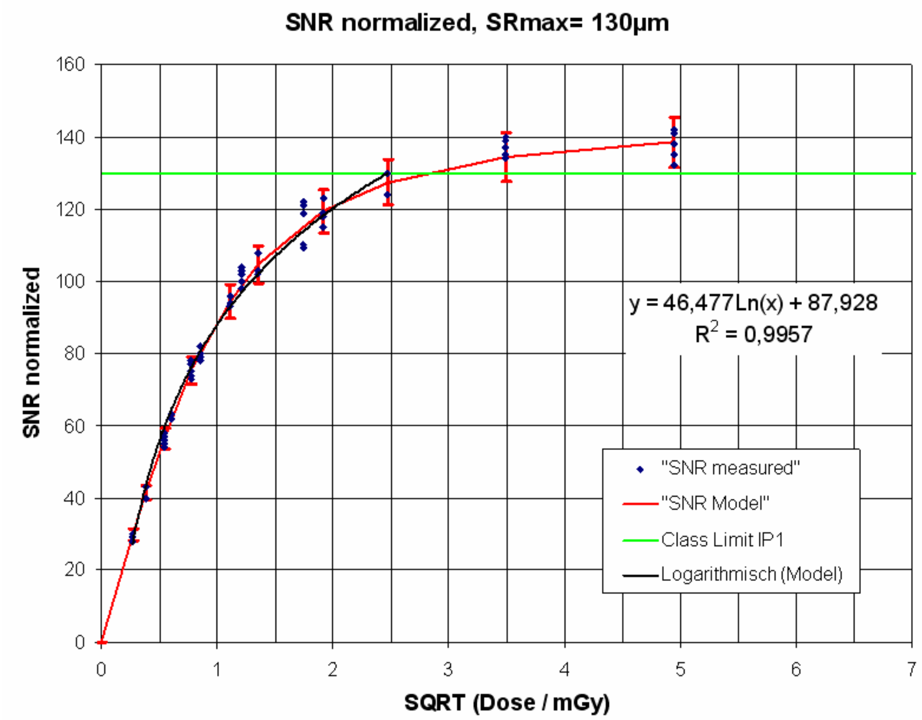


Fig. 6: Example of saturation of SNR_{Norm} by structure noise with the Fujifilm system XG-1 scanner and ST-VI imaging plate. The maximum achievable SNR_{Norm} value is 142.

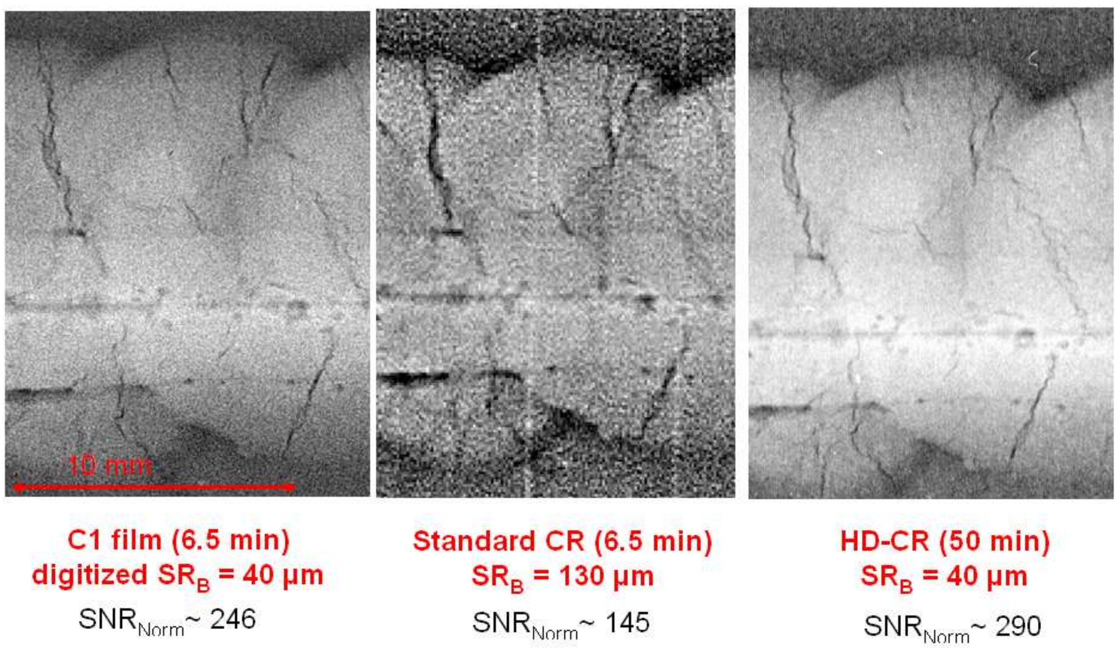


Fig. 7: Comparison of a section of the BAM 5 test weld obtained with the best NDT

film system class C1 (left), a standard CR system (middle) and a HD-CR system (right), for CR systems shown in fig. 5.

An example for achievable image quality at weld inspection is given in fig. 7. The exposure times are high enough, that the image noise is determined by the structure noise of these CR systems. Clearly it shows, that a standard CR system has a poorer image quality (both in SR_b and SNR_{Norm} values) compared with the best NDT film system, whereas the HD-CR system can reach a slightly higher SNR_{Norm} value compared with film, but with 8 times longer exposure time than film. According to EN 14784-2 the HD-CR system reaches testing class B. The standard CR does not achieve testing class A for this example since it is not designed for applications with a wall thickness below 12 mm and X-ray voltage below 250 kV corresponding to table 4 of EN 14784-2.

2.4 Comparison with Image Quality of Digital Detector Arrays (DDA)

The DDA images have been acquired using an XRD 1620 detector of the company Perkin Elmer, controlled by the software “Image.3500” of the company YXLON (see fig. 8 to 11). Two different acquisition set-ups have been used:

1. the weldment directly in front of the detector (magnification ≈ 1) and
2. the weldment in between detector and X-ray tube (magnification $= 3.5$).

The last set-up requires a mini focus X-ray tube to keep the geometrical unsharpness of this set-up below 200 µm at the detector.

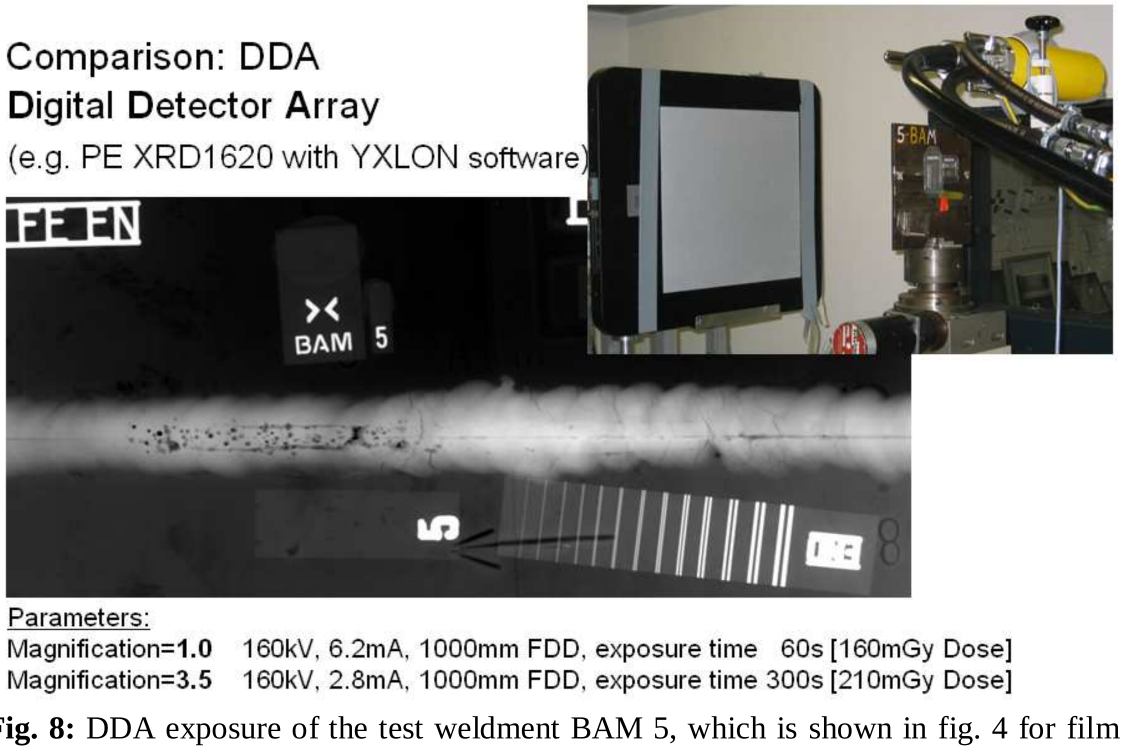


Fig. 8: DDA exposure of the test weldment BAM 5, which is shown in fig. 4 for film radiography. Two set-ups with different magnifications have been used.

Small flaw indications can be visualized clearly by usage of the high pass filtering and a numerically magnified image presentation (see fig. 9 and 10).
The significantly increased SNR_{Norm} of the DDA technology (measured in the base material) allows even at magnification of 1 and a basic spatial resolution of 200µm to detect crack indications, which are hidden by noise in the film image with its much higher SR_b of 50µm (see fig. 10, upper row). At a magnification of 3.5 (fig. 10, right image in upper row, projected SR_b = 70µm) much more details can be resolved with the DDA as compared to film. This increase of image quality based on SNR_{Norm} with DDAs is compared to film radiography.

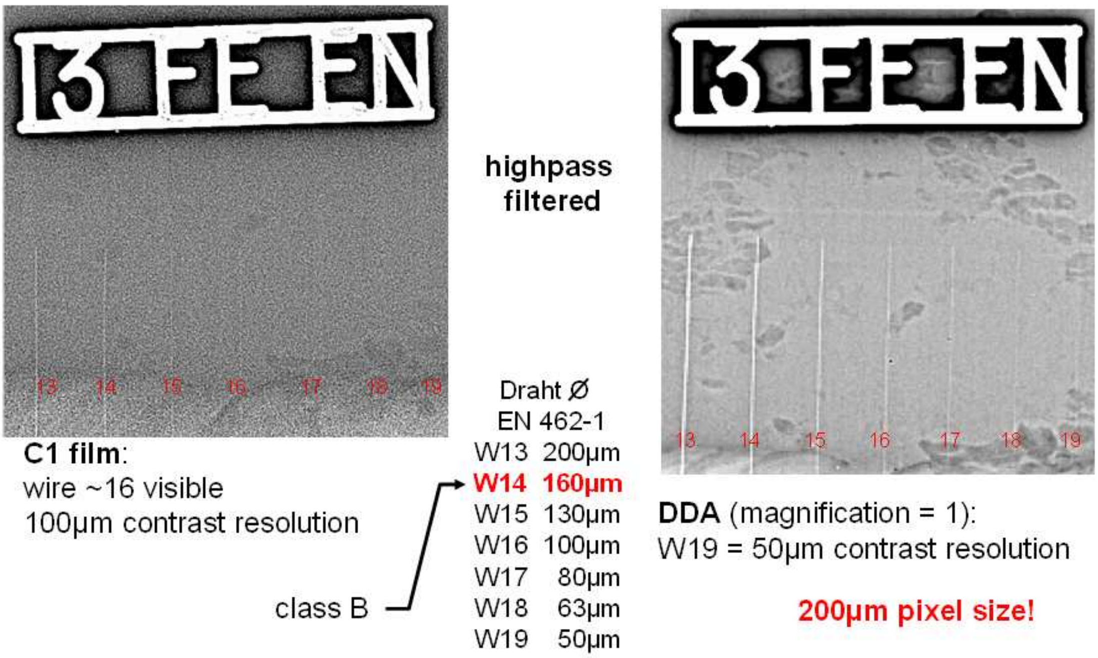


Fig. 9: Comparison of visibility of wire type IQIs according to EN 462-1 for film (left) and DDA (right) at 8mm wall thickness (images high pass filtered for better visualization). The improved SNR of the DDA allows to detect the wire W19 (50 µm diameter) at a pixel size of 200µm!

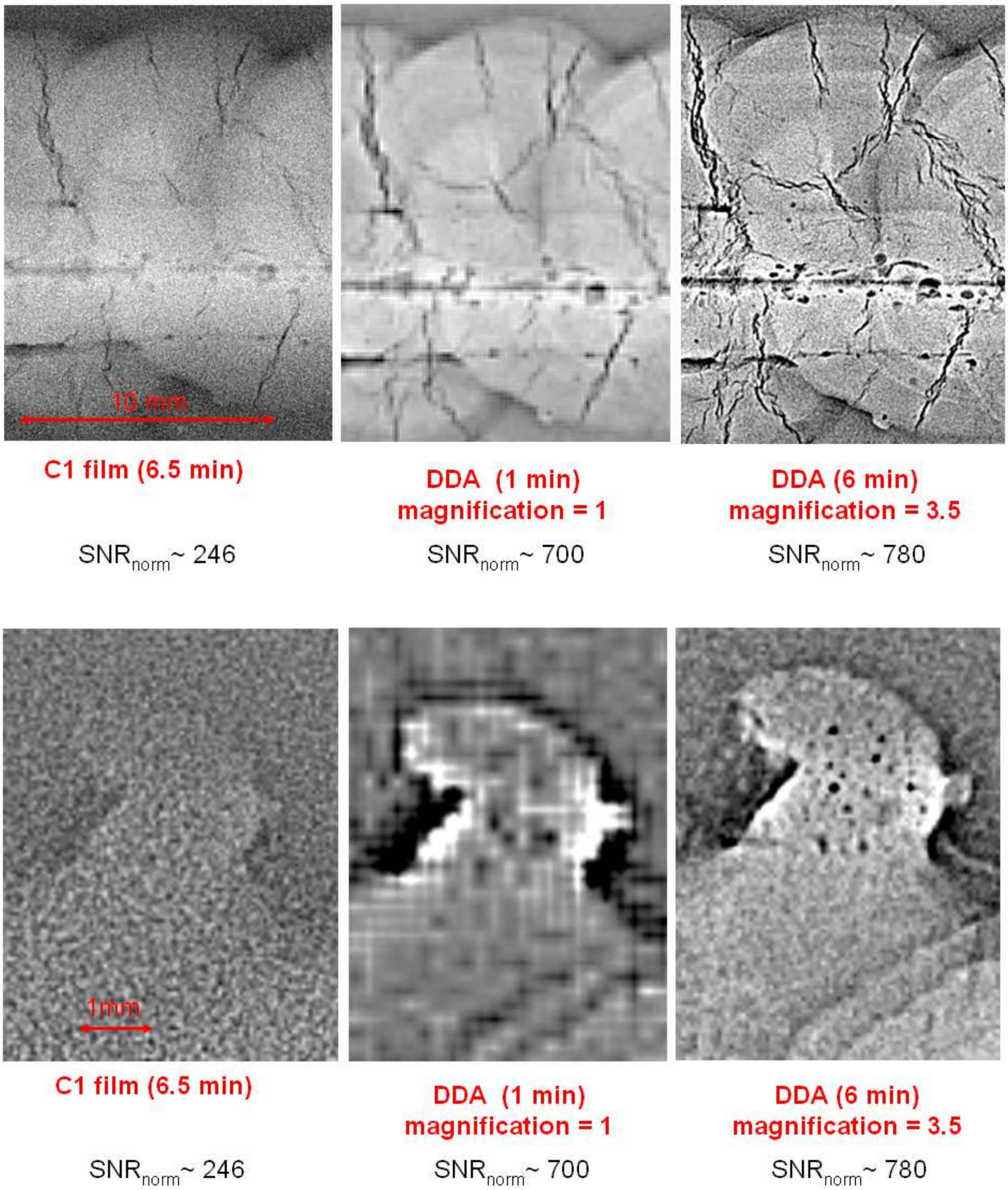


Fig. 10: Comparison of image quality with NDT film class C1 (left column) and DDA (middle column – no magnification, pixel size 200 µm) and DDA with magnification of 3.5 (right column).
Upper row: 12 mm wide region with crack indications, lower row: 5 mm wide region with micro porosity, which is not detectable with film!

2.5 Enhancement of Image Quality with Usage of DDA Systems

As shown in fig. 2, the maximum achievable SNR_{Norm} of the slowest NDT films available is limited basically by the restricted working range of the viewing stations to a maximum optical density of $D \approx 4.7$. This limits the maximum applicable exposure dosage too. Higher SNR_{Norm} values (higher than 250) will require higher exposure doses. But films cannot read above $D > 5$. In the case of CR systems, the image quality is limited by their structure noise (see fig. 6). The maximum SNR_{Norm} measured on a HD-CR system was below 300 up to now.

These SNR limitations with films and CR systems can be overcome with DDAs in the following way: just before saturation of the DDA an image can be read-out, the DDA is reseted and a new exposure cycle can be started. All images of such a cycle can be averaged in the computer generating an integrated image. So, the exposure time can be increased without any limit.

The SNR_{Norm} value will increase with the square root of the number of averaged read-out images and/or the dose. The exposure time of such a cycle can be extended without any technical limit. Fig. 11 shows the linear increase of SNR_{Norm} with the square root of the dosage (equivalent to the exposure time or number of integrated images). In this case the SNR_{Norm} values were calculated from the difference of 2 images taken under identical conditions [6] to exclude the influence of different sensitivities between single pixels of the DDA (internal structure noise).

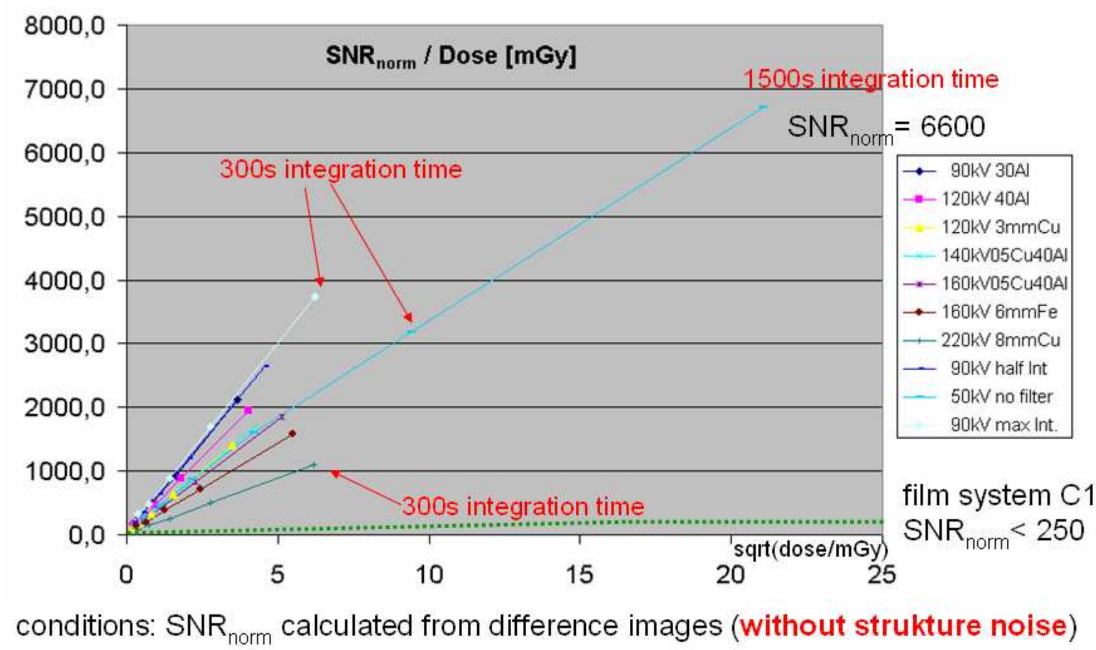


Fig. 11: Improvement of normalized SNR by image integration in the computer. Detector: DIC 100TL of company Ajat. The slopes of the lines characterise the detector efficiency at the selected radiation quality (energy).

The high SNR_{Norm} values as given in fig. 11 are usually not achieved for radiographic imaging purposes. Practical limitations exist: Deviations in the sensitivity of different pixels of the DDA limit the achievable SNR in an image. No further improvement of the SNR_{Norm} can be reached, if the Poisson noise of the X-ray quanta is reduced by long

integration times below these differential deviations between neighboured pixels. The SNR_{Norm} is limited by the structure noise of the detector. This is the same context as for CR.
DDAs have an essential advantage compared with film or CR:
The pixels of a DDA are arranged in a matrix and fixed during the complete exposure and read-out process. In this way small variances between each pixel (e.g. in sensitivity or offset deviations in the read-out channels) are tolerable and can be measured exactly. Because they are typically stable over time, a compensation of the deviations between the different pixels can be compensated by suitable software. This procedure is called detector calibration.

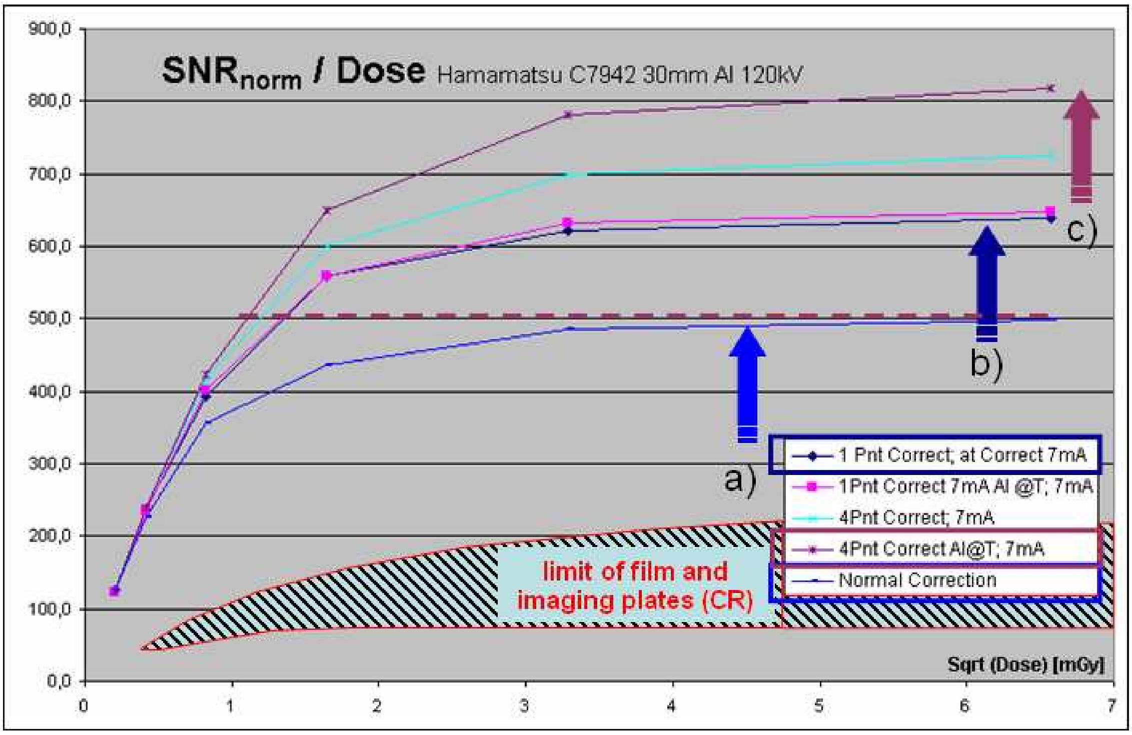


Fig. 12: Achievable SNR_{Norm} with different detector calibrations. Detector: Hamamatsu C7942, exposures with 120 kV, 7mA and 30mm Aluminium.

This DDA calibration is the key to an improved contrast sensitivity (high contrast sensitivity mode) and high SNR because of the reduction of the structural noise of the DDA. Compared to a “standard calibration” with single offset and gain images (fig. 12 a and b) an adapted multi gain correction can produce a much higher SNR compensating the variations of the individual detector pixels (see fig. 12c). In this way the SNR limitations for film and CR can be overcome by a good calibrated DDA system as shown in fig. 12.
The advantage of the adapted multi gain calibration is not only the higher SNR, it also saves exposure time. The required image quality defines the necessary integration time. Compared to a single point calibration optimal exposure conditions based on an adapted multi gain calibration provides the same SNR in a much shorter time frame (fig. 12c). If an application requires a SNR of 500, it will take 250s with a single gain calibration; with an adapted Multi Gain calibration it needs 15s (lower dosage in fig. 12) only.

In contrast to fig. 11 the SNR_{Norm} values of fig.12 are limited; all curves approache a saturation value for SNR_{Norm}. The reason for this effect was investigated and found, that either the structure noise of the detector calibration or the inhomogeneities of the material of the object limits the maximum SNR_{Norm} value in the acquired images.
The same reasons limit the visible material difference in % wall thickness for Aluminium und Steel as shown in fig. 13 and 14. This contrast sensitivity is limited at 0.1%, which corresponds to a SNR_{Norm}.of about 1000. An extension of the exposure time from 60s to 600s improves it only slightly. DDAs allow NDT with much higher contrast sensitivity (means lower % values) than required for film radiography. Fig. 14 shows the comparison of the required wall thickness perception of step hole IQIs (EN 462-2) as required by EN 462-3 in comparison to the values achieved with DDAs.

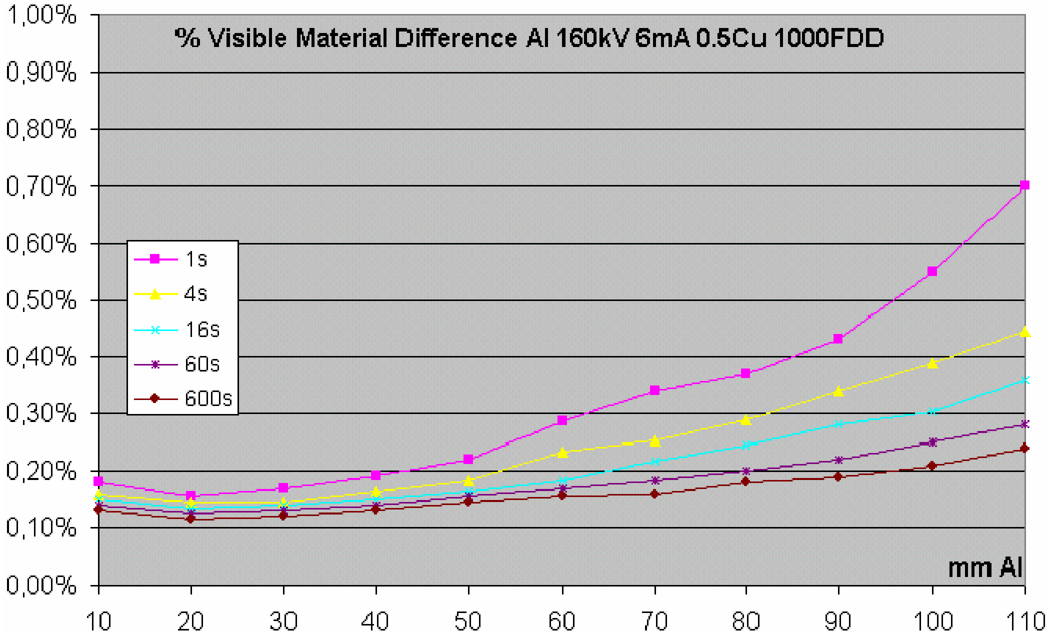


Fig. 13: Visible material difference (%) in Al from 10mm to 110mm wall thickness and different integration times. Detector: RID512 AF1 of Perkin Elmer. A similar contrast resolution can be achieved with steel too (see fig. 14).

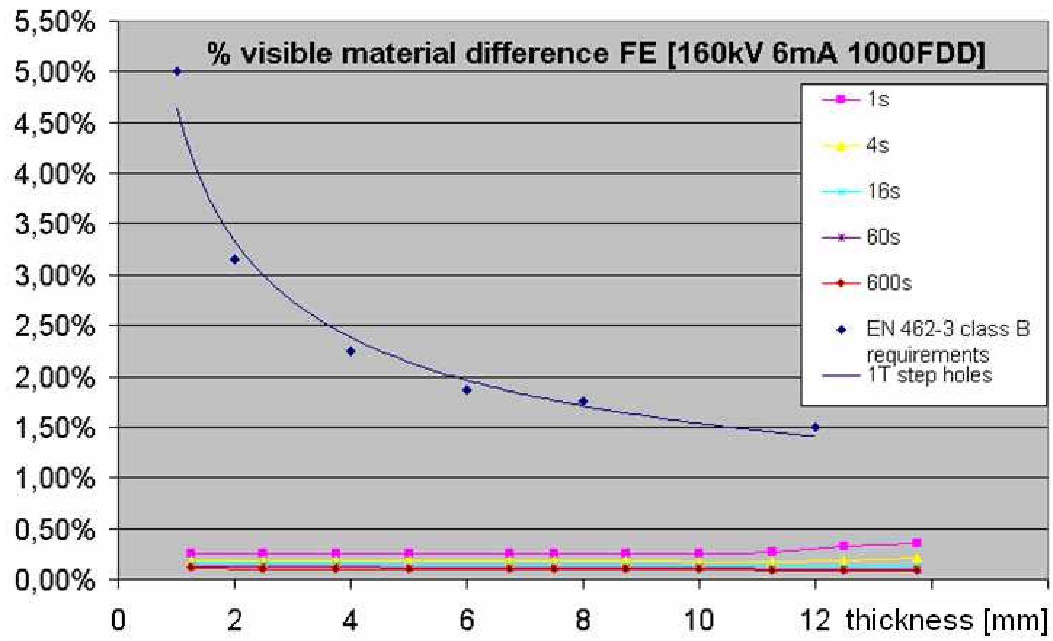
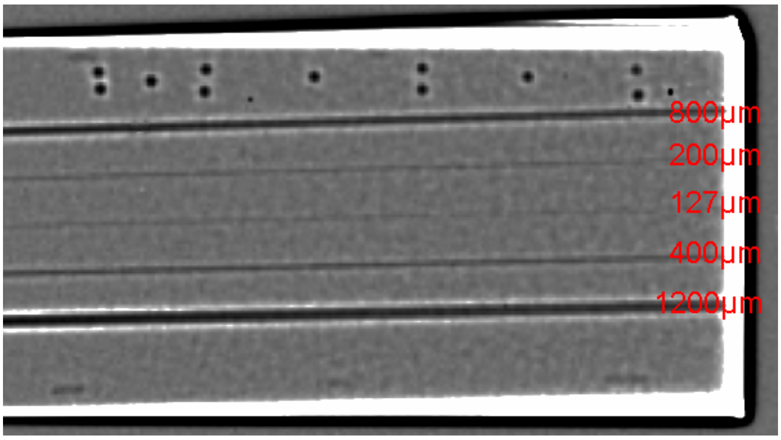
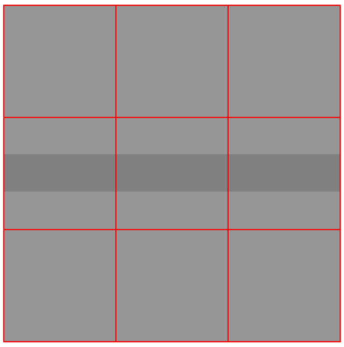


Fig. 14: Visibility limits of 1T step hole IQI of EN 462-2 acc. to the requirements of EN 462-3, testing class B for film radiography and visible material difference for 1mm – 13mm steel (V4A) and different integration times for DDA (RID512AF1 by Perkin Elmer).

2.6 Compensation of insufficient SR_B by high SNR

With a high SNR even very small differences in contrast are detectable. The visibility of details depends on the contrast and the SNR. Fig. 15 shows an image captured with a detector with a SR_B of 320µm – showing even a cross-bore hole which is only 127µm in diameter. Due to the high SNR it can be clearly detected.





The object covers 1/3 of the pixels only.

Fig. 15: Digital radiograph of a test wedge (5mm to 40mm Aluminium) with longitudinal drilled cross-bore holes of different diameters. With high SNR even details smaller than 1 Pixel are visible (shown image: high pass filtered). This effect is called sub-pixel resolution.

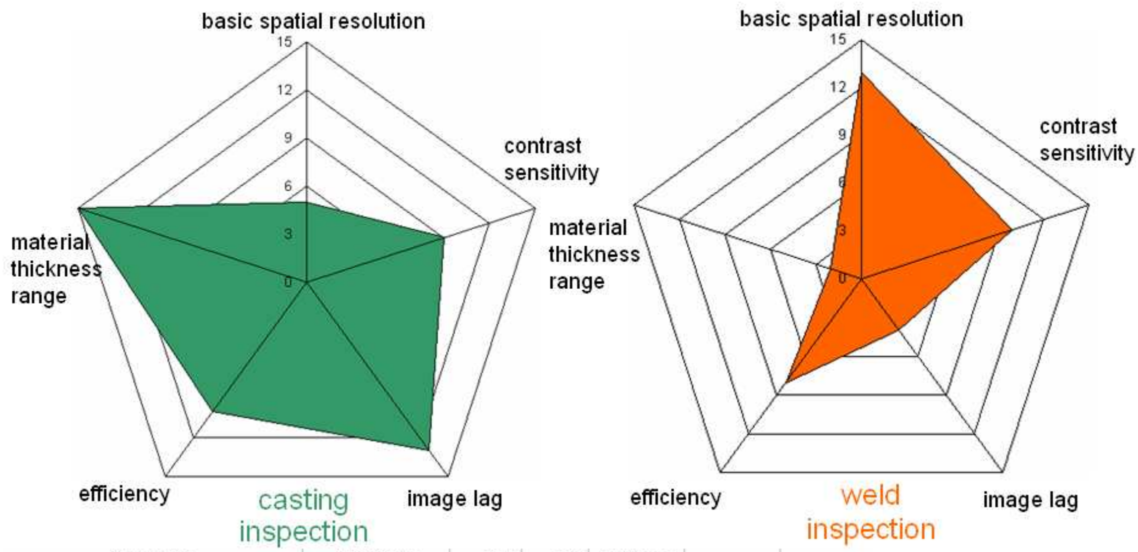
In high SNR images it is sufficient that only a part of the pixel area “sees” the information. In figure 15 just a third of the detector area of a pixel is covered by the cross-bore hole still giving a third of the signal contrast of the line. With a SNR of 900 the required contrast sensitivity of $1/300^{th}$ (~0.3%) can be obtained (hole of 0,127 mm at 40 mm wall thickness).

3. Status of Standardization

For NDT Film digitization (EN ISO 14096 part 1 and 2) and Computed Radiography (EN 14784 part 1 and 2) exist already European standards for system characterisation, classification and practice (application). ASTM E 1936 is a standard for performance evaluation of film digitization systems and for CR is a series of ASTM standards available (E 2446 classification of CR systems, E 2445 long term stability, E 2007 guide, E 2033 practice).

ASTM International is the leading organization in developing standard drafts for digital detector arrays driven by the aircraft industry. With active participation of the authors 4 standard drafts are under development for DDAs:

- DDA guide describing the different technologies of digital detectors,
- DDA qualification, the manufacturer specification for detector qualification and presentation of results (see fig. 16),
- DDA user qualification, the specification of user acceptance tests and how to handle repairs and tests for long term stability,
- DDA practice, the description of good workmanship with DDAs (especially for users interested into film replacement)



Parameter	Aluminium		high	low	Parameter
BSR (basic spatial resolution)	5	285	32	1000	90kV no filter
CS (contrast sensitivity)	9	0,39	0,1	3,2	Al, 160kV, 16s, (% Σ 10 to 100mm)/10)
Image Lag	13	1,52	1	32	1st frame, normalized to [1s]
Efficiency = SNR @ 1mGy	10	746	1000	250	@120kV, 40mmAl 1mGy
Specific Material Thickness Range	15	100	100	30	Al, 160kV, 16s, SNR>130

Fig. 16: Presentation of results of the ASTM draft on “DDA manufacturing qualification”, left: DDA optimized for inspection of castings, right: DDA for weld inspection

The DGZfP committee on Radiology initiated to draft standard versions for CEN after finalization of the drafts at ASTM.

4. Conclusions

New digital systems adapted to NDT requirements are suitable for NDT film replacement. Since the requirements for film radiography for medical and NDT applications are different, standardized algorithms are necessary to measure the image quality for NDT.
The properties of NDT film systems are described in different standards. The basic parameters for digitised films and digital radiologic detectors are the normalized SNR_{Norm} and the basic spatial resolution SR_B. SNR_{Norm} limits for classification can be found in several standards.
NDT film systems are limited in the achievable image quality caused by the available film systems at the market and the upper optical density (about D = 5) which can be read with film viewers. This limits finally the maximum dose for an exposure. Computed Radiography can be used for film replacement. The maximum achievable SNR_{Norm} is basically limited by the structure noise of the used imaging plates.
An essential improvement in image quality of DDA systems compared to film and CR systems is possible with an optimal detector calibration procedure (multi-gain). DDAs can exceed the contrast sensitivity and SNR_{Norm} of film systems by the factor of 10 or even more. The very high SNR gives a superior contrast sensitivity (especially using magnification technique). Depending on the exposure conditions and a proper calibration, DDA systems achieve a contrast sensitivity of about 1/1000th of the wall thickness.
Nowadays, the upper limit of image quality is determined by inhomogeneities in the material of the inspected part and no longer more by the detection technique. High contrast sensitivity can compensate an insufficient SR_B. With a high contrast sensitivity mode fine details below the size of one detector pixel provide enough CNR to become visible.
Adapted high pass filters can even increase the visibility of inhomogeneities. IQIs should be applied to prove the expected material contrast sensitivity. DDAs are mostly suitable for in-house inspections, because they need stabile temperature and moisture conditions as well as careful handling. They are an excellent tool for serial part inspection and Computed Tomography and also for laboratory inspections. Due to its high image quality, dynamic range and speed they dominate stationary applications and speed up film replacement.

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