Image Quality Assessment of CR Systems

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Abstract: Computed Radiography exposure experiments on welded plate sections were performed to demonstrate that the requirements for pressure vessels weld inspection according to EN1435 or EN14784-2 class B can be achieved. The representative comparative studies of the image qualities were performed with standardized image quality indicators and image evaluation procedures on both film and digital radiographs. Recommendations for weld inspections with CR systems are drawn from the results. It is demonstrated that present CR systems can be used for weld inspection and produce images with testing class B if the selected X-ray tube voltage is reduced compared with the max. voltage of EN 14784-2 and set equivalent to maximum X-ray voltage values for steel as defined in the radioscopic standard EN 13068-3. The work was part of the European "Filmfree" Project promoted during the 6'th framework.

Key words: Film, digital radiography, computed radiography, image quality

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1. Introduction

Computed Radiography (CR) is a modern technology which produces a digital radiograph by means of imaging plates instead of X-ray films. Generally, digital images offer the option of image modification by applying image processing on the personal computer. The ability of the online manipulation and evaluation of the digital radiographs on the computer for easier viewing made CR attractive and effective for its use in Digital Industrial Radiography. The first commercial application for the CR systems started in medical radiography around 1980. First experiments on industrial objects resulted in unsatisfied results in case medical CR systems were used. The existing different requirements compared with medicine which are related to the respective specific industrial application could not be covered by an unique constructed CR system. A development of industrial CR systems was initiated afterwards to cover the requirements for a reliable welding inspection in DIR. The technical development process was accompanied by the preparation of different European and American standards such us EN 14784-1, EN 14784-2, ASTM E 2007, E 2033, E 2445 and E 2446. The standards ensure the preparation of digital radiographs with a sufficient image quality, the application of reliable image evaluation techniques and the safe and proper usage of the CR equipment during the industrial inspection in the field and laboratory.

On a first approach, CR systems offer a high potential of efficiency and are considered to be less expensive than classical radiographic films. There is no need for chemicals and the effort on consumptions can be reduced dramatically. The inspection- and evaluation time of the digital radiograph is reduced by shorter exposure time, fast archiving and handling of the digital radiograph on the computer, its online display on the monitor and the option for image analysis, image enhancement and flaw detection assistance. To bear in mind, storing and archiving of the digital radiograph on the computer is very easy. The embedding of the digital radiograph in to the reports or its distribution via internet to other experts is habituated nowadays. Both, the object size and the exposure level range of present CR systems are larger than in radiographic films and offer new application fields such as the radiographic inspection of aluminothermic rail weld sections in combination with mobile X-ray tubes to name but a few.

The replacement of conventional lead screen-film systems is expected to speed up in the next future if modern CR systems can manage the production of digital radiographs with image qualities similar or even better than that of film image on the light box. The paper reports first on the radiographic inspection of welded joints according to EN 1435 by using a conventional C3 class radiographic film and two different CR systems. In a second step, X-ray exposure experiments on the welded plates were continued to demonstrate image quality differences and to verify that requirements for pressure vessels weld inspection according to class B can be achieved by both film and CR radiography. The influence of different exposure parameters on the image quality was evaluated in detail on the base of image quality indicators and image evaluation procedures. Further on, recommendations for CR inspections on welds will be given on the base of the summarized results.

2. Experimental: Radiographic Inspection on welded plates

Procedural guidance for the radiography examination is provided by two European Standards, the EN 1435 (Non-destructive testing of welds - radiographic testing of welded joints) and EN 14784-2 (Non-destructive testing – Industrial computed radiography with storage phosphor imaging plates). The configuration and operating parameters for the radiography were determined by the penetrated wall thickness of steel and the focal spot size (acc. to EN 12543-2) of the X-ray tube. Table 1 represents the test specimen used for the experiments. The test samples are described regarding to their basic properties such us material thickness, reinforcement, welding joint type. The last column in the Table 1 contains information about wire IQI used to prove the minimum quality values (in brackets) according to image class B. The film system, the imaging plate system selection as well as the source to object distances were adjusted according to the requirements of testing class B (improved technique). The exposure quantities were set first according to the class B requirements of the EN 1435 standard. All exposure experiments were performed with an X-ray tube having a spot size of 2.8 mm. A film-focus-distance of 800 mm was initially applied the main cases. The tube energy was selected according to the permitted highest X-ray voltage which is specified in the EN 1435 as function of the penetrated wall thickness. The film exposure experiments were performed with an Agfa D4 film (system class C3) in combination of 0.025 mm front and back screen of lead has been used. The films were machine developed with an Agfa Eco Dev developer and Agfa fix fixer in a 5 min cycle. All film radiographs had an optical density of $D \geq 2.3$ in the weld area. The film radiographs served as reference exposures for the image validation produced by CR. Single wire IQIs in accordance to EN 462-1 and duplex wire IQIs according to EN 462-5 were primary used as quality indicators to verify and to evaluate the image quality of both the digital images and film radiographs.

A representative image of a film radiograph digitised with the film laser scanner Array 2905 HD that is operating with a pixel size of 50 µm and a digital resolution of 12 bit (DB-9 scanner according to ISO EN 14096) is shown in Figure 1. The image in Figure 1 represents the characteristic assembling of the different IQ'Is. The wire type and flat hole type IQI's are located on the basic material for proving the minimum quality numbers according to following standards EN 1435 ASME (Section V Article 2) and ASTM E 1032 respectively. This article will continue the report only on the results for the single wire IQI's.

Table 1: Description of the sample and exposure conditions and arrangement

sample	Thickness [mm]		Material	Welding joint type	IQI and required wire number
	basic material	Basic material & reinforcement			EN 462-1 EN 1435 class B
T3	12	17,2	stainless steel	V-butt weld	10 FeEN (W14)
T4	12	16	steel	V-butt weld	10 FeEN (W14)
T5	9,2	14,5	steel	double V butt w.	10 FeEN (W14)
T6	12,6	18	steel	double V butt w.	10 FeEN (W13)
T7	15,3	21,5	steel	double V butt w.	10 FeEN (W13)
T8	3	6	stainless steel	V-butt weld	10 FeEN (W17)
T9	5,1	9,2	stainless steel	double V butt w.	10 FeEN (W16)
T10	9,7	14,5	stainless steel	double V butt w.	10 FeEN (W14)
T11	13,3	19	stainless steel	double V butt w.	10 FeEN (W13)

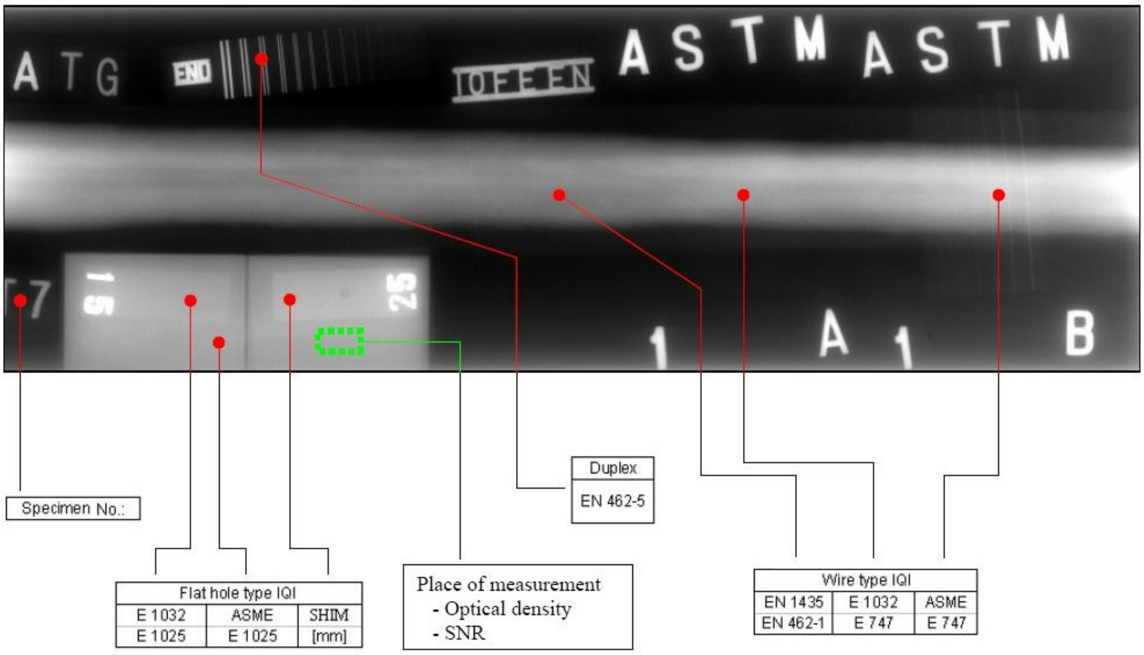

Figure 1: *Radiograph of a test sample T7. The top of the sample was configured with single wire IQI (EN 462-1) duplex wire IQI (EN 462) and flat hole type IQI's (ASME (Section V Article 2) and ASTM E 1032) for image quality assessment.*

3. HD-CR Digital Imaging System

Computed Radiography uses phosphor plates, works via a three-step process and uses X-ray equipment similar to a film. First, the imaging plate with the storage phosphor is used to detect the penetrating X-ray dose. The phosphors on the plate layer produces activated centres during the exposure which are retained. A latent image is formed by this way. Than in a second step, a red laser inside the plate reader scans the layer and pumps photo-stimulated luminescence with an intensity directly proportional to the detected radiation dose. The local allocated blue luminescence of the latent image is detected by a photomultiplier, converted in to a digital signal and subsequently fed in to a digital data file stored on the computer. Usually the after the scan the digital radiograph appears instantly on a computer monitor for interpretation. The plate is completely erased by read or white light in a third step for its reuse for next experiments.

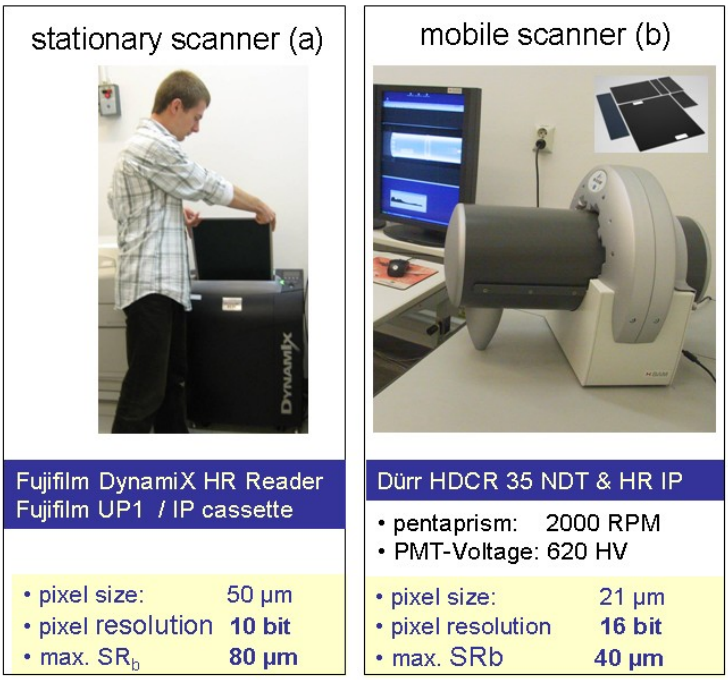

Figure 2: *Photograph of a stationary DynamiX HR (left) and mobile (right) imaging plate scanner system used for the studies. The scanners can be characterized by technical parameters such as pixel size, maximum basic spatial resolution (SR_b) and pixel gray value range.*

Duerr HD-CR 35 NDT scanners in combination with a HD imaging plate (IP) as well as a FUJIFILM DynamIx HR system operating with an UR-1 imaging plate were used for the further comparative studies. Both reader systems can be remote controlled by a customary personal computer via Ethernet or USB connection respectively. The BAM Isee! Image viewer software was used to visualize the digital radiograph previously stored on the computer [1]. The software also assists the operator for image quality evaluation, weld discontinuities assessments as well as image enhancements. A LUT for linearization was applied on the raw image of the FUJIFILM DynamIx HR system because it does not directly provide the data according to a linear gray value - dose - correlation. This is needed for the IP class assignment of the digital radiograph which is based on the measurement of the normalized signal to noise ratios. The normalized SNR (SNR_N) is needed for the further IP classification of the radiograph quality because it defines for the appropriate CR system the minimum exposure conditions which have to be applied for the desired testing class. The system unsharpness which is equivalent to the double of the basic spatial resolution (BSR) is required for the SNR_N calculation. That is why initially duplex wire IQI's (EN 462-5) exposure experiments on both scanners were performed. The duplex wires IQI measure the total image unsharpness and provide the basic spatial resolution (BSR) values of the applied CR scanner - imaging plat - combinations. The Signal to Noise Ratio (SNR) can be measured in the selected Region of Interest (ROI) on the digitized radiographs. Figure 2 shows the photographs of the two different scanners used for the comparative studies.

The Figure 2 also lists the specific technical parameters which are unique for each scanner and must be used for the further experiments.

The CR standard EN 14748-2 requires for the test of metallic objects with X-rays and storage phosphor plates a minimum SNR_N for a sufficient image quality. Initially it was agreed that the digital images must present a minimum $SNR_N = 130$ in a previously defined ROI. The ROI was located in all experiments in the basic material at the vicinity of the weld of the appropriated test sample. The adjusted arrangements are conform to the system class 1 requirements of EN 14748-2. The maximally allowed X-ray tube voltage is defined in the standard EN 14748-2 in dependence of the exposed material and its thickness. The maximum allowed X-ray tube voltage is identical to the values defined in EN 1435. In concern of X-ray voltages similar values could be selected for both radiographic film and imaging plate exposure experiments. Figure 3 shows a representative example of the digital radiograph of sample T7. The operator can use specially designed tools for the objective

image analysis of the digital radiograph. The statistic and evaluation tools are offered by the Isee! Software.
The SNR_N inside the region of interest, the unsharpness and the wire IQI number can be directly acquired by the analysis of the raw data on the computer screen. The application of additional mathematic filters on the image can additionally improve the detail recognition on the digital radiograph (Figure 3).

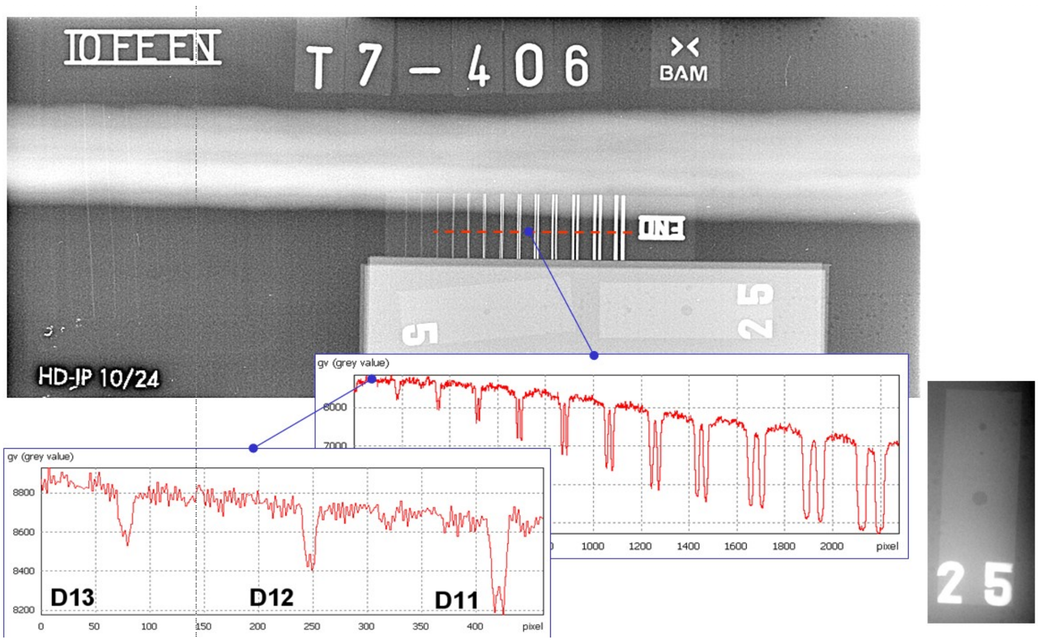

Figure 3: *High pass filtered imaging plate radiograph of test specimen T7. The line profile on the unfiltered image of the duplex IQI access the unsharpness of the radiograph (D13 not resolved with 20%, therefore basic spatial resolution 50 µm). The Isee! Software tools help the operator to submit the Signal to Noise Ratio (SNR) and the wire IQI number of the digital image on the computer.*

Table 2 summarizes the experimental measurement set-ups which mainly differ from each other in relation to the selected voltage of the X-ray tube (radiation quality) and the scanner - imaging plate combinations. The listed exposure times are related to dose exposed on the detector at a distance of 1000 mm from the X-ray focus. The detectable maximal IQI wire number, the SNR_N and the optical density were gathered from the different radiographs to study the influence of the X-ray tube radiation and the imaging plate - scanner combination on the image quality. The detailed description of the single tests series is given in Table 2.

Table 2: Exposure conditions for the different sets of measurements run to provoke image quality changes

SET-ID	**FILM**		**CRDUERR1**		**CRDUERR2**		**CRDUERR3**		**CRDUERR4**		**CRFUJIFILM**	
Detector	**AGFA D4 (C3)**		**HD-CR 35 NDT & HD-IP**		**HD-CR 35 NDT & HD-IP**		**HDCR 35 NDT & UR-1 IP**		**HDCR 35 NDT & HD-IP**		**DynamIx HR & UR-1 IP**	
Probe	U [kV]	B [*]	U [kV]	B [*]	U [kV]	B [*]	U [kV]	B [*]	U [kV]	B [*]	U [kV]	B [*]
T3	200	24,90	195	31,25	160	31,25	160	31,69	145	31,69	160	31,69
T4	195	27,16	195	31,25	170	31,25	170	31,69			170	31,69
T5	180	29,43	190	29,69	160	29,69	160	28,52			160	28,52
T6	200	31,69	210	32,81	190	32,81	190	31,69			190	31,69
T7	220	29,43	225	35,94	195	35,94	195	34,86	155	34,86	195	34,86
T8	130	22,63	130	18,75	100	18,75	100	22,63	80	40,74	100	22,63
T9	160	20,37	155	18,75	125	18,75	125	19,01			125	19,01
T10	180	31,69	190	31,25	160	31,25	160	31,69	130	31,69	160	31,69
T11	205	36,22	215	32,81	185	32,81	185	31,69			185	31,69

* - exposure [mAmin] at a Focus-Detector-Distance = 1000 mm

The results of the different exposures are collected and summarized on three different diagrams on Figure 4. In each graph, the sample with the thinnest penetrated wall thickness is located on the left side of the abscissa the thickest on the right. The ordinates present from above to below the radiation quality (voltage of the X-ray tube), SNR_N und the recognized wire IQI number. The limits for the maximum X-ray voltage, for the IP class and IQI wire number according to the image quality class A and B are also drawn in the different graphs on Figure 4a, 4b, and 4c as a function of penetrated wall thickness of the test samples.

4. Results

Figure 4c points out the influence of the X-ray tube voltage and the selected scanner-image plate combination on the visibility of wire IQI's on the different radiographs The produced film radiographs had an optical density of D > 2.3 in the ROI. The visibility of the wires is in compliance with the image quality class B for each sample. The HD-CR 35 NDT scanner in combination with a HD-IP imaging plate was first used for the repetition of the film exposure experiments. The series of measurement CRDUERR1 was expected to show results similar to the observed of the radiographic film. Remarkable, except for the thinner test samples the image quality class B could not be hold anymore, although the SNR_N was twice higher than the required IP class level for IP_1 (Figure 4b). The IQI wire numbers on the digital radiographs at thicker samples are between two- and three wire numbers lower in comparison to the IQI numbers detected on the films. The requirements of image class B were not fulfilled with CRDUERR 1 above 12 mm wall thickness. The previous experiment was repeated (CRDUERR2) with similar experimental set-ups but with a lower X-ray tube energy. The X-ray tube voltage was dropped between 10% and 20% for contrast improvements. It results in to a gain of single wires numbers for CR, but the images still tend to show lower IQI values at thicker material than observed at the radiographic film. Nevertheless, with the exception of sample T4, the image class B could already be reached. Two additional series of measurements CRDUERR3 and CRFUJIFILM were added to the experiments. The measurements exhibit similar exposure conditions as the CRDUERR2 series but different selected scanner IP combination had been used. In the CRDUERR3 series the imaging plate HD-IP was exchanged with UR-1. The SNR_N increased between 20% and 60% by this way. The changeovers to UR-1 (CRDUERR3 and CRFUJIFILM) provoked a dramatic enhancement of the wire IQI numbers. The digital radiographs of the last two measurement sets offered an IQI wire image quality equal or even better than that observed on the film radiographs. The CRFUJIFILM (DynamIx HR scanner with UR1-plate) set features a drop of the SNR_N values of 50% to 70% in relation to the CRDUERR3 series (DUERR Scanner with UR-1 plate). Partially the allowed IP class limits were underlined (Figure 4b). Additional, the X-ray tube voltage was again reduced up 20 % of the values set in the measurement set CRDUERR2.

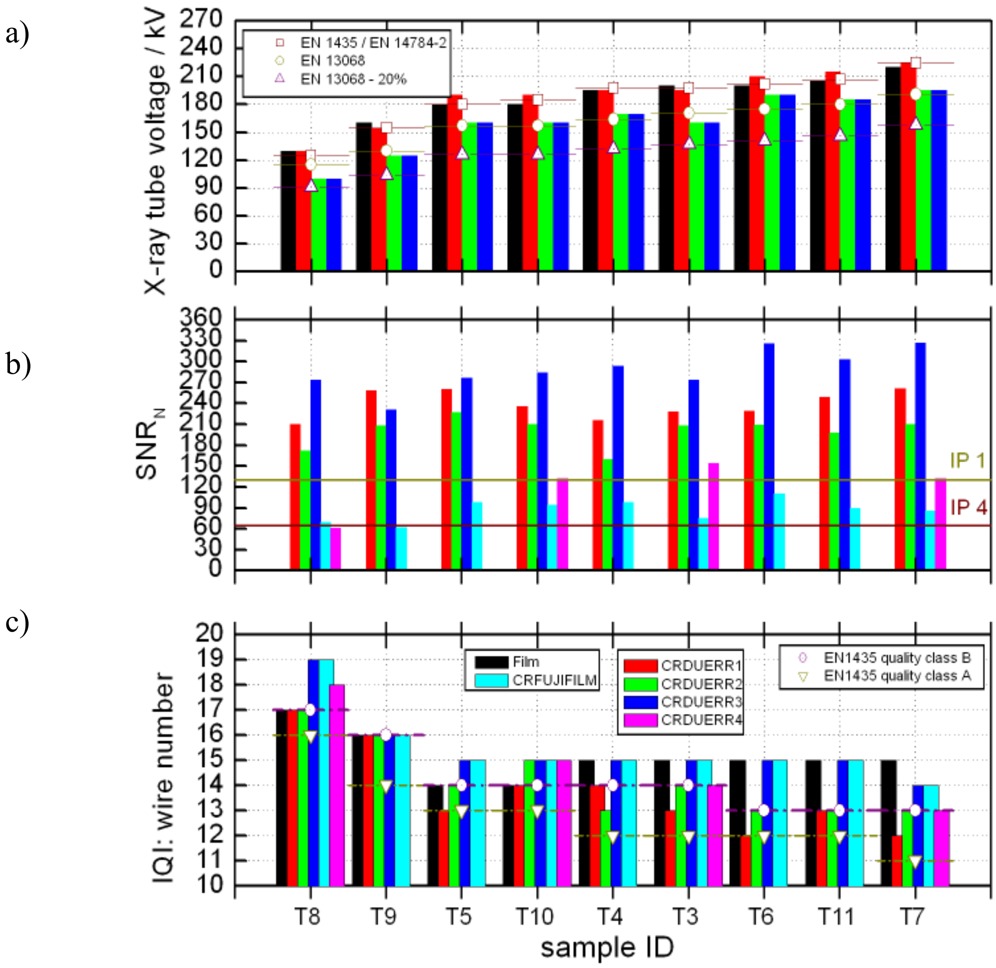

Figure 4: *Influence of selected X-ray tube voltage (a) and IP – Scanner-Combination on image quality expressed by (a) measured SNR_N (b) and image quality wire number (c). The test samples are arranged on the abscissa from left to right with growing basic material thickness. The exposure conditions and further details are listed on Table 2.*

A further increase of the IQI wire numbers (CRDUERR4) could be observed in comparison to the measurement set CRDUERR2. The wire IQI numbers fulfilled reliable the requirements of image quality class B by this way but could not reach the wire visibility as observed on digital radiographs produced with the DUERR HDCR 35 NDT / UR-1 plate combination (CRDUERR3). Similar to the CRFUJIFILM measurement set, the required IP class was partially underlined (Figure 4b). The exposure time would have to be extended to overcome the SNR_N lines, what indicates an undesirable lost of efficiency in practice.

5. Discussion and Conclusions

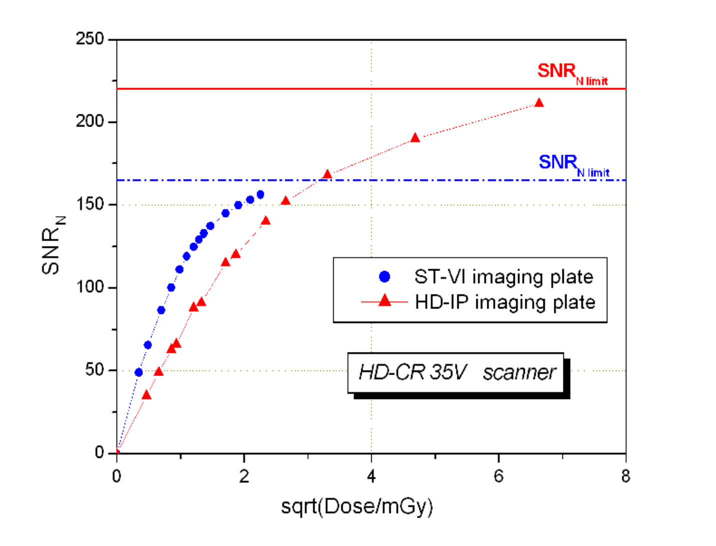

Figure 5: *Example of saturation of SNR_N by IP structure noise with a HD-CR 35 NDT scanner in combination with ST-VI and HD-IP imaging plate respectively. The maximum achievable SNR_N (saturation) value for ST VI is 165 and 240 for HD-IP.*

The SNR is considered to be a operator controlled value comparable to the optical density for films. The European Standard EN 14784-2 issues SNR_N limits for the Region of Interest (ROI) of a digital radiograph. The SNR_N limit requires a correct selection of the exposure conditions such as Detector-Source-Distance, operating X-ray tube current and exposure time for the particular CR system. The selected scanner - imaging plate combination effect the Basic Spatial Resolution (SR_b) and the detector sensitivity, which is described as the grey value difference per dose difference.. A representative example for the SNR_N value changes could be observed if the UR1 imaging plate was combined once with the DUERR HDCR 35 NDT scanner and another time with the DynamIx HR scanner. Whereas the IQI sensitivity of both combinations are identically, the SNR_N values in the images of DUERR HDCR 35 NDT are double than those in the much faster scanning DynamIx HR scanner.

Previous systematic investigation on CR systems could demonstrate a limiting effect in the image quality of CR systems [2]. As shown in Figure 5, the SNR_N increases initially and reaches a maximum achievable value with higher exposure dosages. The limit is caused by scanner effects such us e.g. line ripple and structure noise of the IP originated from production inhomogeneities of the phosphor layer. At higher exposure dosage the quantum noise of the X-rays is reduced such strong that the scanner – IP system fluctuations limit the maximum achievable SNR of CR systems. These maximum limits are CR system specific and can not overcome by longer exposure times. The wire IQI number defines the image quality of a digital image for both a digital image and a radiographic film. The perception of a particular IQI wire number implies a minimal specific Contrast to Noise Ratio (CNR) on the radiograph. The CNR for small thickness differences is influenced by both the effective attenuation coefficient of the material (μ_{eff}) and the SNR of the CR system itself [3].Through the specific SNR_N limit an further increase of the IQI wire number will only be possible if the attenuation coefficient is increased. A reduction of the X-ray tube energy becomes indispensable for granting of the requested IOI wire number on the digital image. The diagrams in Figure 4c elucidate that exposure on the steel plates fulfilled the image quality class B conditions in case the X-ray tube voltage were reduced to values, recommended in the radioscopic standard EN 13068-3 for maximum X-ray voltage for steel (Figure 4a). Modern CR systems offer nowadays an improved IP design (smaller structural noise and higher maximum of achievable SNR_N) and scanner techniques with very high dose to grey value conversion efficiencies. An improved CR system unsharpness and a high contrast to noise ratio on the digital radiographs provide an excellent image quality with IQI wire numbers which can exceed the numbers detectable on radiographic films.

6. Acknowledgement

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7. Literature:

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