Fully Automated Inspection of Welded Seams with a New High Resolution Durable X-ray Camera System

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Abstract. Fully automatic x-ray inspection systems are widely used in light alloy foundries. Now this kind of ADR-system is applied to the X-ray inspection of welded seams. This paper presents a new system for the automatic evaluation of images in combination with a new high resolution X-ray camera with high grey value dynamics.

A new handling concept made short inspection times possible. Instead of conveying the pipe along its axis, a lateral movement was utilised instead. Compared to standard systems, the movement during inspection was shifted to the X-ray source and detector, which led to a 30% reduction in inspection time.

The newly developed X-ray camera features an active area of 200mm by 50mm with a total number of 4.2 million pixels. As neither the electronics nor the sensor is exposed to the X-ray beam, the camera is not damaged by X-ray photons with energy of up to 250 keV. Multiple tests with the PT duplex wire (EN 13068) and the wire IQIs (EN 462-1) have provided an image quality that is superior to the requirements of the X-ray film norm (EN 584) for the X-ray inspection of welded seams.

The images acquired by the camera are used as input for the automatic evaluation. Due to the high grey level dynamics of these images, all processing is performed with 16-bit image operations so that there is no loss of information caused by grey-level downscaling.

In the first image processing step, the grey levels of an image are converted to wall thicknesses. This allows the extent of a defect in the direction of the beam to be measured. In the next step, the detection of the limits of the seam (borders and mid-line) is performed to enable an adaptive filtering. The results of this detection are transferred to the manipulation control to guarantee an optimum positioning of the weld in front of the camera. The adaptive filtering is able to detect faults such as pores, foreign materials and cracks. Finally a quality rule is applied. The image data of a pipe combined with the results of the evaluation is stored in an archive and automatically transferred to a DVD.

1. Introduction

In the past few years, fully automatic X-ray inspection has become a standard procedure for light alloy castings [1][2]. However, due to the irregularities of the seams, which make reference-based image processing impossible, there are only a few solutions available in the field of inspecting welded seams [3][4]. To meet the high demands to contrast and spatial resolution, which can only be achieved by the use of X-ray films, a new digital detector was necessary.

This paper presents a complete explanation the new pipe inspection system. The task of the system is to inspect stainless steel pipes up to 18m in length. One of the main requirements was to reduce non-productive time during handling and also to reduce the measuring time taken in comparison to other similar systems.

To achieve this, an X-ray camera with an active area of 200mm x 50mm was developed by Fraunhofer IIS to test a 200mm long section of welding with a single image. The specified pixel size of 50µm results in a total of 4.2 million pixels per image. In order to meet the contrast resolution requirements of the norm EN 13068 [5], the camera data is digitized with a 12-bit resolution. As a consequence, 16-bit algorithms to process the image were developed. These algorithms, used for seam detection and inspection are extremely fast to keep up with the handling and image acquisition while processing the large amounts of data, notably the quantitative evaluation of the defects in beam direction.

The results of the inspection are not only visualised but also stored on CD-ROM or DVD. High rates of compression without any loss of information also required the development of special procedures.

2. System Overview

Fig. 1 shows the schematics of the inspection system, the interconnection of the various components and the data flow. The distinct components of the machine are described in more detail in the following sections.

The programmable logic control (PLC) of the machine acts as the master. It controls the handling system and submits commands to the image processing unit, which is connected to the detector using an optical link. While image acquisition and movement of the X-ray source and detector are controlled by a handshake protocol, the evaluation of the X-ray images runs in parallel and doesn't conflict with the process of data acquisition.

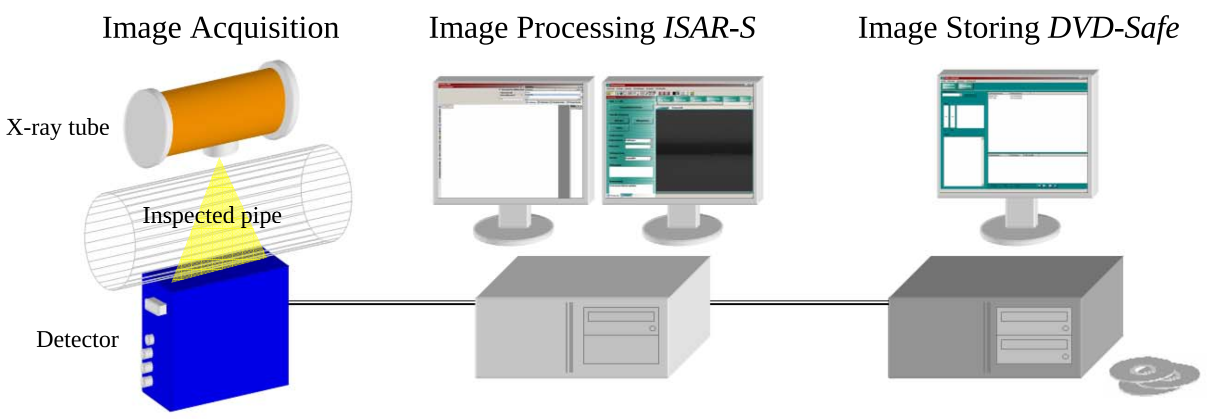

Fig. 1: Integration of system components

Immediately after acquiring an image, a pre-evaluation step is performed by the *ISAR-S* image inspection system to ensure that the seam is inside the optimal inspection window. The results of this seam identification process are transferred to the PLC. Minor deviations in positioning of the weld, are corrected with the next movement of the X-ray source and detector, as they do not influence the automatic inspection of the weld. However, more extreme deviations do result in a repositioning of the weld and a repetition of image acquisition process.

Multitasking and –threading is used to make optimal use of the available processing power for inspection and visualisation of the acquired image data according to user defined inspection and quality criteria. The *ISAR-S* system provides several image processing routines with no references to guarantee the detection of all anomalies with low rates of false rejection.

The acquired and evaluated images are send to the last element of the system chain. The so called *DVD-Safe* stores the data according to the job and pipe identifications and creates the compressed archive for each inspected pipe. Any information available (i.e. name of the inspector, material id, focus detector distance) are also added to the archive together with a scrambled checksum. Archive manipulation can be detected by the use of this checksum during decompression.

The archive is then automatically written to a non-rewritable media , for example, Blu-ray, DVD or CD and can be used for reference purposes.

3. Machine characteristics

The high cycle time requirements combined with keeping the space used at a minimum, led to a completely new concept for handling the pipes. To keep the non-productive time as low as possible, a decision was made against an infeed/outfeed direction along the axis of the pipe (max. length 18 m). Instead, a lateral conveying direction was utilised. This made large and heavy radiation protection gates necessary, but made it possible to change the pipes in less than a minute. Fig. 2 shows the view into the open infeed gate and reveals the inner part of the inspection system. The outfeed of the inspected pipe takes place at opposite site of the infeed. This made it possible to change the pipe in an area a little larger than the layout of the machine itself.

Fig. 2: View into the x-ray cabinet

The pipe to be inspected lays on supports arranged in pairs, which allow the pipe to rotate. This is necessary to align the welded seam in a six o'clock position and to reposition it in case the seam diverges from the ideal position.

The X-ray source is mounted in a carriage, which directly runs into the pipe to be inspected. The source is connected to a high voltage generator with an appropriate cable that is guided by a large wheel. During inspection, the detector runs in a carriage below the pipe synchronously to the X-ray source (Fig. 3).

Where the X-ray source cannot inspect pipes with small diameters, the source runs on a track above the pipe and realises a double wall radiation. This configuration allows the inspection of pipes from 60mm in diameter up to 1260mm. As only the X-ray source and the detector are moved instead of the heavy pipe, there is a significant reduction of up to 30% in inspection time.

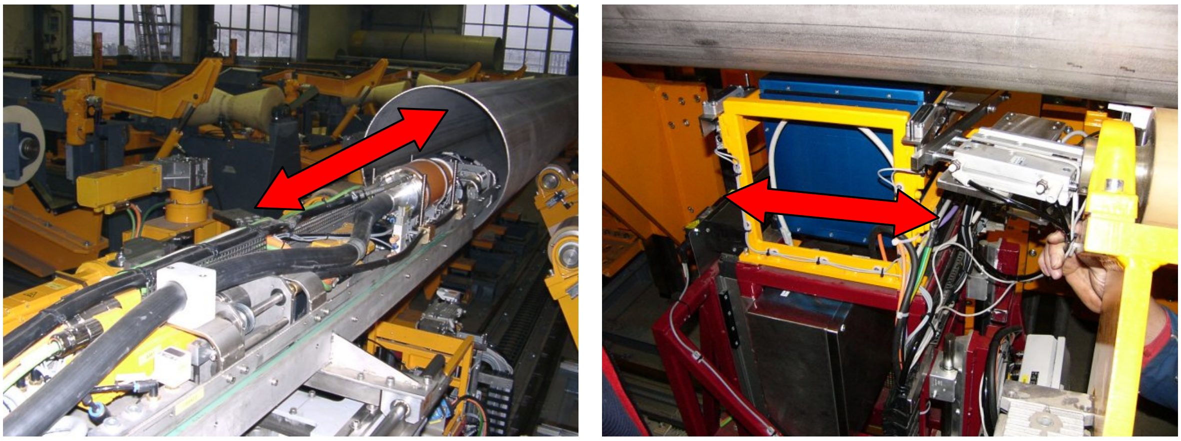

Fig. 3: Carriage and frame with X-ray source and detector (moving directions indicated)

4. Detector System

Fraunhofer IIS developed the X-ray camera used in this system especially for weld inspection at high energy. The main focus of the development was to meet the requirements of EN 13068-3 [5] and EN 584-1 [6] concerning contrast and spatial resolutions, but also to build an X-ray camera which is durable for X-ray tube voltages up to 225kV.

Fig. 4 shows the camera with the active area of 200mm x 50mm marked by the rectangle on the top cover. The total number of pixels is 4.2 million and the pixel size 50µm x 50µm. The type of sensor chosen for this camera is free of pixel defects in the sense that no pixel completely fails. As for any other digital X-ray camera, there are differences in the dark signal and in the gain, which have to be corrected for by the software. During the inspection, images are taken with the long side of the active area aligned to the direction of the weld. The camera consists of three modules lying in this direction. In principle, the active length of the camera is not limited due to the modular concept. The data from the camera is digitized with a 12-bit resolution. The dynamic range - as defined by the quotient maximum signal divided by dark noise - slightly depends on the exposure time. With a typical exposure time for weld inspection of 2 seconds with this X-ray camera, the dynamic range is 1300:1. As the dark signal level increases with exposure time, the maximum exposure time has been set at 10 seconds.

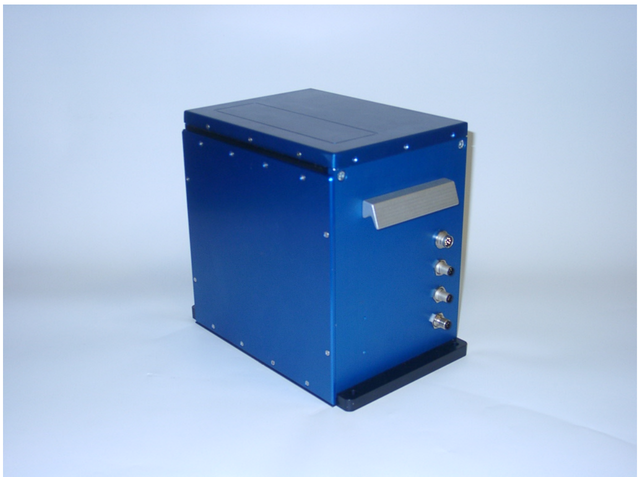

Fig. 4: X-ray camera *XEye*

An optical link provides the best option for transmitting data over a distance of 60 metres from the camera to the computer. In order to prevent the optical fibre from darkening due to radiation damage, the optical transducer is placed in a separate housing outside the X-ray cone rather than inside the camera housing.

Fig. 5 shows an X-ray image taken at 110 kV tube voltage showing a 4 mm thick steel plate together with a double wire tester according to EN 462-5 Duplex IQI [7]. The profile along the red line is shown in the lower part of the image. For this thickness of steel plate, EN 13068-3 specifies the third double wire (No. 11D), from the right corner of the image as the limiting resolution. However, according to EN 462-5, the limiting resolution is given by the third double wire, No. 12D. This is superior to the requirements. Tests with thicker steel plates showed that the double wire requirement could be clearly fulfilled for the whole range of the specified steel thickness.

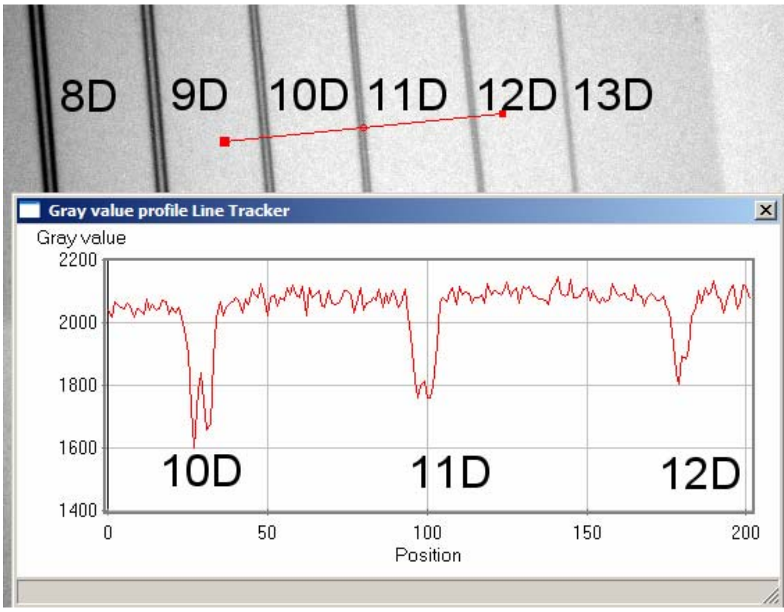

Fig. 5: Double wire test according to EN 462-5 and line profile

Additional tests were carried out using the X-ray camera on steel plates of differing thickness according to EN 462 in order to prove the camera meets the requirements for contrast resolution specified by EN 13068. Again, the X-ray camera meets the requirements for all specified steel thicknesses.

5. Image Processing

The requirements concerning spatial and contrast resolutions, as well as the need for the quantitative measuring of different types of seam anomalies in beam direction presented the greatest challenges to image processing. Below is a selection of anomalies requiring detection:

- Pores
- Lack of penetration
- Undercut
- Internal Undercut
- Slag inclusions

As previously mentioned, it is not possible t o inspect “unsteady” (defect free) welded seams with reference-based image processing. Therefore, a multi-stage image evaluation procedure without references was designed and implemented. This consists of several algorithms, each one specific for a certain type of anomaly. For example, median based filters detect pores and inclusions, while direction sensitive gradient filters detect undercut and lack of penetration.

The seam identification mentioned in Section 2 is the basis for the direction sensitive filters. The first task is to detect the borders and mid-line of the seam in the images. The orientation of the seam is well known as a horizontal. Therefore, a series of vertical profiles $f_i(x)$ has to be evaluated (Fig. 6). The evaluation calculates the first derivation $f_i'(x)$ and therefore, the gradient of the extracted grey value profile (Fig. 7). In a defect free seam, the algebraic sign of the gradient changes in the middle of seam, while the integral - including a small interval - has be taken into account for stability reasons. The integral becomes maximal if measured from the midpoint of the seam in both forward and backward directions.

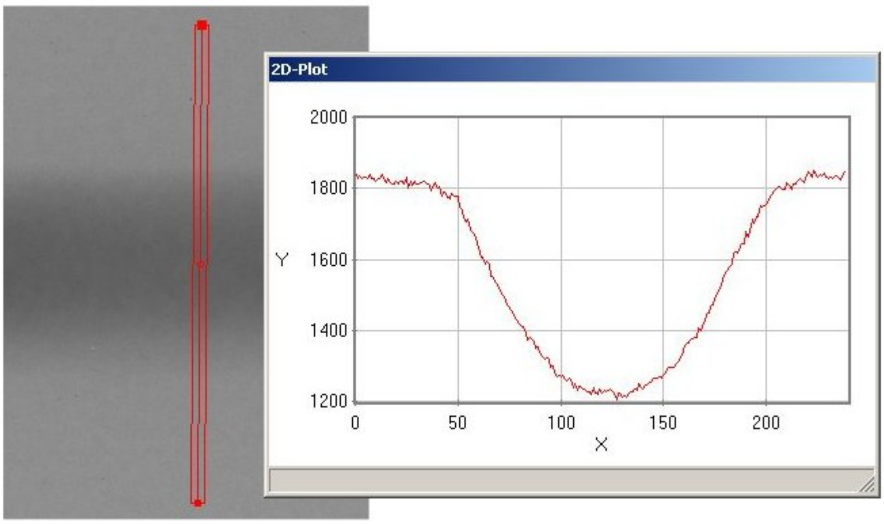

Fig. 6: Cross section of x-ray image of a welded seam and corresponding profile

Starting from the identified mid point, the upper and lower borderline of the seam is detected. The transit from the seam into the base material is characterized by a measurable drop of the gradient. These two transition points (upper and lower) are identified as borders of the seam. Based on this segmentation of the seam, direction sensitive filters are applied, starting at the border points of the seam. These filters are able to detect the above-mentioned anomalies. The quality of the seam identification step is the main influencing variable for the quality of the defect recognition. This method is robust enough against minor anomalies in the seam, but single large anomalies, such as holes in the seam, can lead to miscalculations.

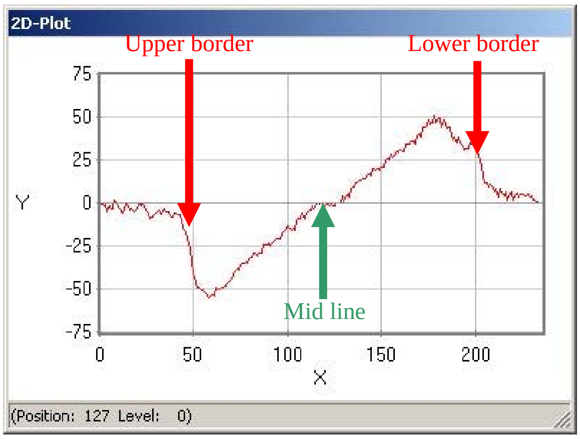

Fig. 7: Gradient of the cross section and detected borders

Detected anomalies can be measured in size in beam direction after the system has been calibrated. This is achieved by the use of X-ray images of a step wedge which consists of the same material as the pipe itself. The difference of the length of path of the anomaly in relation to its surrounding provides the desired size [8].

All the anomalies detected by the different filters are then merged prior to being interpreted by the quality investigative procedure. This step determines whether a detected anomaly is visualised or not.

6. Permanent Storage of Image Data and Results – *DVD-Safe*

It is necessary to permanently record and store image data for specific types of pipe.

Where an inspection system uses an image intensifier and video camera to record images, the quality is poor and the running costs are comparatively high due to the type of media.

As an alternative, the digital storage of images and their transmission on non-rewriteable media, such as CD-ROM or DVD provides superior quality and lower running costs. The *DVD-Safe* uses this technique and stores the images with measurement parameters (kV, mA, Distances) and the results of the inspection. A scrambled checksum allows the detection of a hypothetical manipulation of the image data after the initial storing.

The connection between *DVD-Safe* and the *ISAR-S* inspection system is established via local area network (LAN). All images are stored by order and pipe and are compressed pipe by pipe. After completing the order, the related pipe archives are automatically transferred to the selected media. If an order produces more archives than the media can handle, the transfer is started, when according data volume is reached.

Upon completion, the media is supplied with a unique identifier, which is stored together with related pipe information in a database. The database provides several search functions to allow the tracking of written archives.

Media player software allows the decompression and visualisation of the stored data. The user can display the information according to pre-defined criteria, such as pipe position and inspection results. The media player verifies the data using the checksum and displays an error message if there is a difference.

The *ISAR-S* inspection software comprises an extended version of the media player, which also allows the user to repeat the inspection process. The lossless compression of the X-ray images ensures the traceability of the results.

7. Summary and Outlook

The inspection system introduces a new kind of inspection for longitudinal welded pipes from the initial handling system to the final digital permanent storage solution. An innovative machine concept was combined with a special detector for the inspection of welded seams. The durability of the detector is one of many outstanding features of this imaging component.

In order to rapidly evaluate 16-bit X-ray images, especially developed algorithms are able to detect the plurality of seam anomalies. Despite the large amount of data an inline evaluation of the images is possible with little effect on hardware resources.

The inspection chain ends with the permanent storage of all acquired data and meets the requirements of modern documentation techniques and preservation procedures.

The inspection software is able to detect a variety of different anomalies, but cannot classify them according to criteria such as type of anomaly or risk of failure. This task is still left to the inspection personal. Further development should now concentrate on closing this gap in classification.

In addition, further steps in the development of laser-welded seams have to be completed. In fact, the presented algorithms are able to perform the seam identification process successfully despite the low contrast of laser seams, but a hundred percent detection of all anomalies was not possible for this kind of welded seam.

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