Automated X-Ray Inspection: Industrial Applications and Case Studies

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Abstract. Many industries require that 100% of manufactured parts be X-ray inspected. Factors such as high production rates, focus on inspection quality, operator fatigue and inspection cost reduction translate to an increasing need for automating the inspection process. Automated X-ray inspection involves the use of image processing algorithms and computer software for analysis and interpretation of X-ray images. This paper presents industrial applications and illustrative case studies of automated X-ray inspection in areas such as automotive castings, fuel plates, air-bag inflators and munitions. It is usually necessary to employ application-specific automated inspection strategies and techniques, since each application has unique characteristics and interpretation requirements.

Keywords: X-ray, automated inspection, castings, fuel cells, air-bag inflators, munitions.

1. Introduction

X-ray inspection is a well-established NDE technique in the manufacturing industry. In recent years, there is a growing trend towards automating the X-ray inspection process due to several factors. Nowadays, it is common to find 100% of manufactured parts required to be X-ray inspected. The necessities of production and shipping schedules translate to X-ray inspection machines being operated 24x7. There is an increasing focus on quality of inspection, with an emphasis on more quantitative and uniform product evaluation. Frequently, as well, X-ray inspection is perceived to be the bottleneck in the overall production process, resulting in a constant requirement for faster inspection rates. Shortage of experienced X-ray inspection operators, operator fatigue, training and motivational issues, and inspection cost reduction are other major drivers to this increasing need for automation at every stage of the inspection process.

This paper presents industrial applications and illustrative case studies of automated X-ray inspection. The organization of this paper is as follows: first, an overview of automated X-ray inspection is presented; second, applications to castings inspection and fuel plate inspection are described; and in the third part, an overview of applications to air-bag inflators and munitions is provided.

2. AUTOMATED X-ray inspection

Automated X-ray inspection involves the use of image processing algorithms and computer software for analysis and detection of defects in X-ray images. It can be classified into three categories based on who makes the final inspection decision to accept or reject the part: (i) operator-assist, in which the human operator makes the decision based on computer analysis; or, (ii) semi-automated, in which the decision is a logical combination of independently made human and computer decisions; or, (iii) fully-automated, in which the inspection decision is made only by computer.
FIGURE 1. Processing stages in automated image analysis.

In general, the image analysis process can be split into four stages: preprocessing, defect detection, defect classification, and defect evaluation (Fig. 1).

Preprocessing prepares the acquired raw digital image for the defect detection stage by reducing noise, correcting for background trends (shading correction) and removing geometric structures which otherwise would adversely affect the defect detection stage. Depending on the specific application, this stage could include other steps: for example, conversion to attenuation units; geometric distortion correction and veiling glare elimination in image intensifier systems. It also generally includes an image registration step that precisely locates the inspection zones or regions on the image.

In defect detection, the goal is to identify the physical extent and location of the defect in the X-ray image. This stage is usually the most difficult to perform reliably from an image processing standpoint. Additional factors affecting this step are part movement, detector noise, detector calibration, and variations in the X-ray source.

After defect detection, the next stage is defect classification: in this, the defect is classified into different types that are application-specific. For example, in castings inspection, typical defect types are shrinkage cavity, shrinkage sponge, gas holes, gas porosity, or foreign material.

In defect evaluation, the classified defect is evaluated and graded using predefined standards (for instance, with aluminum castings, the quantitative equivalent of ASTM E2422 [1]) and the inspection decision made on the basis of the evaluation.

3. Castings

X-ray inspection is a well-established NDE technique in the casting industry. Regulatory requirements usually mandate that 100% of safety-critical castings be X-ray inspected. Defects in castings can be of different types such as shrinkage cavity, shrinkage sponge, gas porosity, gas holes, and foreign material. These defects can occur anywhere in the casting and are not limited in area or depth. Defects are usually characterized by local X-ray attenuation changes, resulting in corresponding local discontinuities in the gray values of the acquired image. Automated
inspection of castings employs a number of different image analysis and processing techniques. Preprocessing techniques used include part identification, noise reduction [2], [6], [9] and image registration [3]. Defect detection techniques commonly used include background subtraction [4], matched filters [8], feature-based detection [2], morphological methods [5], adaptive thresholding [6] and neural nets [7]. In the defect classification stage, the defect pixels identified from the detection stage are grouped into connected regions (connectivity analysis), their characteristics quantitatively measured and classified into different types (expert systems are used in [6] for this) such as shrinkage cavity, shrinkage sponge, gas porosity, gas holes, and foreign material. After the defects are classified they are quantitatively evaluated using metrics such as defect area density, defect area and chord length. Inspection decisions and defect analysis information are typically stored in a database for every part. The stored data can then be utilized to improve the overall casting process utilizing appropriate statistical analysis.

4. Fuel Plates

Fuel plates consist of a fuel core within aluminum clad plates. The function of the X-ray inspection system is to image the plate in order to determine the precise location of the fuel core (the “fuel envelope”). Cold-rolled plates are inspected to locate the fuel envelope and compare its outline with a reference template indicating minimum and maximum acceptable fuel envelope dimensions (see Fig. 2 below). The fuel plate is manipulated to center the fuel core within the template. Manipulation of the plate to center the fuel envelope is performed automatically by the inspection system and reference tooling holes are punched by the system for the blanking operation. Plates are then blanked to finished size (see Fig. 3 below) and X-ray inspected to verify conformance of the fuel outline for compliance with reference engineering drawings. The measurement is fully automatic, and generates a report consisting of the maximum and minimum dimensions in each applicable zone. Any values exceeding the reference engineering requirements are flagged as reject. Image processing techniques used include image registration, coordinate transformations, geometric shape analysis and dimensional measurements. An overview of the coordinate systems used in the automated image analysis is shown in Fig. 4 below.

![FIGURE 2. Cold-rolled fuel plate.](image-url)
5. Air-bag inflators

Automotive air-bag inflator materials usually consist of low carbon steel stampings and machinings, inconel burst discs, energetic material and other small components. Defects in the fully assembled inflator occur in predefined areas and are usually of the component presence/absence type. Typical inspection requirements include verification of energetics retainer integrity, presence of auto-ignition cartridge, presence of vent holes and presence of burst disk orifice. Image analysis techniques used include image registration, pattern matching, measurement of X-ray attenuation coefficients in defined areas and dimensional measurement.

An example of automated inspection of a fully assembled air-bag inflator is shown below in Fig. 5 and Fig. 6. In this, the presence or absence of the auto-ignition cartridge within the completed assembly is determined by the measurement of X-ray attenuation in a defined region of interest (ROI). Since an inflator can be arbitrarily rotated (in the plane) when it is imaged, image registration using fiducials is employed to locate the ROI on each inflator.
6. munitions

Munitions such as artillery shells and cartridges are usually X-ray inspected for critical defects that can cause the munitions to malfunction. In one application, a 40 mm cartridge is X-ray inspected for various types of defects such as cracks, voids, fuze armed status, and powder fill level. To effectively inspect the cartridge, it becomes necessary to use computed tomography (CT). The output of the CT image reconstruction process is the 3D volumetric attenuation distribution of the cartridge. This 3D volume is automatically processed to identify and evaluate the different types of defects. Analysis techniques used include histogram-based thresholding, surface fitting and extraction, and morphological image processing. In another application, the base gap of artillery shells is automatically detected from the X-ray image and used for measurement of the gap. Special image processing filters are used for this purpose. An example of base gap detection for different gap sizes in 120 mm artillery shells is shown below in Fig. 7.

7. CONCLUSIONS

Automated X-ray inspection has been an active field of research for the last several years. It is finding increasing use in industrial applications especially those that involve high production rates. Improvement in product quality, operator related issues and inspection cost reduction are major reasons for the transition to automated inspection in such applications. This paper presented several case studies of automated X-ray inspection in applications such as castings, fuel cells, air-bag inflators and munitions. With the increasing availability of low cost, high performance computing, sophisticated image processing and analysis of X-ray images becomes feasible leading to more applications for automated X-ray inspection.
FIGURE 7. Base gap detection in X-ray images of 120 mm artillery shells.

references