PROCESS INTEGRATED INSPECTION OF CASTINGS USING THREE DIMENSIONAL COMPUTERIZED TOMOGRAPHY

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1. Introduction

Automatic two-dimensional (2D) X-ray inspection of cast parts is a standard quality control measure in foundries today. Typically 100 percent detection of defects in all areas of a cast part is necessary to prevent failure due to material defects. But a 2D projection of a defect does not yield sufficient information on the defect's location in the part or its extent. This lack of information often leads to an unnecessary scrapping of parts which can significantly reduce a foundry's output.

Until recently system cost and processing speed of a Computerized Tomography (CT) system capable of computing three-dimensional (3D) images prevented its widespread use except for special applications, e.g. offline inspection of prototypes in the lab. With the steady advances in processing speed in conjunction with a new detector design and optimized 3D image processing algorithms, it is now possible to integrate a CT system into the process, offering 3D reconstruction, fully automatic defect detection and measurement in the cast part in less than 30 seconds per part. Using 3D reconstruction of the entire part including all defects, yields precise knowledge of flaw properties, location and distribution in the part. This information is vital for improving foundry throughput without sacrificing part quality.

The second section of this contribution deals with the inspection method for finding defects in castings. In section three we present the features and results of an Inline-CT system that was realized and customized for casting inspection. We discuss the results in section four and conclude this paper with a short summary in section five.

2. Inspection method

Inline CT methods are only valuable, if an automated analysis of the reconstructed data is available. Although only defect recognition to characterize voids and porosities is covered in this contribution, alternative evaluations are feasible. Further evaluation may concern the dimensional measurement of the sample or of its structures itself. Another working point will be the visualisation of 3D result data for verification of automated image processing methods, which will be especially important during installation and acceptance phase of those systems.

The process of Inline-CT is divided in three individual steps: data acquisition, volume reconstruction and defect recognition. The reconstruction step starts with the acquisition of the first projection and will be finished short time after imaging the last. In order to keep pace with production speed, the evaluation step has to be performed as fast as the data acquisition. The evaluation is then performed in parallel to the scanning of the next part. For the data reconstruction step, an optimized Feldkamp-type filtered backprojection method is used, but also advanced geometries like helical CT are possible.

Software tools for offline data evaluation usually do not deal with reference information concerning the object under investigation. Rather some kind of background modelling is used to generate reference information about the object during evaluation. This is a suitable approach for inspecting many different kinds of objects because no uncomfortable teach-in process is necessary. However background modelling methods are not able to find big surface defects automatically. But this fact carries no weight, because offline tools are only used to support the staff of inspectors and the results will be normally reviewed.

In order to develop an inline evaluation method for detecting all kinds of defects, including surface defects, we have to make use of reference information in addition to background modelling. In spite of an initial registration step we need to characterize the misalignment of reference and object data caused by manufacturing tolerances to perform a suitable comparison. We present the usage of reference data for inline inspection in the following sections.

2.1 Reference data preparation

CT parameters of an inline inspection system do not change during the evaluation of structurally identical objects. Therefore it is straightforward to use a CT reconstruction data set of an accurate object as reference information. In order to achieve a fast measurement of misalignments we have to pre-process the reference data set. There is no disadvantage in using time-consuming image processing at this stage, because these operations are pre-computed only once for each object type and therefore no resources are needed at inspection time.

For $r, s, t \in \mathrm{N} := \{1, 2, 3, \dots\}$ let

$$V_{r,s,t} := \{(x, y, z) \in \mathrm{N}^3 : 1 \le x \le r, 1 \le y \le s, 1 \le z \le t\} \tag{1}$$

be the coordinate system of a 3D volume data set. Since we always assume in the following that the volume data sets have same dimensions we drop the indices r, s, t for convenience. Let $f_{ref} : V \to \mathrm{N}$ be the reference data set. Initially we perform an object labelling step, i.e. we determine all object representing voxels within the reference data set f_{ref}. Let therefore be $A \subseteq V$ the set of object indicating coordinates and $v = (x, y, z) \in V$. Then the binary label volume $l_A : V \to \mathrm{N}$ is defined as

$$l_A(v) = \begin{cases} 1 & , if\ v \in A \\ 0 & , if\ v \notin A \end{cases} \quad . \tag{2}$$

Applying the euclidean distance transform to l_A concludes the reference data preparation step. Consider $v = (x, y, z) \in V$ and $S \subseteq V$. Then the minimal distance between v and S is defined as

$$dist(v, S) := \min_{s \in S} | v - s | \quad . \tag{3}$$

Using this definition the distance transform [1] is given as

$$D(l_A)(v) := \begin{cases} dist(v, A) & , if\ v \notin A \\ 0 & , if\ v \in A \end{cases} \quad . \tag{4}$$

Summarizing the result of reference data preparation is a volume data set where all voxels which relate to object voxels in f_{ref} are equal to zero, and all other voxels are coding the distance to the nearest object relating voxel.

2.2 Reference data comparison

First we define the measure for characterizing the misalignment between reference data and the current volume data set under investigation. Let $f_{cur}: V \to \mathrm{N}$ be the current object data set and let $l_B : V \to \mathrm{N}$, $B \subseteq V$, be the corresponding binary object label volume. The misalignment measure is defined as

$$M(f_{ref}, f_{cur}) := \max\{D(l_A)(v) \mid l_B(v) = 1\} \quad . \tag{5}$$

In other words, the misalignment measure calculates the maximum distance that occurs in the object area of f_{cur} (see figure 1). This measure is suitable for inline inspection, because it can be calculated very quickly at inspection time using the prepared reference data.

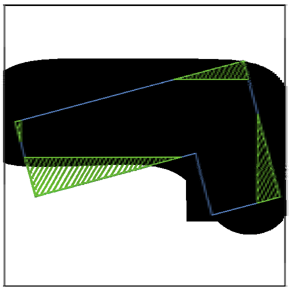


Figure 1: Illustration of misalignment measure calculation: The image shows the distance transform of a synthetic 2D object; bright pixels indicate big distances, dark pixels indicate small distances, the object itself is black. The hatched markings show the misalignment to another object and indicate the distance values where the maximum defines the measure M.

The reference data comparison starts with the calculation of $M(f_{ref}, f_{cur})$. If $M(f_{ref}, f_{cur})$ is in the range of the manufacturing tolerances, no registration is necessary. If $M(f_{ref}, f_{cur})$ is bigger than the production tolerances, a straightforward registration step is performed where the inertial tensors of reference and current data are used to determine the parameters for the corresponding affine transformation. For more details see [1].

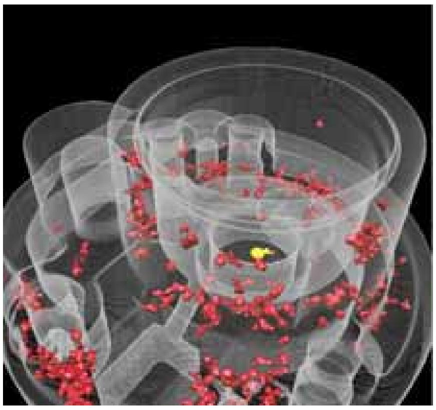
Since a simple subtraction of f_{ref} and f_{cur} yields many artefacts caused by manufacturing inaccuracies, we use a difference operation that takes into account the misalignment. This operation is defined as

$$S(f_{ref}, f_{cur})(v) := \min_{\substack{w \in V \\ |w-v| \le M(f_{ref}, f_{cur})}} |f_{ref}(w) - f_{cur}(v)| \quad . \tag{6}$$

Combining the proposed reference data comparison step and the background modelling as presented in [2] yields a defect detection method that is suitable for inline inspection.

3. Results

By applying advanced parallel image processing it is possible to test parts inline in a cycle time of 30s total (25s of image acquisition and 5s of part handling), allowing 100% 3D-X-ray testing of all production without cycle time penalty. A 3D representation of the inspection result and the realized 3D CT-system for process integrated casting inspection are shown in Figure 2.



a)

b)

Figure 2: a) 3D representation of the inspection result; b) Realized system for process integrated casting inspection using 3D computerized tomography.

A system with these parameters was put into operation in a foundry:

- 66ms exposure time / 15 frames per second
- 375 projections per object
- 256MB volume size (512x512x512 voxels)
- Reconstruction completed after measurement of last projection
- 30 seconds total time requirement per part

An XEye detector is used due to its stable behaviour at continuous operation [3]. The system is capable of automatically detecting flaws in aluminum parts down to a size of 1.2 mm at an object thickness of up to 100 mm with under 3% false rejects.

4. Discussion

A 3D-CT system provides dramatically more information about a part than a 2D system can offer. The information regarding an object feature's depth inside a part is not available in a 2D system, and since features are magnified depending on their location and system geometry, the real size of e.g. a pore can often only be estimated.

A 3D-CT system on the other hand provides exact information about a flaw's location and size inside the object. A 3D-CT-system initially detects more flaws than a 2D-System because of the superior contrast of the reconstruction calculated from a large number of projections compared to the single projection in a single direction used in a 2D system. The availability of the location information in conjunction with the absolute flaw dimensions makes it possible to selectively evaluate each flaw using that information, allowing the use of dynamic thresholds depending on the flaw's location, and ignore non-critical flaws.

It is for instance possible to allow larger flaws in massive areas of a part, and at the same time set a more sensitive threshold in critical areas of the part. A small, normally uncritical flaw may become critical because it appears at the surface after machining. In a 2D system, all flaws could potentially appear at the surface after machining, while on a 3D-CT system it is possible to only mark the future surface after machining as critical, while tolerating minor flaws outside of that area. All this information can be taken into account by an automatic image processing system when making the decision if a part is good or should be scrapped.

In effect, the yield with a CT system can be higher than a 2D system while at the same time offering a higher overall quality level. The more selective classification made possible by 3D-CT can actually reduce scrapping of good parts.

5. Summary

With the use of parallel computing and efficient algorithms it is possible to use inline 3D-CT-systems in foundries without a penalty on cycle time. The availability of 3D-data allows intelligent flaw detection and a more refined evaluation of cast parts and can even lead to a reduction of scrap parts compared to 2D inspection. It is also possible to perform selected measurements on the part in an inline system.

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