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X-ray computed tomography for fast and non-destructive multiple pearl inspection

J. Rosc [a], V.M.F. Hammer [b], R. Brunner [a,*]

[a] Materials Center Leoben Forschung GmbH, Roseggerstraße 12, 8700 Leoben, Austria
[b] Natural History Museum Vienna, Department of Mineralogy and Petrography, State Gem Institute, Burgring 7, 1010 Vienna, Austria

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ABSTRACT

X-ray computed tomography displays a highly valuable nondestructive testing tool in various fields. A major disadvantage of this method comprises its high operating costs. Therefore, the reduction of the scanning times would be highly beneficial. Here, we demonstrate exemplarily for the testing of pearls the possibility to decrease the scanning times. The great diversity of pearls on the market, often of unclear origin, especially used for jewelry, demands non-destructive test methods for the fast and reliable classification and validation. We discuss the use of a nano-focus X-ray computed tomography (nf-XCT) system for fast three-dimensional characterization to distinguish between natural and cultured pearls. We test the approach not on individual pearls but for a more demanding task namely for a pearl necklace, that is multiple pearls on a strand. We show that with just one scan the 3D image data of the individual pearls within the whole necklace, which is composed of about 200 pearls can be scanned and reconstructed in only about 24 minutes. That is, we illustrate that nf-XCT as a inspection method is highly competitive to conventional radiography or radioscopy. The presented work also reveals possibilities for other fields like microelectronics etc.

1. Introduction

In recent years lab based X-ray computed tomography (XCT) has become an important nondestructive testing (NDT) tool in various fields like material science [1,2], bones and minerals [3,4], microelectronics [5,6] etc. The major advantage of XCT in comparison to other X-ray imaging based methods like radiography or radioscopy is the capability to display the internal structure in 3D and the resulting possibility to perform the analysis slice by slice with respect to failures, porosity, inclusion, fiber orientation, etc. e.g. [2,6–8]. However, so far high operating expenses due to long analysis and reconstruction times display major disadvantages of lab based XCT systems. This becomes highly crucial if plenty of test objects need to be tested, or the prize per unit is lower or comparable than the measurement and analysis costs. In this context, pearl testing represents a good example, where from individual test objects of unclear origin and value to plenty of test objects, need to be tested. Today the vast majority of pearls on the market are cultured ones from pearl farms. In 2010 China already produced 20 tons of cultured saltwater pearls from the Akoya oyster and 1500 tons of freshwater cultured pearls from different mussels. Australia is the major producer of South Sea pearls worldwide with ten tons per year, while Tahiti provides 16 tons of black pearls per year [9]. Due to the big variety on the pearl market the distinction

* Corresponding author.
E-mail address: roland.brunner@mcl.at (R. Brunner).

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Table 1
Summarizes the relevant parameters used for the XCT scans of the pearl necklace.

FOD [mm]	FDD [mm]	Voxel size [μm]	No. of images	Scanning time [min]	Reconstruction time [min]	Voltage [kV]
86	300	28.6	2400	20	4	55

between natural and cultured pearls becomes more and more demanding. Today's equipment for pearl testing comprises a great diversity of methods, as described by [10] and references therein. Two NDT methods widely used to characterize the interior of the pearls are X-ray radiography and X-ray radioscopy, applying X-ray sensitive films and digital X-ray detectors respectively. X-ray micro-computed tomography (μ-XCT) represents a more recent method to characterize pearls [11]. In contrast to X-ray radiography and X-ray radioscopy, long measurement and reconstruction times prevented μ-XCT from a wide use in NDT. However, X-ray radiography and radioscopy have some disadvantages, especially when it is necessary to interpret small or complex internal features like thin layers, fissures, small cavities or enclosed material. Even if a pearl is radiographed from different directions, the images give incomplete two-dimensional information about the pearl. Therefore radiography, although consuming less analysis time, may result in misleading interpretations [11]. Therefore, the application of fast characterization of pearls by using XCT would be highly preferable for accurate NDT.

In this case study we use a so-called nano-focus XCT system (nf-XCT) to map the internal structure of a pearl necklace which is composed of about 200 pearls. We show for the first time that the pearls in the necklace can be classified according to their internal features within one scan. Furthermore, we demonstrate that the performed inspection time of about 24 minutes is far lower than those reported previously for single pearls and give comparable 3D image data quality for the inspection (e.g. [11]). The study shows that XCT becomes highly competitive in comparison to other established fast X-ray methods like X-ray radiography or X-ray radioscopy.

2. Method

In this study we use a nanotom *m* (GE Measurement and Control Solutions) lab system, operating a nano-focus X-ray tube™ with a maximum acceleration voltage of 180 kV and maximum X-ray current of 880 μA. The used XTC system is based on a cone beam configuration where the sample is rotated around 360° within the X-ray and located between the X-ray tube and detector indicated by the focal object distance (FOD) and the focal detector distance (FDD), respectively (Table 1). The minimum focal spot size is about 800 nm. However, the focal spot size of this X-ray tube can be optimized according to the resolution needed for the particular task. Here, an optimization for a voxel size of 28.6 μm was performed (Table 1). The detector installed in the nanotom *m* provides 3052×2400 pixels, with 100 μm per pixel which gives an overall detector area of about 300×240 mm. The flat panel detector provides a high dynamic range of greater than 10000:1 and low noise which enables low exposure times [12]. This large area and dynamic range gives room for the possibility to crop the used detector area however maintaining still sufficient image quality. The exposure time for one single image and overall number of projections taken for a scan was 500 ms. Such an nf-XCT system is capable to realize (1) a voxel size of about 400 nm [13], or (2) as demonstrated in this paper, allows fast 3D inspection as shown for the pearl necklace with an image quality comparable to previous studies obtained for single pearls. The scanning and reconstruction time including the specific sample related parameters are summarized in Table 1. The used parameters were optimized to provide information regarding characteristic features necessary to distinguish between natural and cultured pearls with shortest possible inspection times. The inspection time is thereby defined as the sum of scanning and reconstruction time. A resume concerning characteristic features of natural and cultured pearls is briefly given in e.g. in [11]. The characteristic of natural pearls is mainly defined by an onion-like growing structure of thick calcium carbonate and thin less dense conchiolin layers. Cultured pearls, in contrast to natural pearls like fresh water non-beaded pearls contain small cavity structures in their centre. Several test scans for the optimization of image quality (amount of grey values, pixels and reduced artefacts) have been performed in advance on individual pearls and pearl necklaces. These found parameters give a good basis for any further fast pearl inspection. For the reconstruction [14] of the 3D volume a commercial software package is applied (datos 2 rec). The software is also used to reduce artefacts like beam hardening. For short reconstruction times a commercially available desktop workstation with 192 GB RAM and an external graphic interface unit with five additional GPUs is used.

3. Results and discussion

In the following, we show that the nf-XCT setup is highly suitable to characterize not only individual pearls but also to analyse a number of pearls at once, as necessary for multiple pearl testing e.g. for a necklace. Fig. 1 shows the measurement setup where the pearl necklace composed of about 200 individual pearls is fixed straightforwardly with pins on a foam block. It has to be taken into account that the pearl necklace has to be positioned in the path of the X-rays in such a way that the overall material thickness is low enough to be permeated by the low-energy X-rays (Table 1).

In Fig. 2 the nf-XCT 3D data of an exemplary pearl necklace is depicted. The necklace exists of small pearls. Each shows a diameter between 2–2.5 mm. Clearly the drill holes can be seen. In the following discussion we focus on three pearls within the necklace as indicated by I, II and III. Fig. 3 shows slice images from three directions of pearl I and its vicinity. Fig. 3(a)