Enhancement of probing depth and measurement accuracy of optical coherence tomography for metrology of multi-layered ceramics

Rong Su[1*], Ernest Chang[2], Peter Ekberg[1], Seok Hyun Yun[2], Lars Mattsson[1]

[1]Industrial Metrology and Optics, Production Engineering, KTH Royal Institute of Technology, 68 Brinellvägen, S-100 44 Stockholm, Sweden
[2]Wellman Center for Photomedicine, Massachusetts General Hospital, 50 Blossom St. Boston, MA 02114, USA

*corresponding author electronic address: rongs@kth.se

ABSTRACT

Light scattering strongly limits the probing depth and speckles degrade the image quality in optical coherence tomography (OCT) detection of embedded features in high-scattering ceramics. For high-precision metrology application we evaluated an OCT system working at a centre wavelength of 1.7μm in order to improve the probing depth, and developed a dedicated image processing algorithm for improving the measurement accuracy and speed. The results are demonstrated for 3D OCT measurement of embedded laser-machined pattern in ceramics.

Keywords: metrology, optical coherence tomography, ceramics, micro manufacturing, Image processing.

1. INTRODUCTION

A promising concept of ceramic micro manufacture is the so-called "roll-to-roll multi-material layered 3D shaping technology", which is based on tape casting, advanced micro-manufacturing and printing technology [1]. For the quality control and inspection of the manufacturing process and products containing embedded geometric microstructures optical coherence tomography (OCT) has the potential to provide non-contact and in-process monitoring that is required by the roll-to-roll manufacture.

Although Bashkansky et al. [2] have used OCT for determining the size and distribution of subsurface defects in various ceramics, the technique has not been applied for high-precision metrology application, where it is not enough to only detect free and embedded surfaces, but more important to determine the measurement tolerance of the instrument and method, and develop new methods to improve the measurement accuracy in micrometre scale.

For high-scattering ceramics OCT detection is hampered by its limited probing depth in the material due to the dominant multiply scattered photons by obstacles, air-filled pores, inclusions and surface roughness. In this study we evaluate an OCT system working at a centre wavelength of 1.7μm in order to improve the probing depth. In addition, we have also developed a dedicated image processing algorithm which provides high-precision automated recognition of features from noisy OCT images and handles massive 3-D data rapidly. This technique therefore enhances the measurement accuracy and speed significantly.

2. MATERIALS AND METHODS

2.1 Alumina and zirconia ceramics

The tests have been performed on alumina and zirconia ceramic materials are provided by Swerea IVF AB and produced by tape casting and sintering technology. The porosity is about 1~2% and the average pore diameter is around 0.4~0.6μm in the materials. And the average size of the grains is in the micrometre range. The alumina sample containing laser-machined rectangular patterns is provided by Cardiff University. The smallest pattern has a lateral and depth dimension in tens of microns.

2.2 OCT setups

For comparison of probing depth in ceramics, the laboratory swept-source OCT setups with 1.3 and 1.7 μm center wavelengths [3] were used for imaging the ceramic samples. The specification is tabulated below.

Table1. Specifications of Swept source OCT systems

Centre Wavelength	Spectral Bandwidth	Sensitivity	Transverse pixel size	Axial pixel size	Transverse Resolution	Axial Resolution
1.3 μm	120 nm	110 dB	7.4 μm/pixel	4.1 μm/pixel	12 μm	12 μm (in air)
1.7 μm	165 nm	110 dB	7.4 μm/pixel	4.7 μm/pixel	18 μm	12 μm (in air)

2.3 Image processing algorithm

In OCT images noise and speckle degrade the measurement accuracy to a great extent. We have found that a proper thresholding of the filtered OCT image combined with an advanced statistical treatment of local neighbourhood of pixels is a successful approach to find and localize the backscattering peaks of the OCT signal with sub-pixel precision [4]. Figure 1 shows schematically the sub-pixel precision algorithm.

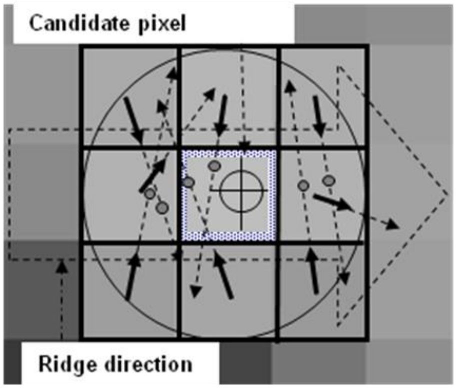

Fig.1. Schematic of the sub-pixel precision algorithm estimating the gradients of eight neighbouring pixels. The hair cross is the estimated sub-pixel location of the candidate pixel in the middle. The gradient vectors are shown as black arrows, and the opinions of the locations of the intensity maxima are marked with small grey dots. An individual neighbour’s opinion must be inside the large circle to be accepted.

3. RESULT AND DISCUSSION

Light scattering caused by pores and grains inside sintered alumina and zirconia ceramics can be reduced with increasing wavelength in near and mid-IR region where the absorption is negligible in the material. We built an embedded micro structure by stacking a flat alumina layer with thickness of 300μm atop the alumina layer with laser-machined patterns. In figure 2 the patterns in x-y plane at an embedded depth of 300μm can be detected much more clearly by 1.7μm OCT compared to the 1.3μm OCT, which shows a pronounced improvement in probing depth.

As shown in figure 3 the dedicated image processing algorithm generates firstly a logical map providing candidate pixels and then makes the sub-pixel precision estimation of the real backscattering peaks corresponding to the boundaries. Rapid and high-precision measurement is therefore enabled.

The goodness of the result is verified in an x-y plane cross-sectional OCT image of the patterns as shown in figure 4.

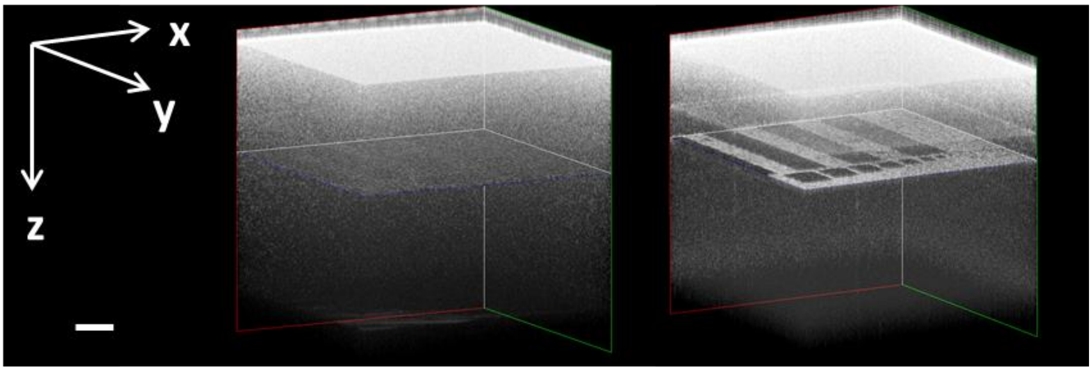

Fig.2. The 3-D image obtained by 1.3µm (left) and 1.7µm (right) OCT systems for embedded features in alumina. The bar is 500µm in x-y plane.

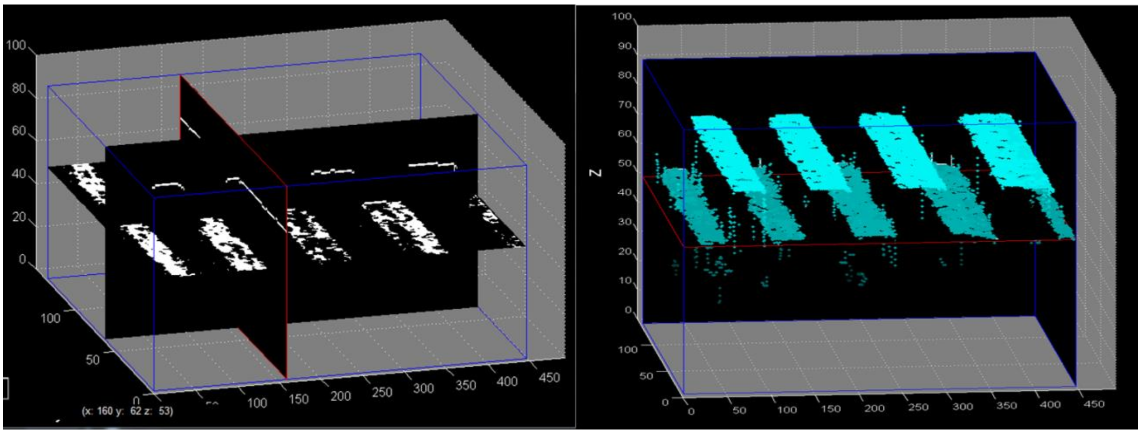

Fig.3. digital processing of measured OCT image of the ceramic patterns.

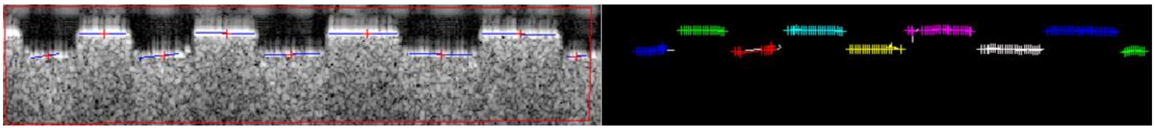

Fig.4. digital processing result of cross-sectional OCT image in x-y plane.

ACKNOWLEDGEMENTS

This work is funded by the Multilayer project (FP7-NMP4-2007-214122). Dr. Stiernstedt and Dr. Petkov are acknowledged for providing the ceramic samples.

REFERENCES

[1] S. Bredeau and L. Federzoni, “Multilayer: a large scale production of micro devices via new rolled multi material layered 3D shaping technology,” in *Proceedings of the 4M/ICOMM 2009 Conference*, V. Saile, K.Ehmann and S. Dimov, ed. (Karlsruhe, 2009), 419-422.

[2] M. Bashkansky, D. Lewis III, V. Pujari, J. Reintjes, H. Y. Yu, “Subsurface detection and characterization of Hertzian cracks in Si_3N_4 balls using optical coherence tomography,” *NDT E Int.* **34**, 547-555 (2001).

[3] Utkarsh Sharma, Ernest W. Chang, and Seok H. Yun, “Long-wavelength optical coherence tomography at 1.7 µm for enhanced imaging depth,” *Opt. Express,* **16**, 19712-19723 (2008).

[4] R. Su, Mikhail Kirillin, Peter Ekberg, Arne Roos, Ekaterina Sergeeva, and Lars Mattsson, “Optical coherence tomography for quality assessment of embedded microchannels in alumina ceramic” *Optics Express*, **20**, 4603-4618 (2012).