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Low Coherence Interferometric Fibre Based In-situ Measurements of Surface Roughness in Air and in Water

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Abstract
In many high-value manufacturing applications there is increased demand for component surfaces with enhanced geometric complexity. In order to ensure accurate adherence to design specifications and to compensate for any deviations, an in-situ measurement system capable of providing feedback on surface geometry within reasonable range is an important tool for manufacturing processes. While there have been many sensing techniques used for monitoring the manufacturing process, many of these are limited in terms of their ability to provide accurate reliable real-time measurements, are off-line systems, or are inappropriate for the hostile machining environment.
In this work, a fibre based common path low-coherence interferometric technique has been successfully developed to measure surface step heights and surface roughness, in air, but more importantly in water. Results are produced from slip gauge sets and reference roughness comparator standards, demonstrating the ability to achieve close to nominal value agreement in air, but water based step height and surface roughness *Ra* values depart further from nominal as a function of media refractive index and dispersion characteristics.

Low-Coherence Interferometry, Metrology, Surface Roughness

1. Introduction

Low Coherence Interferometry (LCI) has been successfully employed as an imaging technology in the biomedical field. Referred to as "Optical Coherence Tomography" (OCT) this interferometric technique owes its growing popularity and interest over the past few decades to its ability to perform non-invasive visualisation of structures at the micron scale. Modern OCT systems are capable of real-time acquisition with high frame rates [1], with resolution, up to 1 µm [2], and delivery systems allowing for imaging of hard to reach areas, making it an attractive sensing modality in a variety of application areas including, high-value manufacturing [3,4].

Although OCT is commonly used for biological samples the same methodology can be applied to achieve high-resolution profilometry [5, 6]. The main difference between OCT and LCI is centred around their light sources wavelength and bandwidth, where typically, OCT systems make use of light sources that are tuned for a biological transmission window. In this work, experimental investigation of the feasibility of a common-path LCI system for measuring smooth and rough surfaces in water and air is considered, as a prelude to in-line surface metrology.

2. Experimental Setup

The setup shown in Fig.1. shows an all-fibre based system, which is principally based on a Michelson interferometer type configuration with a common path that acts as both sensing and reference arm. The system consists of a super-luminescent diode (EXS210068-01, Beratron GmbH), with a 3-dB bandwidth of 58 nm and a maximum power of 5.14 mW. A single mode fibre coupler with a splitting ratio of 50:50 was used for the beam splitting and coupling. The single-mode output leg was held in a fixed fibre clamp with fibre tip positioned parallel to the base of the translation stage.

A Y-Z translation stage, (Zaber Technologies), driven by a stepper motor with manufacturer stated microstep sizes of 0.0467 µm and 0.124 µm were used to move the sample laterally and vertically respectively. The back reflected/scattered light from the sample was coupled back into the single-mode fibre and channelled by the coupler to a spectrometer (MayaPro2000, Ocean Optics) with a 2048 x 64 pixel array CCD detector that covered a wavelength range from 756 nm to 930 nm and an average resolution of 0.21 nm. The noise floor of the electronic instrumentation is negligible being more than 20-dB below the light source noise level. The samples used were: A pair of steel slip gauges (Pitter Gauge & Tool) stacked close together to provide a single translational step height of 12.7 µm and N6 and N7 (0.8 µm and 1.6 µm *Ra*) grit blasted comparator scales (Rubert & Co. Ltd).

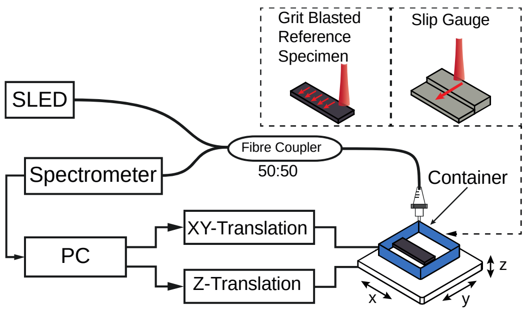

Figure 1. Schematic of the low coherence interferometer based on the common-path approach.

3. Acquisition

In order to resolve the FFT peak location into a depth position from the fibre tip, characterisation of the optical path length between the sample and fibre tip was performed. Characterisation of the fundamental peak relating to the optical path difference (OPD) and subsequently depth was achieved by tracking the maximum peak position, whilst performing translation in the z-axis in small increments up to a distance of 200 µm from a stand-off distance of within microns from the tip of the fibre. Simultaneously, readings from a Michelson interferometer (Renishaw XL-80) setup recorded the stages position. Data was taken in quick succession under controlled room conditions. Comparison of the Renishaw's readings against the tracked peak position, yielded a depth-resolved profile as a function of step size movement and applying a least squares linear fit to this data provided a relationship between z-axis translation and peak position of the FFT data.

Surface roughness measurements were acquired by taking 5 line profiles at discrete points as shown in Fig.1. Similarly Slip gauge height measurements were also obtained in air and in water by taking a single line profile across the height change region. In both cases for the surface roughness and slip gauge measurements, data was recorded at 10 µm intervals for a translational length of 4 mm. Processing of the captured data from the spectrometer was processed in MATLAB and further analysed using Digital Surf MountainsMap software. The sequence of data analysis in this software involved levelling (*least square* line method), to obtain *Ra* values (standard Gaussian filter, cut-off length of 0.8 mm, ISO 4287) for surface roughness measurements and step height measurements.

3. Results and Discussion

The surface roughness measurements for a N6 (nominal *Ra* - 0.8 µm) and N7 (nominal *Ra* - 1.6 µm) grit blasted sample in air and in water using two methods of analysis is shown in Table 1. In Method 1, each line profile was individually processed and an *Ra* value produced, these were then averaged to give an overall *Ra* for the sample. In Method 2, pre-processing averaging was applied to obtain the mean value of the 5 line profiles before analysing the data in MountainsMap.

Analysis from Method 2, makes it possible to observe that the mean measured *Ra* values in air come close to the stated nominal values. In comparison, the mean values shown in Method 1, are not as close to the stated nominal values and are in fact higher. It can be seen that distinct differentiation between N6 and N7 samples can be gathered from the data, this presents the opportunity for surface roughness characterisation of samples using the proposed system setup.

Additional to surface roughness measurements, step height measurements using slip gauges were also taken. A 12.7 µm step height change between two slip gauges was measured in both air and water, giving 12.0 µm and 17.6 µm steps respectively.

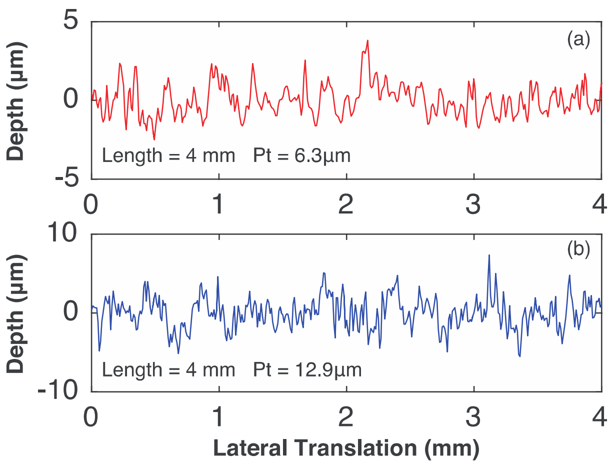

Figure 2. Processed surface profile of a grit blasted N6 Rubert sample in (a) air and (b) water.

For measurements performed in water, readings obtained were not as close a match to those carried out in air. This is due to the optical path length difference as a function of the refractive index change in water and other dispersion characteristics. By accounting for this refractive index change it may be possible to determine correct surface texture values.

Table 1 Measurement results on grit blasted Rubert reference specimens in air and water processed using two diferent methods.

	Method 1 (µm)						Method 2 (µm)
	Ra_1	Ra_2	Ra_3	Ra_4	Ra_5	Mean	Mean
N6 in Air	1.66	1.55	1.44	1.12	1.30	1.41	0.71
N6 in Water	2.71	2.52	2.78	2.59	2.8	2.68	1.41
N7 in Air	4.5	5.51	4.13	4.42	3.73	4.45	2.04
N7 in Water	5.67	5.88	4.98	6.33	7.88	6.14	3.07

4. Summary, Conclusion, and Future Work

This work is exploring the potential of common path LCI as a real time measurement sensor for surface depth and roughness measurements in non-ideal environments, for potential for in-process and on-machine production systems. LCI has potential advantages; resistant to environmental factors, fibre deployable all within good resolution, and at a low cost.

Initial work has demonstrated measurements of step heights on idealised reference slip gauges in air and water, and to the authors knowledge, the first measurement of grit blasted surface roughness using this type of sensing in water. It has been found that variation in step height and texture results will be present when varying the medium, thus raising the challenge for media compensation. In addition, different processing routes may lead to variation of result.

Current work is investigating compensation factors for media conditions, with the view to enabling real time non-contact manufacturing control as a function of depth and surface texture. Additionally, a longitudinal study analysing impact of environment conditions, and a full uncertainty analysis with further exploration of methodology for processing raw surface texture data is being developed.

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