3D profiling in a laser micromachining station using dual-comb LiDAR

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Abstract. We present a coaxial dual-comb LiDAR integrated into a laser micromachining station, enabling in-situ 3D profiling of machined parts with sub-micrometer axial precision, offering a cost-effective solution with high precision capability.

Introduction

Laser micromachining has emerged as the key technique for creating many precision components across various industries, including aerospace, defense, automotive, medical, consumer electronics, and even jewelry. The primary challenge in laser micromachining is the significant time and expertise required to develop and qualify a suitable micromachining process. Development typically involves multiple iterations of micromachining a part, followed by inspection with an external device, such as a laser scanning microscope or white light interferometer. The need to remount the part for inspection introduces challenges in maintaining precision and prolongs the qualification period. Additionally, even with a developed process, success is not always assured due to potential variations in material quality or laser performance, which may necessitate requalification.

The integration of in-situ non-destructive testing (NDT) and evaluation is crucial for establishing an active feedback loop that ensures the achievement of the desired 3D profile, irrespective of variations in sample or laser quality. This could be in principle achieved by incorporating an optical coherence tomography (OCT) system into the micromachining station [1]. However, the typical ultra-high resolution OCT systems are expensive and challenging to integrate. Here we demonstrate an alternative approach utilizing the emerging dual-comb ranging technique [2], which has compelling advantages such as high precision, an extensive working range, and the potential for cost-effective implementation.

Experimental Setup

Figure 1 shows the experiment setup and a typical experimental signal obtained per single scanner position. We integrated a recently reported single-cavity dual-comb laser [3] operating at 1056 nm center wavelength, with 23 nm FWHM bandwidth and 1 GHz laser repetition rate into a laser micromachining station. For laser micromachining we used a Time-Bandwidth Duetto 1064 nm picosecond laser. Because of wavelength overlap the two lasers have been combined via polarization.

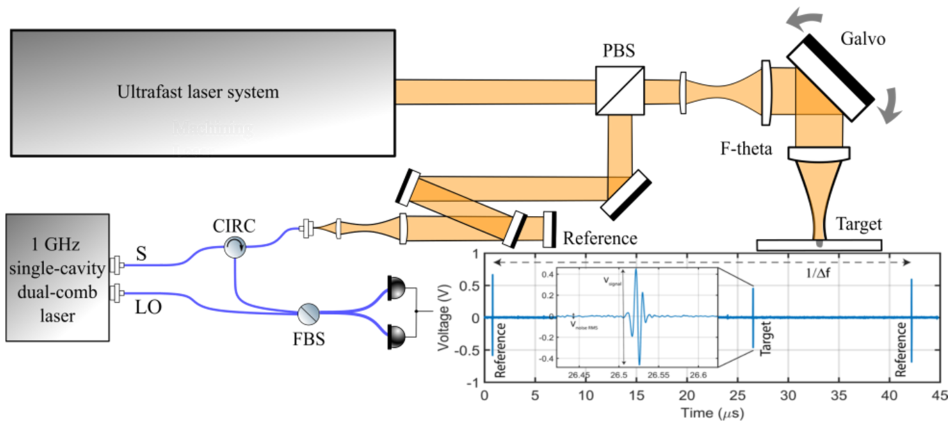

Fig. 1. Experimental setup. S – signal, LO – local oscillator, CIRC – circulator, FBS – fiber beam splitter, PBS - polarizing beam splitter. Inset shows example dual-comb LiDAR signal.

Coaxially combined laser beams are then sent into a beam scanning system (intelliSCAN14, SCANLAB), after which the beams are focused with a 100 mm focal length f-theta lens on the sample. The backscattered dual-comb laser light is collected and mixed with a local oscillator to coherently amplify the returning light. The measurement setup was estimated to be sensitive to sub-nW average power of returning light while up to 60 mW have been sent towards the target indicating ranging sensitivity up to 77 dB. The interferograms have been digitized with a 250 MS/s sampling card and acquisitions were triggered on the scanner motion. In this proof-of-concept demonstration, the data was processed offline, but the used data acquisition card is compatible with real-time signal processing as we have reported previously in the context of dual-comb range tracking application with a similar dual-comb laser [4].

Experimental Results

Figure 2a shows the obtained 3D profile of a laser micromachined part (at the end of machining). This part was then 3D profiled (Fig. 2b) with an external Laser Scanning Microscope (LSM) (Keyence, VK-X3000). In addition, we also profiled with dual-comb LiDAR the sample prior and during the machining process. A representative cross-section is shown in Fig. 2c. The 3D profile observed using the dual-comb LiDAR setup matches well to the one obtained using with LSM, except that the dual-comb LiDAR could measure high-aspect-ratio holes better. To judge on the dual-comb LiDAR performance, we have collected 20 measurements (Δf cycles) per point. The standard deviation of the obtained distance measurements was on average 680 nm at 20 kHz update rate. The depth measurement precision was increasing as a function of square root of number of averages and in case of 10 averages (2 kHz update rate per point) it reached 220 nm average standard deviation per pixel. Because of this, dual-comb LiDAR data also allow to gain insights into the surface roughness.

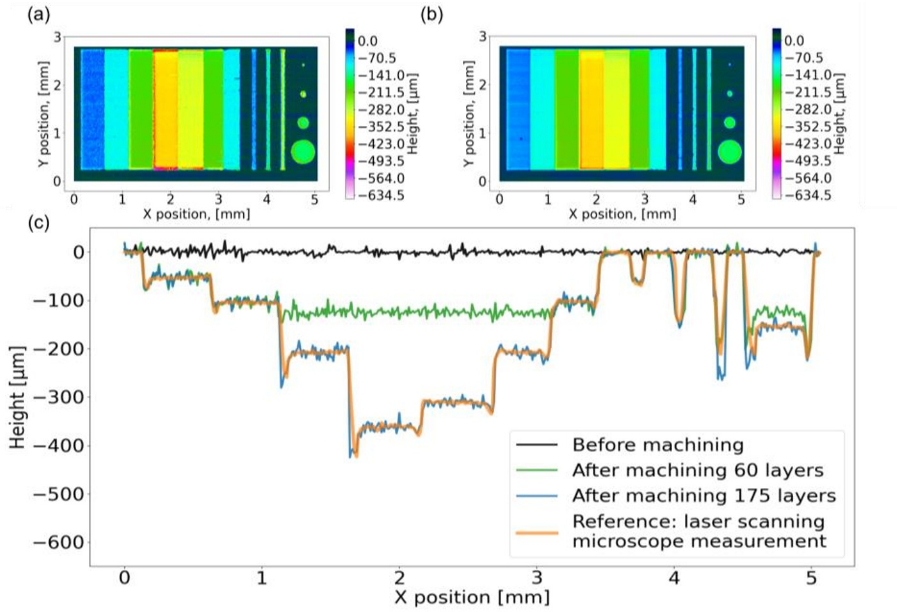

Fig. 2. 3D profile of laser micromachined part: (a) measured in-situ with dual-comb LiDAR, (b) measured with external laser scanning confocal microscope. (c) Example profile of the 3D profiles, including prior, during and after the machining process.

In conclusion, we have demonstrated coaxial dual-comb LiDAR integration in a laser micromachining station, allowing for high-performance 3D profiling during the micromachining process. The integration allows for NDT and evaluation of the machined parts, helping to dramatically reduce the effort when developing the micromachining process. In comparison to the confocal LSM, the presented technique offers better capability when measuring high-aspect ratio features. The presented technique can not only serve as a replacement of a 3D profiler, but also it may provide auxiliary functions, such as autofocus and may be used as a way to obtain active machining control.

References

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