euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025

www.euspen.eu

M3MH on-machine multi-scale 3D metrology in SLM-based Ultra Short Pulse adaptative micro-machining

Borja de la Maza[1] , Toni Ventura-Traveset [1]

[1]*DataPixel (Innovalia Metrology)*

bmaza@datapixel.com, toni.ventura@datapixel.com

Abstract

Ultrashort pulse (USP) laser micromachining has emerged as a key technology for precision material processing, offering exceptional accuracy in applications such as micro-ablation, cutting, and drilling. The integration of Spatial Light Modulators (SLMs) for dynamic beam shaping has significantly enhanced processing efficiency and flexibility. On-machine multi-sensor 3D dimensional metrology is crucial for ensuring precision in fabricating micro-scale features, with recent advancements focusing on adaptive control systems to improve process reliability and efficiency. The M3MH™ multi-scale on-machine metrology solution provides a competitive and cost-effective alternative to traditional metrology off-line methods. M3MH's extended point cloud processing and analytical capabilities simplify and optimize SLM-based USP operations, implementing critical operations for micro-machining planning and execution. This approach revolutionizes the production of complex parts with micro-structures, enhancing flexibility and ensuring superior accuracy across different scales. The platform offers an extendable solution for future integration of new-generation micro and nano-scale sensors, reducing the cost and time of implementing complex manufacturing processes.

On-machine dimensional control, multi-scale 3D metrology, Ultrashort pulse (USP) laser micromachining, Spatial Light Modulators (SLMs)

1.Adaptative SLM based USP micromachining

Ultrashort pulse (USP) laser micromachining has become a pivotal technology for precision material processing, offering unparalleled accuracy in applications such as micro-ablation, cutting, and drilling. A significant advancement in this field is the integration of Spatial Light Modulators (SLMs) for dynamic beam shaping, which enhances processing efficiency and flexibility.

On-machine dimensional metrology in ultrashort pulse (USP) laser micromachining is critical for ensuring precision and accuracy in the fabrication of micro-scale features. Recent advancements have focused on integrating real-time monitoring and adaptive control systems to enhance process reliability and efficiency.

A notable development in this field is the combination of data-driven machine learning with physical modeling to optimize laser-induced micromachining [1]. This approach efficiently captures the comprehensive optimization process, achieving high material removal rates and precise microgroove depths. Such integration allows for real-time adjustments during machining, leading to improved outcomes. These approaches require a very accurate knowledge of the surface's topography, achievable only by integrating multiple metrology sensors working at different scale dimensions.

The work presented in this paper was supported by the EU project "METAMORPHA—Made-to-measure micromachining with laser beams tailored in amplitude and phase." [2]

2.On-machine multi-scale 3D metrology

No single metrology tool covers all scales with the required accuracy and productivity for flexible USP-based industrial micro-machining equipment. This is why external off-line measurement instruments are the usual metrology solution in micro-machining processes. Nevertheless, on-machine dimensional metrology offers clear advantages: it minimizes errors caused by handling, repositioning, or environmental factors; it reduces downtime, reducing setup and inspection time; and it enables digital recording of measurement data for quality control, compliance, and closed-loop process improvement. The new developments of M3MH™ on-machine multi-scale 3D dimensional metrology integrate multi-sensor capabilities to existing micro-machining equipment, maintaining high precision across different sensors, combining data from different scales (nano, micro, macro) and offering seamless integration of measurement techniques with differences in resolution, accuracy, and traceability.

2.1. M3MH™ metrology platform

Innovalia Metrology M3MH™ is a well-known platform [3] for on-machine 3D measurement (on-machine verification) in CNC machines. It allows manufacturers to perform precision metrology directly in their machining equipment, improving productivity, reducing errors, and minimizing downtime.

M3MH™ offers a complete CAM software platform, allowing CAD-based measurement programming, simulation, measurement execution, automatic geometry feature extraction, disparity map computation, and data analytics.

The actual capabilities of M3MHTM have been extended to allow the integration of different optical metrology sensors at the micro and nanoscale, adding new data processing modules for textured surface characterization. The multi-scale data can be used for micromachining process planning, CAM programming, microstructures quality control verification, and closed-loop process optimization.

2.1. Combining the best of each optical metrology sensor

To prove and test the concept, an M3MH™ set-up has been developed, successfully integrating a micro-scale new generation DataPixel Optiscan MH sensor with a customized nano-scale Precitec chromatic confocal sensor using as testing platforms a TRIMEK Spark CMM, and a Lasea USP micro-machining center.

The new generation of DataPixel Optiscan 3D optical sensor (figure 1) implements high-accuracy structured light triangulation in a very compact and light unit, making integration into existing CNC machines easier. The unit allows scanning with an axial resolution < 2 1m and is capable of acquiring more than 100 Kpoints/s; this sensor is specially designed for high-speed 3D surface characterization at the micro level in CNC machining centers.

Additionally, a nano-scale Precitec chromatic confocal sensor has been tailored to M3MH, offering nano-scale axial resolution < 45 nm, a working range of 2.1 mm at a working distance of 15 mm.

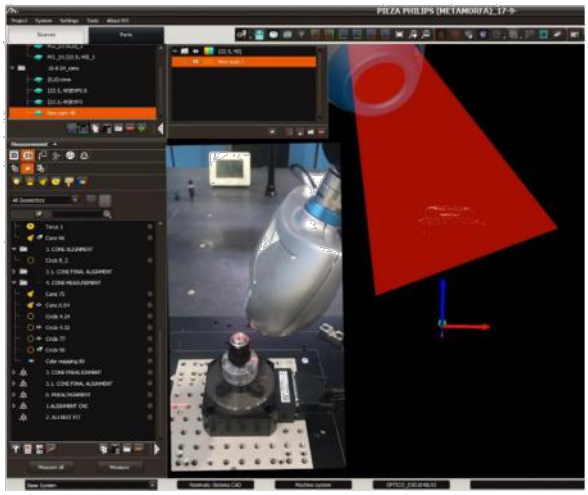

Figure 1. Datapixel Optiscan MH integrated in the USP micromachining solution

M3MHTM's new, improved Smart CNC Interface and Data Fusion components (figure 2) extremely simplify the use of both sensors in the same working piece. Optiscan MH is used for fast surface 3D data capturing, and the Precitec confocal sensor is used for very high-resolution topography measurements, with lateral resolution < 3 1m . Both point-clouds can be combined in the same digital object, simplifying data fusion and multi-scale data management.

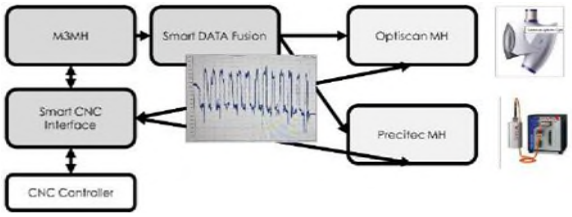

Figure 2. Basic architecture of the multi-sensor on-machine M3MH™

2.2. Intregrating OPC-UA CNC controllers

For CNC machine control, M3MH™ integrates an innovative CNC interface with most of the existing controllers in the market, using a real-time automatic G-code generator.

Industry 4.0 is pushing CNC controller manufacturers [4] to adopt OPC-UA, and M3MH™ has also been extended to support last generation OPC-UA controllers. The developed interface has been tested with OMRON CNC.

Additionally, OPC-UA has been adopted and implemented in M3MH™ for process automation, simplifying synchronization of piece loarding/unloading, metrology and manufacturing processes.

3. Closed-loop process optimization

M3MH™ capabilities have been extended to simplify and optimize USP micro-machining operations. The new software modules implement critical operations for micro-machining planning and execution, including: surface topography characterization of micro-structures; micro-scale pointcloud optimization and filtering; disparity map computation and processing for USP process planning and generation; automatic slicing for USP processing; simulation.

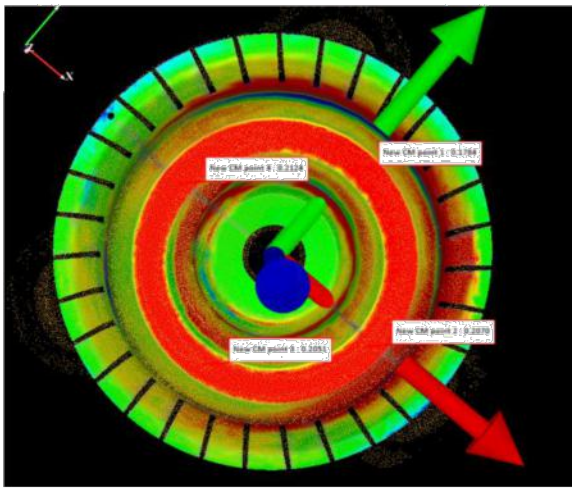

Figure 3. A computed disparity map indicates areas where material removal will be performed by USP micro-machining.

5. Conclusions and future work

On-machine multi-scale 3D metrology for ultrashort pulse (USP) laser-based micro-machining enables real-time measurement and quality control, revolutionizing the production of micro-structured complex parts. This approach enhances flexibility by integrating metrology directly into the manufacturing process, reducing the need for external inspections and minimizing errors. It allows manufacturers to achieve high precision across different scales, ensuring superior accuracy in intricate micro-features. M3MH™ offers an extendable platform for future integration of new-generation micro and nano-scale sensors in sophisticated micro-machining equipment. This simplifies multi-scale metrology and reduces the cost and time of implementing adaptative manufacturing processes.

References

[1] Buske, P., Jansses, F., Hofmann, O., Stollenwerk, J., Holly, C. "Enhancing three-dimensional beam shaping accuracy through cascaded spatial light modulators using diffractive neural networks", (17 June 2024); Proc. SPIE 13023, Computational Optics 2024, 130230A

[2] METAMORPHA—Made-to-measure micromachining with laser beams tailored in amplitude and phase, metamorpha.eu

[3] Innovalia Metrology, M3 MH: Complete Measurement Software for Machine Tools, innovalia-metrology.com

[4] Haskamp, H., Meyer, M., Möllmann, R., Orth, F., & Colombo, A. W. (2017, July). Benchmarking of existing OPC UA implementations for Industrie 4.0-compliant digitalization solutions. In 2017 IEEE 15th *International Conference on Industrial Informatics (INDIN*) (pp. **589**-594). IEEE.