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Generic integration tools for reconfigurable laser micromachining systems

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ABSTRACT

Laser micro-machining (LMM) is an attractive manufacturing process due to its intrinsic machining characteristics such as such as non-contact processing and capabilities to machine complex free-form surfaces in a wide range of materials. Nevertheless, state-of-art LMM platforms still do not offer the repeatability, reproducibility and operability of conventional machining centres, e.g. the flexibility to realise complex machining configurations and also to combine LMM with other complementary processes in hybrid manufacturing systems and production lines. The paper presents the development of three generic integration tools for improving the system-level performance of reconfigurable LMM platforms. In particular, the research reports the design and implementation of modular workpiece holding device, automated workpiece setting up routine and automated strategy for multi-axis LMM machining employing rotary stages. An experimental validation of their accuracy, repeatability and reproducibility (ARR) are performed on a representative state-of-art LMM platform. The results demonstrate the flexibility and operability of the proposed tools to address important system-level issues in LMM by creating the necessary pre-requisites for achieving machining ARR better than $\pm 10\,\mu m$.

1. Introduction

Technological advances across different application areas, e.g. micro-electromechanical systems, micro-sensor systems, micro-electronics, smart communication systems and biomedical devices, have driven the demand for product miniaturisation, increased accuracy and precision of products while satisfying constantly growing requirements for production efficiency and reliability and improved environmental footprint [1–3]. To address both product and process development requirements underpinning the product miniaturisation trends, considerable research efforts are focused on increasing the capabilities of various manufacturing processes such as milling, forming, additive manufacturing and laser processing. Also, this includes the development of hybrid manufacturing platforms that combine innovatively the capabilities of complimentary processes and thus to exploit the advantages offered by their integrations while overcoming some of their shortcomings [1].

Laser micro-machining (LMM) is a research and development area that have been attracting a significant interest both from the research community and industry due to its appealing intrinsic machining characteristics such as non-contact processing, capabilities to machine complex free-form (3D) surfaces in a wide range of materials and also to combine/integrate with other complementary processes in manufacturing platforms. Other important reasons are the underlining advances in laser technology to meet manufacturing requirements for increased throughput and quality of miniaturised products that incorporate functional features with different scales and geometrical complexity while extending the process capabilities for in-situ selective surface treatment and functionalisation [4–6]. Some examples that demonstrate the wide ranging manufacturing capabilities of the LMM technology in different industrial sectors and contexts are the production of: aspheric micro-lens on transparent materials [7], coronary stents on metallic samples [8], MEMS-based variable capacitor device [9], a diffractive optical device on carbon nanotubes-based buckypaper [10] and replication masters with micro- and nano-scale features on bulk metallic glasses [11]. Furthermore, another direction in broadening the capabilities of the laser micro machining technology is its integration in hybrid manufacturing platforms [12]. For example, an integration of micro-milling and laser structuring was reported to produce complex biotechnology products with feature sizes smaller than the cutting tool diameter without compromising machining time [13].

However, the literature review reveals that even though commercial LMM platforms are available, the broader take up of this attractive manufacturing technology both as a stand-alone

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fabrication route and also as a component in hybrid manufacturing solutions is still to come [14]. A detailed capability maturity model of the process also shows that in comparison to micro-milling, which is ranked as a mature process and is widely used across different industrial sectors, laser micro processing is considered not sufficiently mature due to various open issues related to the process fundamental characteristics, process predictability and process reliability [15]. In addition, the literature shows that in the last two decades the research efforts were mainly focussed on investigating laser-material interactions, process modelling and empirical process optimisation to address specific manufacturing requirements, such as surface integrity and processing time, while not paying sufficient attention to the development of generic tools and techniques for extending the LMM capabilities both as standalone machine tools or a component technology in manufacturing platforms. The research on improving the performance and reliability of LMM platforms as machine tools was mostly limited to:

- advances in optical beam deflection systems and their simultaneous use with mechanical stages for processing laser surface areas [16,17];
- development of generic tools for counteracting the dynamics effects of optical beam delivery systems [18–20];
- Beam-path generation tools based on commercially available CAD/CAM systems for creating NC part programmes for machining components with high geometrical complexity [21–23].

At the same time there are significant advances in LMM component technologies, e.g. the growing number of short and ultrashort laser sources with constantly increasing maximum pulse energies and repetition rates [24], decreasing pulse durations and shorter wavelengths [25], ultra-high speed variable focus elements for advance beam delivery [26], high dynamics optical beam deflection systems with integrated digital scanner motor control electronics [27], linear and rotary mechanical axes with a repeatable positioning resolution of less than 0.1 μm and less than 30 μrad, respectively [28]. Nevertheless, the advances in these component technologies do not immediately translate into improvements of the LMM performance at the system level in terms of machining accuracy, repeatability and reproducibility (ARR) unless adequate integration tools and techniques are used to achieve the necessary level of components' synergy without compromising their performance. The importance of integration tools and techniques in LMM installations is exemplified in a comparative study of three different LMM systems that have comparable component technologies with very similar specifications, but in spite of this, their ARR results were significantly different and far away from the stated specifications of the equipment manufacturers [29]. Thus, this reiterates the importance of developing and validating critical integration tools and techniques for LMM platforms and thus to bring the technology to a maturity level of well-established manufacturing processes such as micro-milling. Such research and development efforts are necessary to underpin both the standalone use of LMM systems and also their integration in hybrid manufacturing platforms in different application contexts.

This paper reports research on developing and validating generic system-level solutions for integrating component technologies in LMM and thus to improve significantly the process ARR. First, key component technologies of LMM systems are introduced and important integration solutions are identified by conducting a system-level critical analysis of state-of-the-art LMM platforms. Then, three generic integration tools are proposed and validated on a representative LMM system. Finally, conclusions are made about the capabilities of proposed system-level integration solutions.

Table 1
Functional specification of component technologies for LMM.

Main component technologies
• Short/ultra-short pulsed laser source(s) with capabilities to vary the average power, repetition rates, wavelengths and laser spot characteristics for realising different material processing mechanism
• 3D optical beam deflection system with high dynamics
• Focusing telecentric lens for a consistent beam incident angles within the field of view
• Linear mechanical stages with high positioning accuracy and precision to realise Infinite Field of View (IFV) processing
• Rotary mechanical stages for realizing different manufacturing configurations
• Measurement probes for inline inspection and alignment of parts
• Optical beam delivery path with capabilities to vary the beam spatial profile
Auxiliary Component Technologies
• Machine frame structure to minimise any disturbances from the surrounding environment
• Enclosure for Class 1 laser processing [30]
• Laser fume extractor
• Inline energy/power measurement device
• Laser beam profiler for setting up optimal laser machining parameters
• Modular workpiece holding for realising different machining configurations and robust integration into hybrid manufacturing systems
• Workpiece's setting up routines
• PC-based control system with specialised Graphical User Interface (GUI)

2. System-level critical analysis of factors affecting the LMM performance

2.1. Component technologies' requirements

A reconfigurable LMM platform should have sufficient flexibility to realise different processing operations, e.g. structuring of parts that incorporate functional features with varying sizes and geometrical complexity, polishing of free-form parts, capability to process different materials, e.g. metals, polymers and glasses, while satisfying specific requirements in regards to ARR, surface integrity and processing efficiency. Such concentration of operations in a single machining setup requires system-level functionalities that are determined both by the component technologies employed for their realisation and also by a range of integration tools and techniques used to assure their functional operability within predefined ARR constraints.

A system-level analysis of five different implementations of such reconfigurable LMM platforms was conducted to identify the common component technologies that were necessary for their implementation. It is important to note that the five investigated LLM systems integrate similar and in some case identical state-of-art representative component technologies and they are built by different system integrators. In this way an attempt was made to identify and assess objectively the system-level integration issues in implementing LMM systems. An example of such representative LLM platform is described in [51], while another representative laser micro-machining platform is presented and explained in details in Section 4.1. The results of this analysis are provided in Table 1, where their component technologies are split into two categories, in particular main component technologies, which were available across all LMM configurations and auxiliary ones, whose implementation and functionality varied between the platforms but were required to fulfil common requirements in regards to systems' operability, stability, flexibility and safety.

2.2. System-level integration issues

To conduct a critical analysis of integration issues in designing and implementing LMM platforms, it is very important to study laser systems with almost identical or comparable hardware