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Industrial demands to ultrashort pulse laser machines

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Abstract

Ultrashort pulsed laser processes provide numerous advantages for raising applications in nearly every emerging market. Therefore machine manufacturer face the challenge to integrate and control a variety of laser sources, specialized optical and multi-axes motion systems and provide at once a robust, productive and proven machine frame at reduced number of units. At the Laser World of Photonics 2015 micar presented a USP laser machine that had been designed in a multidisciplinary framework of experts in metal sheet manufacturing, USP laser processing and machine frame modelling. Special attentiveness had been given to:

- A Machine Condition Monitoring System, e.g. by the assortment of parameters, their data management and outlining of benefits for production
- Plattform design – dedicated to ultrashort-pulse laser micro machining, e.g. the installation space for beam guiding and forming systems, the encapsulation of the machine compartments and their thermal optimization
- Advanced Extraction System, e.g. optimization of fluid flow to avoid recirculation, dead water and vortex regions

Keywords: ultrafast laser machining; machine condition monitoring system; internet of things; IoT industry 4.0; micro machining

1. Introduction

Beyond the first enthusiasm driven by its outstanding processing quality ultrafast laser applications face the challenge of providing evidence to its productivity. Beside investigations to reduce the primary processing time e.g. by high speed scanning systems or massive parallelization further reasons have strong influence on the uptime and productivity of laser micro machines, e.g. handling issues, inherent precision of machine frames as well as the reproducibility and traceability of machine conditions and failures. The following topics of the ultrafast laser machine C554.1 are discussed here:

- machine condition monitoring
- frame material
- analyzation and optimization of thermal expansion by finite-element method
- analyzation and optimization of fluid flow by finite-volume method
- flexibility of the machine design

Nomenclature

UFL	ultrafast laser
CFD	computational fluid dynamic
FEM	finite-element method
CMS	condition monitoring system

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1.1. Application

Machine Condition Monitoring systems (CMS) are intended to predict from unwanted machine conditions in order to avoid sudden machine breakdown and to reduce the reject rate (Schöning 2014). In practice error diagnostics with replication and re-tracing of errors lead easily to machine standstill of several hours. With machine hour rates in the range of 100 € it is economically worthwhile to control ultrafast laser machines by CMS. Quality criteria of a CMS are:

- Capability for multiple sensor types and architectures
- Time-coordinated data storage
- Data storage and appropriate data compression algorithm (Schöning 2014)
- Preliminary of a set of interfaces, e.g. RS232/485, USB, analogue and digital Inputs
- Connectivity of processing sensors, especially laser sensor devices and cameras
- Messaging, plotting and reporting functions
- Data access and ability for continuative data processing / data matching

1.2. Machine Condition Monitoring

The integrated machine condition monitoring system consists of a stand-alone 19-inch controller rack with attachable tethered sensor devices (Pulsar 2016). Based on failure mode analyses of multiple laser micro processes several sensor types had been selected to cover the most influencing machine and ambient conditions according to Fig.1 below: temperature, ambient / process gas pressure, humidity, vibration, image based information, digital and analogue inputs and software executed commands.

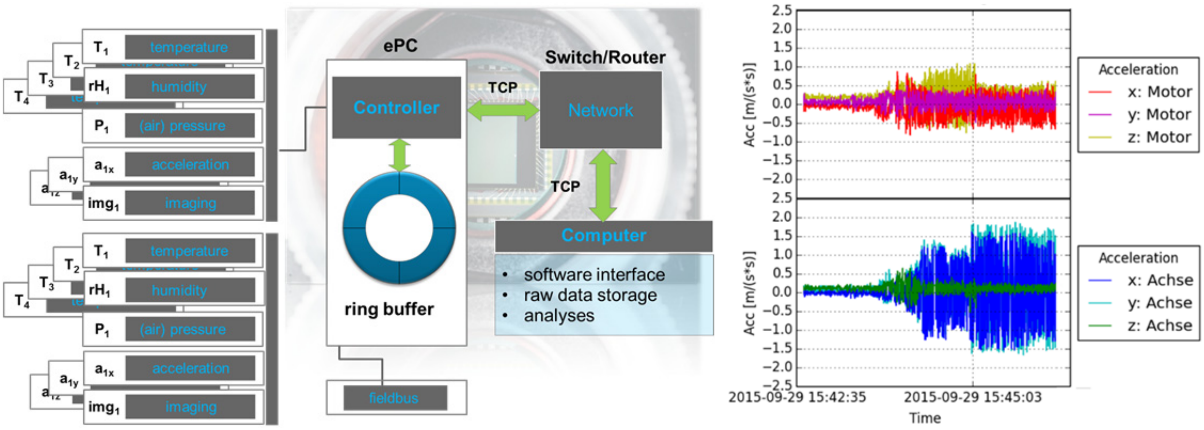

Fig. 1. (a) sensor grid architecture with embedded PC and network interface and paired peripheral sensors; (b) 3D acceleration plotting of vibrations during run-up of a high-speed drilling head for ultrafast laser machining.

1.3. Frame material

The machine frame is made of mineral casting which is a multi-component material consisting of basalt, quarz and epoxy resin. The material is established in the field of machine frames including applications with highly dynamic processes. The material properties show good damping behavior, the thermal expansion coefficient is comparable to steel. Yield strength and E-Modulus are a bit lower than hard stone but usually that is not important when dealing with machine frames. The required stiffness can be obtained by choosing wall thicknesses appropriately. The cold hardening process of the mineral casting offers advantages regarding the flexibility in shape design. Compared to steel/iron casting residual stresses or cavities are not an issue when large accumulations of material are requested which can be necessary in order to optimize the thermal expansion behavior of the machine frame. Furthermore due to the cold nature of the casting process interface elements like inserts or mounting plates or piping and wiring can be positioned in the mould. They retain a highly accurate position when the hardening process is finished. Cutting processes like drilling or milling on the large machine frame can be avoided this way. With respect to the moulding process the design of the machine frame is subject to very low restrictions.

This offers the opportunity to place the material in an optimized manner in order to fulfill mechanical requirements which result from the thermal expansion behavior or the response to dynamic excitation. The thermal expansion coefficient is comparable to steel and close to aluminum, much closer than the thermal expansion coefficient of granite. This leads to advantages in the thermal expansion behavior when exposed to temperature changes, as long as the axis are not build out of granite themselves.

1.4. Analyzation und optimization of thermal expansion by finite-element method

After the first installation the machine is exposed to the local conditions at the installation site until it reaches steady state. This can last to order of 10^2 hours. The thermal expansions which result from the differing temperature fields between transport history and the conditions at the installation site can then assumed to be completed. The offset parameters of the laser-optical components which strongly influence the precision of the C554.1 can now be adjusted. After installation is completed the C554.1 is supposed to operate in constant ambient conditions in order to avoid an offset drift leading to exceeded tolerances.

Since experience shows that constant ambient temperature cannot be achieved in daily industrial practice, the sensitivity of the machine frame with respect to disturbances in ambient temperature has to be investigated. In (Gleich 2008) the author points out that thermally imposed errors in machine tools need to be analysed in more detail during the development process, because other typical errors, like static or dynamic deformation, were increasingly controlled and diminished concerning their order of magnitude. Finite-Element calculations were mentioned as an outstanding tool for estimation and optimization.
In (Galant et al. 2015) (Neugebauer et al. 2015) (Franke et al. 2010) it is stressed that thermo-elastic simulations are essential for description of the long term behavior of machine tools and therefore important for the design of error compensation solutions.

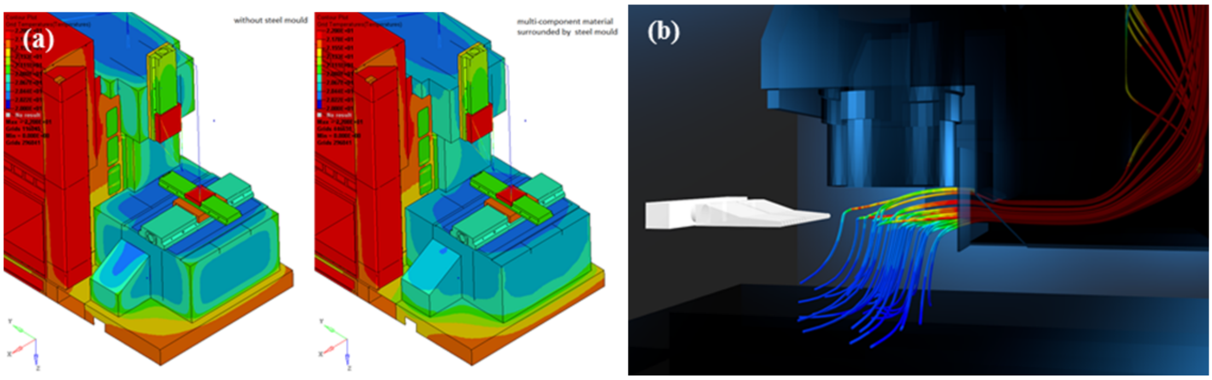

Fig. 2. (a) Temperature field after 1h heating by a change of the surrounding temperature by 2K. Comparative effect of the steel mould on the temperature of the components. T_{parts} [°C] 20 °C - 22 °C; (b) Pathlines of laser smoke particles blown by air nozzles and sucked by the suction system, integrated into the z-axis mounting bracket

In this application the thermo-mechanical analysis is based on a FEM model of the machine frame and the laser beam path. The calculation process consists of two steps. In the first step different scenarios for changes in ambient temperature are applied as thermal boundary conditions. The scenarios include different heating/cooling rates and different locations of the temperature changes on the machine frame. The result is a 3D temperature field. In the second step this field is mapped on the mechanical model with its kinematic boundary conditions (mainly: interface between machine foot and floor). The final result of this step is a displacement field of the machine frame driven by thermal expansion. The offset drift can be evaluated at the characteristic points of the beam path. Based on this method the following conclusions can be drawn and actions can be taken respectively:

- The design of the machine frame can be fine adjusted in order to minimize thermal expansion effects before the prototype is built.
- Scenarios of change in temperature which cause a large effect on the thermal expansion can be identified and special caution can be taken during operation of the machine.

1.5. analyzation and optimization of fluid flow by finite-volume method

Using the C554.1 with ultrafast laser processing results in the generation of nanoparticles. Their possible health risks are still under discussion and not conclusively investigated but it seems reasonable to have a controlled removal of these particles (Jakschik 2016). As a consequence the C554.1 is equipped with a suction and filter system capable of depositing nanoparticles. The particles have to be transferred from the location where they emerged to the inlet of the suction system. This has to be achieved by the fluid flow in the workspace which is dominated by the current velocity of the inlet of the suction system. Due to their very low mass the particles follow the streamlines of the fluid even on paths with distinct curvature, inertia phenomena are not an issue. If one can assure that the majority of streamlines in the workspace reach the inlet of the suction system the particles will reach it too.

In order to sustain this a computational fluid dynamic (CFD) analysis was performed. The simulation model contains the workspace with its major inlet sections, the air conveyor which is mounted on the motion axis and the piping which leads to the suction system. Based on the CFD analysis the characteristic curve of pressure drop vs. flow rate can be calculated for the upper mentioned model geometry. A similar characteristic exits for the suction system. The intersection of these two curves represents the operating point. The conditions of the operating point are used to calculate the field of velocities and streamlines originating from the area where particles emerge. These two results indicate vortex areas and dead flow regions where unwanted deposition of particles might occur. With the CFD analysis parameters of the suction system like the position of the suction inlet and the inlet of the workspace were optimized.

1.6. flexibility of the machine design

The C554.1 is based on a platform ground carrier with an integrated interface for network, power and air supply at the rear side and two-sided openings for fork lift transportation. Access to the working space is provided from two sides by an L-shaped pneumatic lift gate and additionally for service operations from one side by a swing door. Consequently and as substitute conveyor belts, loading and robotic systems can be attached to the frontend of the machine bed. The combination of a metal frame dead-mould with inner mineral casting leads to a monolithic machine base (see fig. 3 (b), emphasized in green) with improved thermal properties and leads to an open machine architecture and high capabilities of integration (Neugebauer 2012), e.g. sensors, lead through or internal cooling devices (Jakisch 2016). The eponymous C-shaped machine bed is mounting platform for crossed linear stages, a vertical z-stage with integrated suction duct and provides generous mounting space for all large ultrafast laser sources with up to three beam paths and / or secondary fiber guided laser sources.

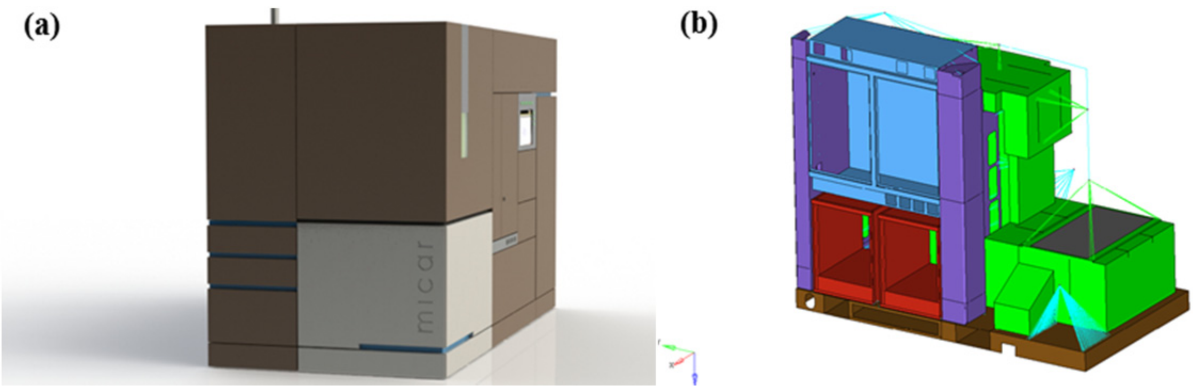

Fig. 3. (a) Ultrashort pulse laser machine C554.1 (b) modular machine platform of C554 with monolithic machine base, platform ground carrier, thermal isolated electrical compartment.

Power engines, e.g. vacuum pump, controller, electric energy converter, stand-alone supply units and exhaust systems can optionally be integrated into the electrical cabinet, in two extendable 19-inch racks or roll-guided carriers, hidden behind foldable doors at the machine rear side. Machine compartments and feedthroughs are IP encapsulated in direction to the laser, laser optics and working space to provide laser safety and prevent from contamination. The housing itself is double walled in order to ensure laser light protection, thermal insulation and - in a limited range - air tightness which is important for a proper guidance of the air flow inside the workspace.

An integrated compartment for pneumatic supply provides pressured air supply for various applications, e.g. supply of pneumatic lift gate, zero point clamping devices, grippers, cross jet and contains multiple electro-magnetic valves as well as a zero-air-generator that can be attached to the tube-guided beam path from the laser source to the scanning system. In the backend the software architecture of the machining systems allows to attach control plug-ins, e.g. for process specific processing heads and peripheral systems.
A growing library of machine stages, scanning systems, measuring devices and laser sources allows to meet customer specific requirements without having costly construction and programming efforts instead of having benefits of a mature machine design dedicated to ultrafast laser processing.

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