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Application of laser doppler vibrometry to characterize the laser drilling process

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Abstract
Laser drilling is being used more and more frequently in many industries, such as the aerospace, medical and electronics industries, to produce precision bores. A wide range of technically difficult-to-machine materials are applied. Laser drilling has already been intensively researched in order to investigate the basic mechanisms of the drilling process and the influences of various machining parameters on the quality of the holes. These findings have explicitly led to more successful machining processes of various technical components and industries. Despite all the advantages, there are some limitations of the laser drilling process and thereby a demand for innovative solutions to increase productivity. This paper presents a novel approach to the characterisation of the laser drilling process through the analysis of the acoustic signal characteristics. The objective is to apply a new generation of optical microphones to detect key aspects of the laser drilling process. This enables the development of new strategies to optimize the laser processing parameters, increasing repeatability and productivity for industrial applications.

Laser drilling, acoustic emission, optical microphone, process optimization

1. Introduction

Laser machining of materials is widely used in a wide range of technological applications thanks to its versatility and efficiency. It is increasingly used for drilling, cutting and surface structuring of industrial materials and biomaterials [1]. Laser machining is a non-contact micromachining technology that competes directly with conventional tool-based processes such as micro electrical discharge machining (µEDM) and mechanical micromachining. The tool-based processes have significant wear problems that lead to a reduction in shape accuracy G_F and productivity at high production volumes [2]. In addition, mechanical micromachining has limitations in the production of brittle and high-strength materials [3].

Laser drilling is applied to produce precision holes in a wide range of materials that are technically difficult to machine. It is used specifically in the manufacture of products with the highest requirements and quality [4], for example in aerospace, medical and microsystems technology. In aerospace, turbine construction in particular is a core topic with many approaches for technical optimisation, such as a large number of closely spaced cooling holes in the engine components. These include turbine blades, nozzle guide vanes, combustion chambers and afterburner areas. In the biomedical field, laser machining enables the production of microsurgical instruments and microcomponents for implantable systems. Other fields of application for laser drilling extend beyond the manufacture of microelectronic components. One example is the production of silicon wafers, in which many micro-holes have to be drilled with high positioning accuracy.

Laser-induced ablation is determined by the absorption of photon energy on the surface of the material, which enables the ablation of material [5]. The laser excitation takes place via the interaction of the photons with the bound electrons of the material. Depending on the irradiated workpiece and the optical properties of the surface, the energy coupling of the laser radiation can be linear or non-linear. This absorption leads to elementary excitation of the solid state lattice already below the ablation threshold [6]. The threshold value depends on the material properties, including the melting and evaporation temperature ϑ, the material density ρ, the specific heat capacity c_P and the absorption coefficient α [7].

When a laser beam is focused on the surface of a material, the focal diameter d_u can be in the order of magnitude of the wavelength λ of the laser. Based on the laser fluence φ at the focal point, the material is heated, melted and/or vaporised. By controlling the laser fluence φ and the exposure time t_E on the material surface, the above-mentioned types of processing can be realised [8]. Laser drilling is a non-contact, precise, flexible and reproducible manufacturing process that can be used to produce holes of any shape in all types of materials regardless of their hardness. The special advantages of laser drilling include the following [4]:

- Producing holes in all types of engineering, difficult-to-machine materials such as diamonds, hard metals and superalloys, ceramics and composites without tool wear;
- Achieving high hole quality with minimal burr and spatter;
- Freedom of size and shape;
- High precision;
- Produce holes at any angle.

Laser drilling has already been intensively researched to investigate the basic mechanisms of the drilling process and the influences of various machining parameters on the quality of the holes. These findings explicitly led to more successful machining processes of various technical components and industries. However, research and development is still ongoing to improve hole quality by eliminating deformation and spatter and minimising taper. Drilling holes in delicate and brittle work materials, increasing repeatability and improving productivity are current active research areas [9,10,11,12,13,14,15,16,17].

2. Optimization of the laser drilling process

Laser drilling has several advantages to conventional processing, especially considering micromanufacturing. However, there are still limitations considering the online monitoring and real time quality control.

The laser radiation induces a thermal gradient on the surface of the material, which promotes its melting of vaporization. The ablated material is removed out of the borehole by the recoil pressure. If the material is not completely sublimated, some of the ejected molten material settles as splashes around the borehole opening or solidify and stick to the inner wall and edge of the borehole. This negatively affects the shape accuracy G_F and the quality of the hole. Often the diameter d of the entry and exit holes are different or asymmetric. The heat conduction in laser drilling can create a certain heat-affected zone around the drill hole. Thus, laser drilling is sometimes associated with geometric errors related to hole size b, taper, roundness and metallurgical errors. Examples are spatter, recast layers, micro-cracks and structural changes in the heat-affected zone. There is a need to increase repeatability and productivity while improving the quality of the bores for existing laser machine systems. In particular, the development of systems for monitoring and automatic process control promises an increase in drilling quality and productivity.

The aim of the research activities is the development of a compensation system for real-time detection of the drilling condition, in order to optimize the process parameters during the laser processing. For this purpose, an innovative drilling optics compensation system consisting of a vibration detection module and a signal analysis unit will be developed. Patterns of the acoustic signal measured are correlated with the expected quality of the boreholes, allowing the real time variation of the processing parameters. Thus, an integrable compensation system will be made available for the industrial practice of laser machining, which will significantly enable an increase in productivity and economic efficiency.

3. Laser monitoring with acoustic emission

The intended technological development of the research is the provision of an innovative laser drilling compensation system not available on the market, consisting of a vibration detection module and a signal analysis unit. With the innovative drilling optics compensation system, it will be possible to retrofit industrial laser machines in order to achieve a considerable increase in productivity an quality. The concrete difference to the state of the art is the online data acquisition with direct compensation via the machine control and the real-time optimisation of the laser drilling process based on the pulse energy E. By optimizing the process parameters in real time, the laser beam power P_L can be adjusted before the borehole breakthrough to increase its quality.

During the drilling process with ultra short pulse (USP) lasers, the predominantly ablation mechanism is the sublimation. Thereby it is possible to monitore the acoustic emmissions originated by the laser drilling process. The basis of process characterisation is laser Doppler vibrometry (LDV). The reliable characterisation of air-ultrasonic fields opens up the possibility of recording the acoustic field parameters of the workpiece. The measurement principle of LDV is based upon the pressure p, in the particular case acoustic pressure p_a, can alter the optical density of medium it's applied to [18]. To measure changes in optical density, and therefore sound pressure, LDV-devices implement a laser beam to determine the change of optical density and, therefore, refractive index n of the medium.

In the case of acoustic measurements as presented in Figure 1, the beam is transmitted from laser source via optical fiber to the Fabry-Perot etalon (FPE), in other words, microphone head of the measurement device. Inside the FPE, the beam is exposed to the medium and mirrored back to the measurement device. The device then detects the intensity of the laser beam exposed to the medium. The detected light's intensity is proportional to the acoustic pressure p_a within the medium.

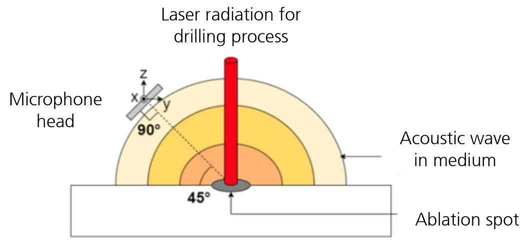

Figure 1. Positioning of FPE relative to the ablation spot

For the study of USP laser drilling acoustics a LDV acoustic measurement system Eta250 Ultra, Xarion Laser Acoustics GmbH, Vienna, Austria, is applied. The measurement system is capable of detecting signals with maximum acoustic frequency $f_a = 1$ MHz. The device provides a sensitivity $s = 10$ mV/Pa at maximum voltage output of $U_o = 7.5$ V and can withstand relative acoustic pressure change of $L_r > 194$ dB. The signal-conditioning unit SCU of the measurement system features four cutoff frequency f_a filter levels between $10 \text{ Hz} \leq f_a \leq 200 \text{ kHz}$. The full system also consists of the data acquisition computing (DAC) unit HFMES, QASS GmbH, Wetter with the software Optimizer 4D, QASS GmbH, Wetter.

Figure 2 and Figure 3 show the experimental setup in the laser machine sytem. The laser processing is realized in the MICROGANTRY® NANO5X, Kugler GmbH, Salem, Deutschland. The laser machine system has ultrashort laser pulses with pulse duration tL = 10 ps and beam quality $\Pi < 1.03$ (TEM00). It is built on a granite bed, has the laser scanner dynAxis S 10, Scanlab AG, Puchheim, and telecentric lenses with focal length $\kappa = 80$ mm. It has an average beam power $P_L = 3.0$ W with laser beam diameter of $d_u = 12.0$ µm at the focusing position. The wavelength $\lambda_{UV} = 355$ nm is applied for the experiments.

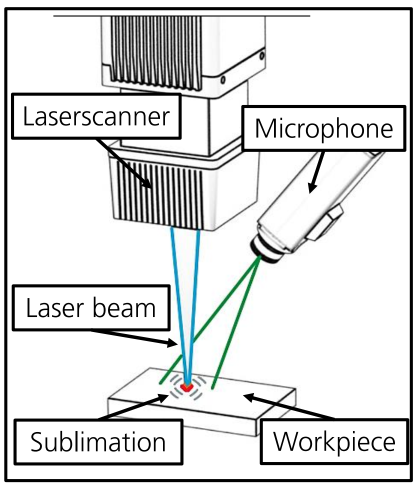

Figure 2. Schematic diagram of Experimental setup

Laser processing in the picosecond range corresponds to the boundary between melt and sublimation ablation. In the case of melt ablation, the vapour is ionised and forms an ionised material vapour cloud. In the process, overheating takes place below the surface, which can lead to an increased pressure build-up. At the end of the laser pulse, the melt heated under high pressure is ejected explosively, which is usually referred to as ablation. Very high intensity processing is performed in sublimation ablation by lasers with pulse duration $t_L \leq 10^{-12}$ s, where the laser radiation is absorbed not only by the classical absorption process, but also, by non-linear absorption mechanisms, such as multiphoton absorption and avalanche processes.

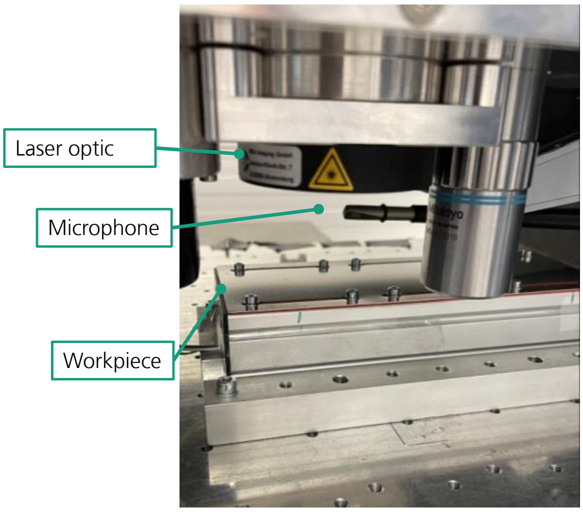

Figure 3. Experimental setup

4. Expected results

The planned research activities addresses the main challenge for the application of laser technology within the micromanufactuing of parts. Mainly the microsystems, aeroespacial and medical industry will profit from the novel acoustic-based characterization method for ultrashort pulse (USP) laser drilling process

The formation of porosities and cracks results in the generation of an acoustic emission signal, an elastic sound wave that travels from the source to the LDV and travels through the air until it reaches the acoustic emission sensor. In response, the sensor generates an electrical signal that is passed to the electronics for further processing or detection of a fault. This signal will be filtered in order to eliminate noises from the machine itself. Figure 4 shows a schematic illustration of the acoustic signal to be recorded during the laser processing.

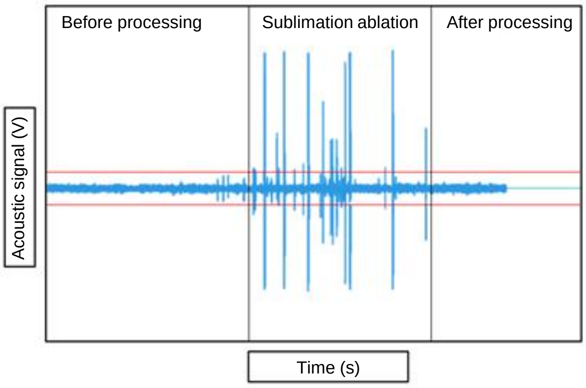

Figure 4. Example of acoustic signal

Parallel to the acoustic analysis, the bore holes are measured with a Scanning electron microscope to determine its quality. This data is than correlated with the acoustic emission profile and the laser parameters in order to characterize the process as shown in Figure 5.

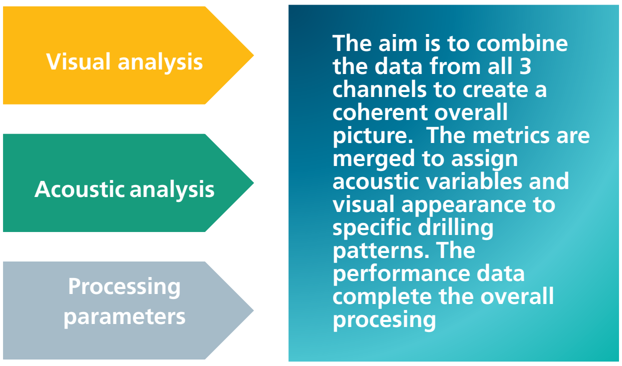

Figure 5. Data correlation

The development of a characterization method will provide a basis for an adaptive laser parameter control system, which can adapt the USP laser drilling parameters to specific applications automatically, implementing the online acoustic monitoring. The developed characterization method is based on a state-of-the-art acoustic sensor, using laser-Doppler-vibrometry (LDV) technology to monitor acoustic pressure p_a generated by the material ablation. The processing parameters can be monitored and controlled by a calibration setup previously adapted for the production. This technology will allow to create an adaptive parameter control system, improving the economic viability of the USP laser drilling process.

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