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Advances in macro-scale laser processing

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ABSTRACT

Laser material processing is a technology with an increasing number of industrial applications, especially for aviation and automotive. The present keynote paper focusses on the advances in macro-scale laser processing, meaning that the laser generated structures are large enough to be visible with the naked eye. Next to that, also the reasons for the advances, especially the improvements regarding the power and the beam quality of the laser sources, the higher capabilities of the systems technologies and an increasing process understanding are shown. Nevertheless, challenges like a holistic understanding of the physical phenomena and the evolution of defects in some processing methods remain to be solved in future.

1. Introduction to advanced macro-scale laser processing

Due to its high flexibility and potentially high processing speed, the laser is used as a tool in an increasing number of industrial applications, which will lead to a doubling of the world market for laser material processing from 2011 to 2020 to a total amount of 43 Billion Euros [15]. Moreover, using the laser as a tool contributes to the goal of a waste-free production by reducing the use of resources and increases production efficiency [15].

Thus, laser material processing was a topic of prior CIRP keynote papers, focusing on additive manufacturing [223] or micro material processing [141]. In contrast, this keynote paper focusses on the advances in *macro-scale* laser processing. For confining the subject the macro-scale scale is defined as the length scale on which laser generated structures are large enough to be visible with the naked eye and without magnifying optical instruments [100].

In recent years, an exponential increase in possible applications for macro-scale laser processing techniques can be observed. The present keynote paper aims to summarize the reasons for this increase, shows specific examples for new applications for different processes and gives an outlook on emerging technologies.

2. Driving forces for advances in laser machining processes

As the major driving forces for advances in laser machining new markets, materials and systems technology can been identified. Especially aviation, automotive and heavy industries are innovative industrial sectors where new potential applications for the laser as a tool for material processing evolve. However, each market has its own requirements and regulations regarding e.g. the size of the machined structures and quality definitions up to safety regulations. These specific demands, which act as driving forces for the development of new laser machining processes, are shown in the following section.

2.1. Markets

Macro-scale laser processing includes cutting and joining processes as well as surface treatment. A large number of application areas can be identified, e.g. laser cutting or laser welding, drilling, cleaning and structuring [200].

Revenues of the laser material processing market show a strong dominance of macro material processing with >1 kW power sources, accounting for 59% of total sales. This area also recorded a strong growth rate of 9%. These revenues are mainly attributable to the cutting of metal, especially sheet metal, as displayed in Fig. 1. Laser

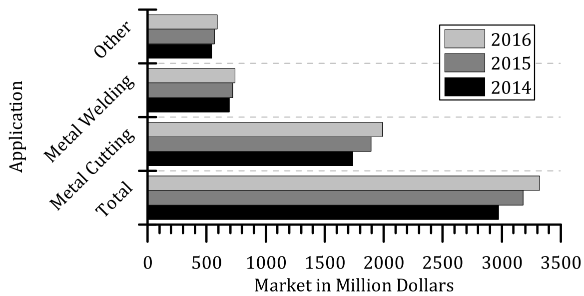

Fig. 1. Laser revenues by application [24].

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beam welding recorded a very high growth rate (17%) in 2015, due to the strongly increased sales figures of the global automotive industry. The most important markets for laser material processing are presented in the following sub-sections [24].

2.1.1. Aviation

Lightweight components are of particular interest to the aviation industry. The goal of weight reduction must be accompanied by high production efficiency and component performance. Laser beam welding and brazing offers the possibility to join light metals (e.g. aluminum, titanium, magnesium) and their combinations. Especially reinforced titanium structures for aerospace applications show the potential of a combination of laser welding and straightening for the precision manufacturing. However, laser welding of those light metals still suffers from statistically occurring weld seam irregularities such as notches or holes, which reduce the mechanical properties of the joint.

2.1.2. Automotive

Increased product customization and decreased time-to-market cause intensified levels of competition among car manufacturers. A high performance and sustainable production becomes an essential feature to address the growing consumer demand for greater variety of goods and services [35]. In the future, automotive manufacturing will be characterized by an increased automation, a higher flexibility, and a modular architecture [40]. The need for higher flexibility might be met by a larger operating distance.

For decreasing the amount of CO_2 emissions, lightweight construction is of particular importance [235]. The use of new materials such as aluminum and fiber reinforced plastics (FRP) requires new production processes for these materials. For example, the cutting process of carbon fiber reinforced plastics (CFRP) is a challenging task due to the abrasive character of the carbon fiber.

Also new production processes for the connection of different materials are necessary. A joint of FRP and aluminum can be realized by thermal joining, whereby the polymer is melted by an external heat input and then pressed with the aluminum. However, in order to meet the requirements of the automotive industry regarding the joint strength, the metal surface must be pretreated. Depending on the polymer, a pulsed or a cw laser beam source can be used. The required process speeds for inline production pose high demands on the laser system with regard to the maximum output power of the beam source and the deflection speed of the optics [80–82].

Another approach to achieve the emission targets is the increasing electrification of the vehicle fleet. The production of the essential energy storage systems provides completely new areas of applications for laser material processing. In particular, the production of the battery modules and the corresponding electrical contacting of the battery cells might be executed by laser radiation [137,139,224,225]. Lasers can also be used throughout the entire process chain for the production of battery cells, e.g. for cutting electrodes [128,135], contacting the battery stacks, or welding the battery housing [114]. Another challenge associated with electro-mobility is the processing of highly conductive materials such as copper or aluminum. The high reflectivity complicates the laser process, so that beam sources with high intensities or wavelengths in the visible range must be used [55,144].

2.1.3. Heavy industries

For heavy industries, new products and production possibilities are developed to machine the large structures used, such as thick profile welding in shipyards, steel structures under permanent stress and large steel structures for pressure vessels [218]. These areas require welding with large welding depths.

Flexible beam guidance and the development of compact and robust beam sources are needed to make it possible to use laser radiation on large workpieces such as those used in shipbuilding. In this area of application, the workpiece is no longer transported to a special workstation, but the beam source is used at different locations. In addition, the machining station does not have to be larger than the workpiece [218].

2.1.4. Electronics industry

Macro-scale laser material processing is increasingly applied in other markets due to technological and scientific progress. An example is the electronics industry, where wire bonding is often used to produce electrical contacts. Applications include chip-on-board technology, power module technology, high-frequency technology and the assembly of microsystems. Wire bonding is a welding process in which an automatically fed wire is joined by ultrasonic welding on two or more substrates [76]. To increase the process stability and to weld larger wire cross-sections, a laser-based wire bonding system might be used. However, highly brilliant laser radiation and beam oscillation are needed for this application to increase the joining area and to regulate the welding depth [157].

2.1.5. Requirements due to Industry 4.0

Industry 4.0 is one of the biggest trends in production engineering. Recent advances in the manufacturing industry have led to the use of cyber-physical systems (CPS), in which information from all perspectives is recorded, monitored and exchanged between the physical factory floor and the cyber computational space. In addition, networked machines can work more efficiently, cooperatively, and robustly by using advanced information analysis [136]. Within laser material processing, the progress of suitable sensor technology is the enabler to fully exploit the potential of Industry 4.0 at the manufacturing level. Examples are flexible and reconfigurable systems that adapt to changing requirements or self-optimizing processes that can independently acquire or derive process parameters for a new task [14,164]. The requirements cannot be fulfilled at present, or only partially. For this reason, intensive work is required in the field of manufacturing technology in order to develop new solutions such as predictive models or inline process monitoring. Overall, the extensive data collection combined with Industry 4.0 can lead to a further continuous growth across all markets presented.

2.2. Systems technology

The advance in systems technology is another important reason for new possible applications. The ongoing change from CO_2 to solid state lasers with a better beam quality, so called high-brightness lasers, and new direct diode lasers with higher wall-plug efficiency opens new fields of applications. Especially the beam quality is an important feature of a laser source since a better beam quality (i.e. a smaller beam parameter product) allows a smaller laser beam focus on the work piece, smaller processing optics or a larger working distance between the processing optic and the work piece. Particularly the latter one increases processing speed and thus efficiency.

On the other hand, an increased process understanding, supported by new process observation and modelling methods, allows a better use of available process windows and the development of new application scenarios. The defined driving forces and their effects are described in detail in the following sections.

2.2.1. From CO_2 to solid state

Typical macro-scale laser processing is characterized by the conversion of photonic into thermal energy by radiation absorption and the resulting well-defined, spatially limited heating of the material to be processed. In this respect, the laser wavelength is a decisive factor for the interaction with the material, in particular, as industrial laser processing can only be realized economically if processing velocity and quality are high enough. The absorption of