Basic Concepts of Laser Drilling

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Abstract. The state of the technology of $\mu$s pulse laser applications is dominated by single pulse drilling, percussion drilling and even trepanning used for high speed drilling with melt expulsion. However, short ps pulses have to be addressed anyway, since there are technical aspects in addition to achieve high speeds in drilling, namely, structuring and tapering while maintaining the mechanical integrity of operation. As an example, to avoid delamination of thermal barrier coatings while structuring the inlet of cooling holes in turbine manufacturing as well as to avoid cracking at the drilled wall forces the scientist to take into consideration the mechanisms of short pulse ablation at least in the case of ps pulses.

The variety of intriguing physical phenomena runs from recast formation (well known from the action of $\mu$s-pulses), via formation of cracks typical of ns- to ps-pulse duration, to homogeneous expansion, phase explosion and spallation characteristic of fs-pulses. The numerous phenomena are related to physical models describing propagation and absorption of radiation, ionisation, evaporation and non-linear transport of mass, momentum and energy. Technical achievements like lasers emitting 100 ps or shorter pulses and related experimental observations imply a future need for simulations to cope with the kinetic properties of beam-matter interaction. Temperatures approaching the critical state during ablation with pulse durations in a range from some ps to a few hundred ns raise the question whether Equation of State phenomena contribute to the overall appearance in drilling. In particular, beam aberrations instead of a free running or multiply reflected beam pattern are encountered in modelling independent of pulse duration. Beam aberrations are not only introduced by the action of beam guiding and forming optics, but also by spatially distributed feedback from the dynamical shape of the ablated material surface. Effects changing the phase distribution of the incident laser radiation are incorporated in the models for the first time: for example, some temporal and spatial changes in density in the gaseous phase. In drilling, the dynamical phenomena governing the shape of the drilled hole are identified experimentally and can be related to the processing parameters theoretically.

5.1 Introduction

Actually, modelling and simulation relevant to developing improved technical applications improved by extending the scientific basis from macro
applications into the field of shorter pulses of about a few nano-seconds and smaller length scales down to the wavelength of the radiation is considered. Some key physical phenomena become apparent and more dominant on smaller scales. As a result, there is also feedback from improved models on the micro-scale to simulations describing macro-applications. The analysis deals with the interaction of physical quantities including photon and wave properties of radiation, energy flow density and photon energy, via evaporation dynamics changing from quasi-steady to kinetic behaviour with shorter time scales and changing material properties while approaching the critical state at large temperatures, towards non-linear transport phenomena due to the fast movement of the ablation front in drilling with µs and ns pulses.

Research directions in the field of pulsed beam-matter interaction are twofold. While diagnostic methods are extended and refined to reveal additional phenomena and to improve understanding of them [1, 2], the investigation of phenomena that are already known are also detailed to achieve a mapping of the dominant phenomena to the causal radiation properties. To detail the relevance of the different physical phenomena requires the division of the parameter space spanned by the radiation properties and the processing parameters into subspaces, which are called processing domains. Different processing domains can be distinguished either by the different properties of the final processing result or by the corresponding path the system undergoes in the physical phase space during the interaction. As a result, a single processing domain is then characterised by a unique subset of selected physical phenomena, which are found to be dominant. Their typical time scales and intensity regimes are indicated. The theoretical goal is to reveal the specific model structure which reproduces the characteristics of the different processing domains. The approach consists of iterative extension, refinement and reduction of the specific physical models so that finally the essential physics is included, but there is no unnecessary complexity.

5.2 Technology and Laser Systems

The state of the technology of pulsed laser applications is dominated by single pulse and percussion drilling with µs-pulse duration used for high speed drilling with melt expulsion (Fig. 5.4). Drilling cooling holes and fuel filters as well as drilling holes for lubricant feed is performed with top-hat like spatial beam profiles [3]. Experiments for this application suggest the use of gas for drilling [4] to provide protection for the optical system from metallic melt ejection and to improve drilling quality when drilling breakthrough occurs. Establishing high combustion temperatures for greater efficiency of aero-engines has raised the problem that plasma-sprayed Thermal Barrier Coatings TBC made out of zirconia are fault-prone to delamination when exposed to thermal gradients [5]. Use has been made of a high pulse energy $E_p < 50\, \text{J}$ for high rate percussion drilling and it remains attractive, even when dealing with the properties of melt expulsion such as recast formation [6]; subsequent