Chapter 2

Laser micro machining

In order to comprehend the laser micro machining as a process as well as its possibilities and limitations, an extended background information about this technology is required.

In this chapter an overview of the physical principles related to laser processes will be given, as the interaction between electromagnetic radiation and matter, with special focus on the absorption of laser radiation in metals, as well as a product of the laser radiation absorption, the laser ablation. Moreover the state of the art in monitoring techniques for laser based processes will be described and discussed. Finalizing the chapter, an overview of the current challenges and demands regarding the process monitoring will be presented.

2.1 Interaction between electromagnetic radiation and matter

Laser radiation is described as electromagnetic wave by the Maxwell equations [EE06]. Based on this model, an electromagnetic beam incident on the surface of a workpiece can be reflected, refracted, absorbed, scattered or transmitted (figure 2.1). Considering the usage of laser radiation for material processing, e.g. laser micro machining, the desired results are primarily dependent on the phenomenon of beam absorption and its amount compared to other involved phenomena.

Taking into account the propagation of electromagnetic radiation through matter, material properties play an important role in the modeling of their interaction with the existing charge carriers and resulting behavior of the light. Several material properties are dependent on environmental conditions as e.g. the temperature, which also need to be considered. Furthermore the laser beam properties also impacts this complex process.

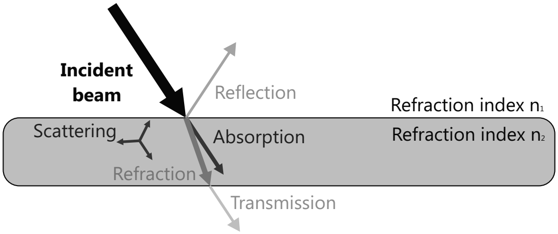

Figure 2.1: Interaction of laser radiation with matter. [DH08]

A list of influencing factors over the interaction between laser radiation and matter is given by [Pop05]:

- Material properties
  - Refraction index *n*
  - Absorption index *a*
  - Electric conductivity σ
  - Heat conductivity *K*
  - Specific heat *c*
- Surface properties
  - Topography (Roughness / Form)
  - Morphology
- Ambient conditions
  - Temperature
  - Presence / Type of process gas
- Laser beam properties
  - Wavelength ω
  - Optical power
  - Polarization
  - Illumination time / pulse duration
  - Repetition rate
  - Angle of incidence
  - Beam shaping (e.g. focus length)
- Geometry of the workpiece
  - Thickness
  - Boundary geometry
- Changes of the workpiece and environment induced by the absorbed laser energy
  - Local heat
  - Phase changes
  - Laser-induced plasma

2.1.1 Absorption of laser radiation

As discussed in Section 2.1, the laser radiation can be modeled by an electromagnetic beam, i.e. an electric and a magnetic vector field. The fraction of the incident electromagnetic radiation, which passes into a material, interacts with its charge carriers / electrons. In the case of metals it occurs in a thin part of its surface, due to the high absorption typically found in metals.

The absorption of the laser radiation can be modeled by the energy attenuation of an incident beam in dependency of the depth in a specific material. For a beam with incident energy E_0, the transmitted energy, E, at a depth of z, can be expressed by the Lambert-Beer' law [Ion05]:

$$E(z) = E_0 exp(-az) \tag{2.1}$$

where a is the absorption coefficient (e.g. $\sim$ 5 x 10 ^{5} cm^{-1} for metals and wavelengths in the visible range).

Based on this equation, the attenuation length L is defined as the distance in which the intensity is decreased by a factor of 1/e (Equation (2.2)) [Ion05]. This parameter characterizes the penetration depth of the electromagnetic radiation on the surface and gives a direct information about the region of interaction. The attenuation length for wavelengths in the visible range in the case of metals is within the range of some nanometers and so the absorption occurs in a thin layer of its surface [Pop11]. This parameter is directly related to the absorption coefficient by:

$$L = \frac{1}{a} \tag{2.2}$$

By traveling through matter the electric field will exert an electric force on the charged particles present in the material, which will be set in motion. The forces generated in this process are just able to excite electrons (free or bounded) to oscillate, but not the atomic nucleus. The process of photons being absorbed by electrons is called "inverse bremsstrahlung effect" (braking radiation) [SM10]. This laser radiation is absorbed in a thin layer of the material's surface by the free electrons in the range of some femtoseconds (10^{-15} s), whereas the electrons' relaxation time is in the order of magnitude of 10^{-12} to 10^{-13} seconds. For interaction times lower than these no thermal equilibrium can be achieved and non-thermal processing mechanisms apply (e.g. low range picosecond (10^{-12} s) and femtosecond (10^{-15} s) pulsed lasers) [Ion05][MDG$^+$02]. During the laser irradiation time, which is below the relaxation time of the electrons, all laser energy is stored in the thermal energy of the electrons. Afterwards, during the relaxation period the energy is transferred to the lattice and a thermal equilibrium will be achieved. The thermal conduction through collision of electrons and lattice defects is the dominant heat conversion / transfer mechanism.

The absorbed heat in the thin layer of the target's surface will diffuse then to the bulk material. The diffusion depth d is described by [MDG$^+$02]:

$$d = \sqrt{4bt} \tag{2.3}$$

with b as the thermal diffusivity (ratio of the energy transmitted by conduction to the energy stored in unit volume of material) and t the diffusion time.

On the one hand, by using thermal processing mechanisms, the absorbed radiation energy is converted into heat, leading the material e.g. to change its state by melting or vaporization.

On the other hand, by using non-thermal processing mechanisms, the absorbed radiation energy is sufficient to excite the entire electronic structure. This results in different temperatures for electrons and the lattice, striping electrons from atoms and leaving them momentarily charged, during which time they repel each other by Coulomb forces [SM10]. These laser pulses remove material without significantly heating the surroundings. Systems based on this phenomena are therefore especially interesting for machining applications where the remaining workpiece material should suffer minimal mechanical changes resultant from the laser material process itself [LRR$^+$11].

Besides the interaction time, the interaction of electromagnetic radiation and matter, as well as the consequent absorption of laser radiation, is also dependent on further involved parameters, as listed in the beginning of the section. This aspect needs to be taken into account for the estimation of the overall laser energy absorption.

For instance, the laser beam absorptivity of different materials is strongly dependent on the radiation wavelength, as it can be seen in figure 2.2. This relation (Absorptivity and radiation wavelength) is however also dependent on the material's local temperature, as presented in figure 2.3.

Furthermore the surface roughness influences the absorptivity, as the surface structure can lead to multiple reflections and thus to an enhanced absorption. In other words, the radiation previously reflected interacts again with the surface and can be absorbed [SM10].

The final amount of energy absorbed considering the overall parameters lead to different physical effects, as heating, melting and vaporization of the material [DH08] (see figure 2.4) and will thus result in a different final topography of the machined part.

In the following sections the targeted effect in the laser micro machining of metals, the material removal, and the related physical phenomena will be further described.

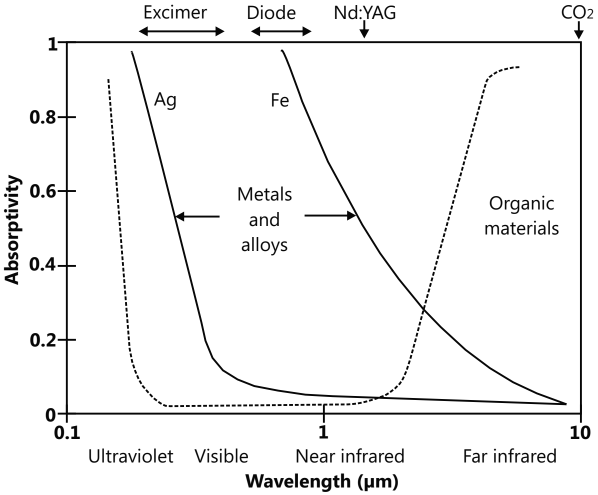

Figure 2.2: Material specific absorptivity variation related to the wavelength for metals and its alloys. [Ion05]

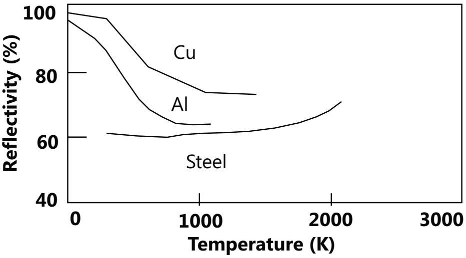

Figure 2.3: Material specific reflectivity variation related to the temperature for a laser radiation with a wavelength of 1.06 µm. [SM10] [DH08]

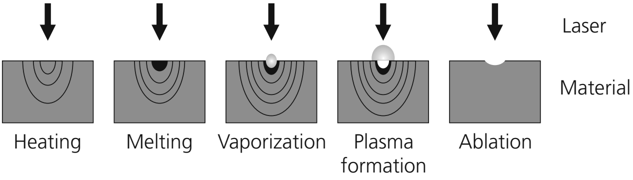

Figure 2.4: Effects of laser material interaction. [SM10] [DH08]