Laser light absorption on molten metal

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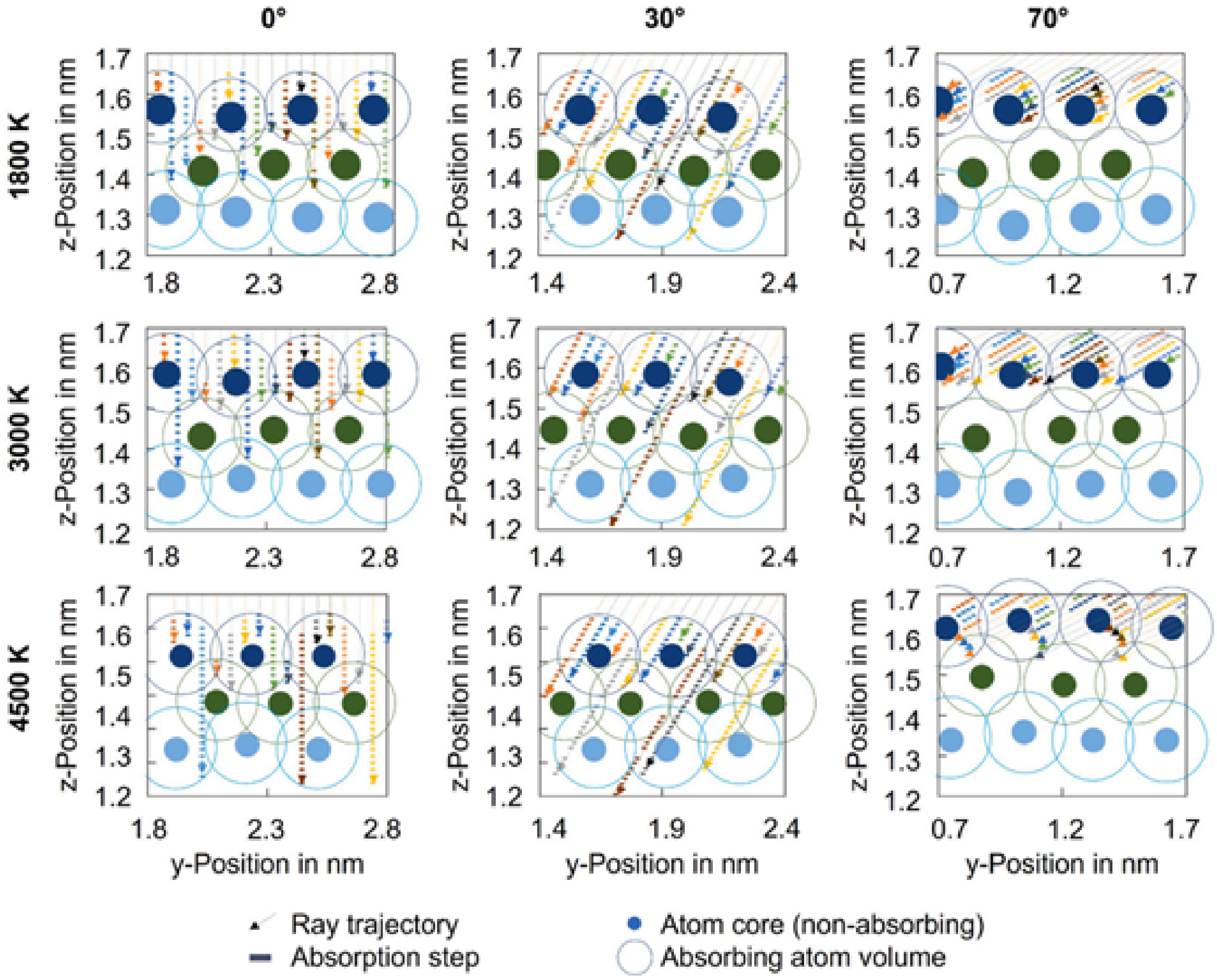

Figure 1. Sketch of surface atoms and laser rays being absorbed at different temperatures and incident laser beam angles (2)

Light absorption at high temperatures is highly impacted by interband absorption in addition to intraband absorption

When light interacts with a surface, it can be reflected, transmitted, or absorbed. In the context of laser beam material processing, transmission is generally not a factor. However, the amount of energy absorbed is crucial for both the effectiveness of the processing and its energy efficiency. Reflected energy does not contribute to the processing. Absorption depends on the light wavelength and surface characteristics. However, the impact of high temperatures on absorption values and mechanisms is not well understood yet, although many manufacturing processes operate in those regimes.

Light absorption

Laser energy input into the material is mainly defined by the absorption of the material surface. Photons mainly transfer their energy to the electrons of the material atoms and increase their energy state. Afterwards, the energy is further transferred to atom vibrations and then by heat conduction into the material. Light absorption depends on several factors. The well-known Fresnel equations consider the material properties as the refraction coefficient and the extinction coefficient, as well as the incident angle of the light in relation to the surface. Separate equations are necessary to describe parallel and perpendicular polarized light.

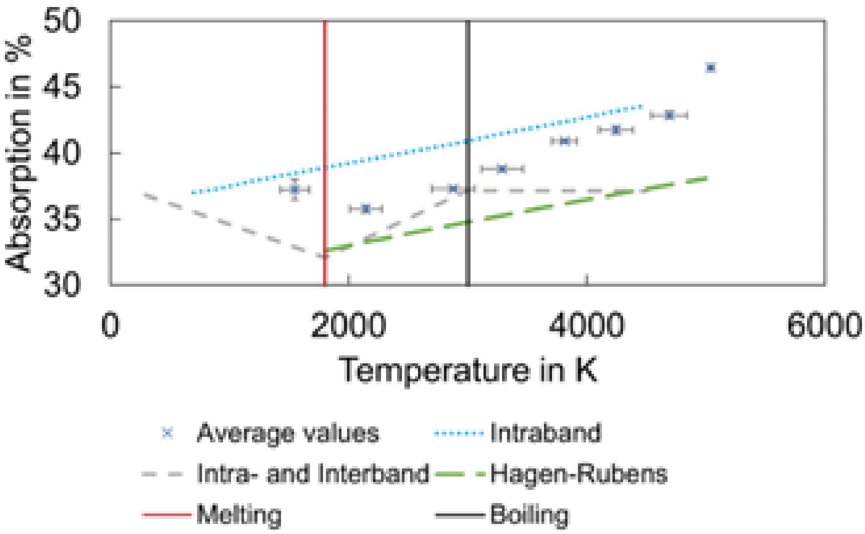

Figure 2. Theoretical absorption predictions compared to measured absorption values

Absorption mechanisms

There are two main absorption mechanisms known to appear in metals: inter- and intraband absorption. The interband absorption lifts bound electrons to higher energy levels, while intraband absorption includes free electrons. It was typically assumed that only electrons in the conduction band (intraband) contribute to light absorption.

Recent absorption measurements based on measuring reflected laser light from a molten metal surface, [1] combined with an absorption simulation, could give more insight into absorption at high temperatures. [2] The penetration depths of light rays vary significantly at different incident angles and different temperatures (Fig. 1).

Comparing theoretical predictions and the actual measurements, the trend of the measured values deviates from theoretical predictions (Fig. 2). Just above the melting temperature, the measuring points indicate a decrease in absorption compared to the solid. At higher temperatures, measured absorption values tend to follow the intraband calculations.

Therefore, it was concluded that in addition to the intraband absorption of conduction band electrons, interband absorption makes a contribution to the total absorption even at high temperatures. Interband absorption must be considered even at such high temperatures, in contrast to common theoretical assumptions.

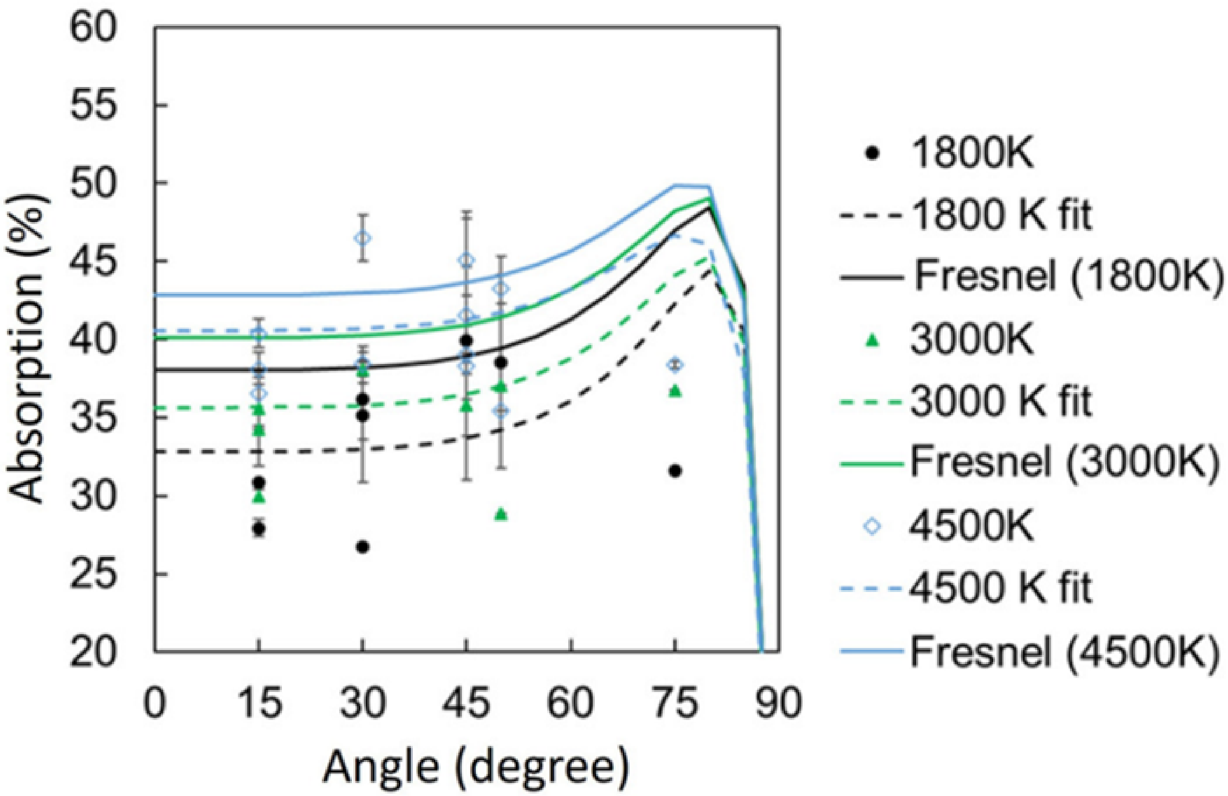

Figure 3. Absorption measurements at different temperatures and incident laser beam angles (dots) with fitted curves (fit) compared to Fresnel predictions (3)

Brewster maximum shift

The Brewster angle is the angle at which the absorption of parallel polarized light shows a maximum value. Most metals show a Brewster angle that is close to an incident angle of 90° from the vertical axis at low temperatures before the absorption drops to zero at 90°. Recent investigations [3] show that at temperatures around the boiling temperature of steel, the absorption peaks appear at comparatively low angles (Fig. 3). This shift cannot be represented properly using the Fresnel equations, which indicates that at high temperatures, our absorption theories need to be adapted. It was concluded that additional effects, like the effect of multi-interface absorption caused by surface layering and Knudsen layer formation, need to be considered when describing the system. Surface layering was seen to decrease the Brewster angle and was identified as a potential reason for the Brewster angle reduction at elevated temperatures.

The newly created knowledge can help to develop more energy-efficient material processing techniques to reduce the high energy needs of the manufacturing industry.

1. Volpp, J. (2023). Laser beam absorption measurement at molten metal surfaces. Measurement, 209, 112524.
2. Volpp, J. (2023). Laser light absorption of high-temperature metal surfaces. Heliyon, 9(10).
3. Volpp, J. (2023). Laser light absorption and Brewster angle on liquid metal. Journal of Applied Physics, 133(20).

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