Lasers in Manufacturing Conference 2023

High-temperature laser absorption of steel

Joerg Volpp[a,*]

[a]Department of Engineering Sciences and Mathematics, Luleå University of Technology, 97187 Luleå, Sweden

Abstract

Laser light absorption is a complex process including several absorption effects to transfer photonic energy into material. Absorption values and knowledge about impacting factors are relevant to simulate laser processes and get a better understanding of laser-material interaction. However, due to the high temperatures and dynamic melt surfaces of liquid steel, absorption measurements are difficult to conduct. Theoretical predictions show differing tendencies for high-temperature absorption values. Therefore, a radiometric absorption measurement is proposed in this work to derive absorption values above melting and even above boiling temperature of steel. While a 'heating' laser beam was used to create the melt pool, a 'measuring' laser beam in combination with an intensity sensor was used to derive reflection data. In general, an increasing tendency of absorption at increasing temperature was seen. The absorption drop just above boiling temperature is assumed to derive from vapor effects.

Keywords: Boiling temperature; laser beam absorption; reflectometry; vaporization

1. Introduction

Laser light absorption enables many industrial applications from measurements to processing technologies. Inter- and intraband absorption are the two main mechanisms of direct interaction between light and many metal material surfaces. Interband absorption energetically lifts bound electrons, while intraband absorption includes free electrons. Absorption can be theoretically predicted using electric material properties. Since absorption depends on the electron configuration of the material, relations to electrical parameters were suggested (Drude, 1900). When knowing the complex refractive index of the material, Fresnel equations can predict the absorption for several materials, but typically only for lower temperatures (Zaitsev et al., 2018).

* Corresponding author. Tel.: +49 (0) 920-493969.
E-mail address: jorg.volpp@ltu.se.

For higher temperatures and in particular in the molten state refractive indexes and absorption values are unknown.

Experimental absorption measurements can be based on emissivity measurements (Kirchhoff´s law) since spectral emissivity is equal to the absorption at normal incidence (Dausinger & Shen, 1993). More precise predictions were theoretically made by Drude and the Bramson extensions. However, those models were only verified for solid state material surfaces. Typically, calorimetric methods for direct absorption measurement or indirect radiometric methods by radiative properties (reflectance, emittance) are used (Indhu et al., 2018) to determine absorption values. Some of the more commonly used methods are laser calorimetry, gonioreflectometry, integrating sphere or integrating mirror reflectometry and emittance spectroscopy (Sacadura, 1990). Experimentally, also the determination of absorption in liquid state under different laser processing conditions was possible (Bergström et al., 2005). E.g. Dausinger &Shen (1993) could show that the absorption of 1 µm laser radiation decreases with increasing temperature.

Since many laser processes include high temperatures, it is of high importance to gain insight in general laser-material interaction mechanisms like absorption for enabling sufficient process simulation models and better process understanding.

2. Methods

A radiometric measurement was proposed and set up (Fig. 1). Two laser beams were installed. While the heating laser beam (IPG YLR-15000, wavelength 1070 nm at 1.5 kW output power) created the melt pool, the measurement beam (Cavilux, cw, 808 nm wavelength, multimode, no preferred polarization, spot diameter on material: ~10 mm) was positioned with an angle onto the molten material to be reflected into the intensity sensor (RedLake Mono N4-S2, recording at 500 fps). A notch-filter was used to guarantee the measurement of only the reflected light from the measuring beam and avoid the impact of glowing of the vapor. The measured grey-scale values were related to reflected intensity values. A thermal sensor measured the surface temperature on the melt pool using 2-channel data to avoid errors from emissivity assumptions and minimize the impact of glowing vapor on the measuring results. A high-speed camera was positioned to record the material surface to identify dynamic conditions and exclude reflection measurements accordingly.

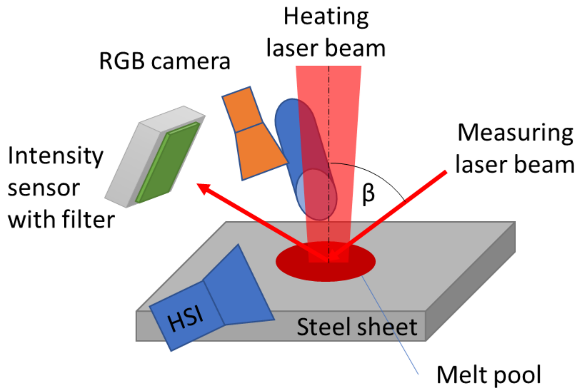

Fig. 1. Sketch of the radiometric measurement setup

3. Results and Discussion

The valid measurements of four recordings show variations in particular between melting and boiling temperatures (Fig. 2). However, the average follows the calculated trend of the prediction that takes intra- and interband absorption into account (black line in Fig. 2). This indicates that interband absorption plays a role in this temperature range. Above boiling temperature, high absorption values were measured in the range of the prediction of sole intraband calculations, which indicates that intraband absorption is the dominating mechanism at very high surface temperatures.

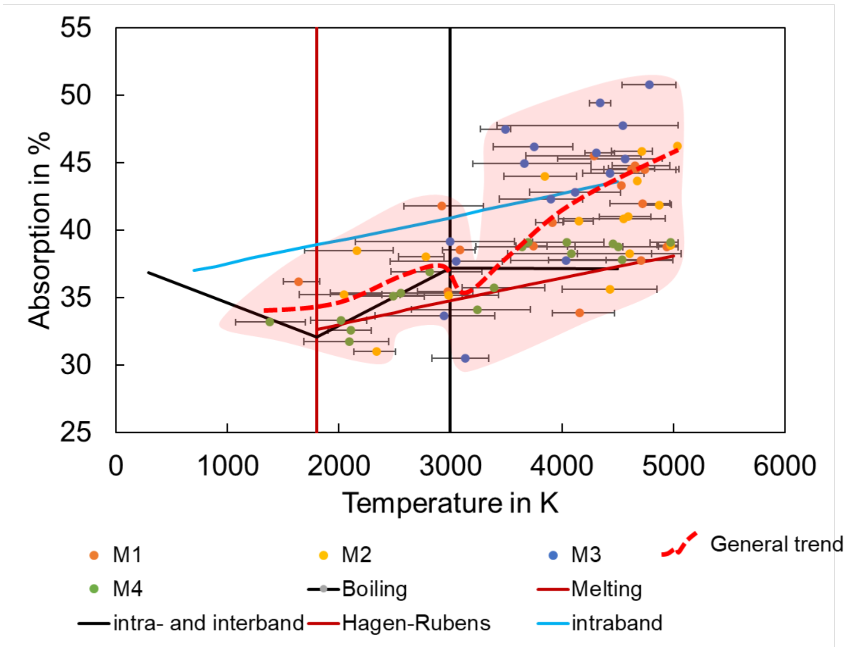

Fig. 2. Absorption measurement values of four recordings (M1-M4) compared to calculated absorption values

At 1 µm wavelength, Dausinger & Shen (1993) found that interband transitions dominate, which leads to a decrease of absorption at increasing temperature. Further, Fisher et al. (2001), who considered absorption of femtosecond-laser pulses at high intensities at 800 nm wavelength saw that at increasing peak intensity, absorption decreases. The measured trend of increasing absorption values above melting temperature was, however, predicted already theoretically by Drude and later e.g. by Bober et al. (1980).

Surprisingly just above boiling temperature, an absorption drop was seen before the increasing trend of absorption is continued at higher temperatures (Fig. 2). At boiling temperature, increased amounts of surface atoms are ejected from the surface in form of vapor. Therefore, surface 'holes' should exist that should lead to a rougher surface and thereby increased absorption due to a higher probability of multiple reflection and absorption of the laser beam rays (e.g. Volpp & Vollertsen, 2017). In addition, the increasing resistivity at increasing temperatures should also lead to a general increasing absorption. Therefore, counteracting effects must be dominating. A possible mechanism can be the increased vapor absorption of the ejected metal atoms that increase the vapor pressure and the vapor absorption. However, if that is the main mechanism, at higher temperatures, the absorption should decrease due to more vapor ejection, which was not observed. It might be possible that the vapor speed influences how much vapor is actually absorbing. Just above boiling temperature, the vapor ejection speeds are relatively low and vapor can accumulate, while according to the Knudsen layer theory, the ejection speed increases at higher temperatures and the vapor can expand into the ambient atmosphere more rapidly.

4. Summary

It was possible to measure laser absorption values at high temperatures using a radiometric measurement setup. Measurement data show a general trend of increasing absorption at increasing temperature with an absorption drop just above boiling temperature. It is suspected that the vapor above the material surface absorbs laser energy that reduces the absorption of the metal surface.

Acknowledgements

The author acknowledges the funding of PoSAddive – Powder Sheet Additive Manufacturing (EIT raw materials, No. 22021) and SMART - Surface tension of Metals Above vapoRization Temperature (Vetenskapsrådet, No. 2020-04250).

References

Bergström, D., Kaplan, A., Powell, J. Laser absorptance measurements in opaque solids, in: Proceedings of the 10th Nordic Laser Materials, Processing (NOLAMP) Conference, Lulea, Sweden, (2005), pp. 91–115.

Bober, M., Singer, J., Wagner, K. Spectral reflectivity and emissivity measurements of solid and liquid U02 at 458, 514.5 and 647 nm as a function of polarization and angle of incidence. Seventh Symp. Thermophys. Prop. (Edited by Cezairlyian, A.) 344–350 (1980).

Dausinger, F., Shen, J. Energy coupling efficiency in laser surface treatment. ISIJ international, 33(9), 925-933 (1993).

Drude, P. Zur Elektronentheorie der Metalle. Ann. Phys., 306: 566-613 (1900). https://doi.org/10.1002/andp.19003060312

Fisher, D., Fraenkel, M., Henis, Z., Moshe, E., & Eliezer, S. (2001). Interband and intraband (Drude) contributions to femtosecond laser absorption in aluminum. Physical Review E, 65(1), 016409.

Indhu, R., Vivek, V., Sarathkumar, L., Bharatish, A., Soundarapandian, S. Overview of laser absorptivity measurement techniques for material processing. Lasers in Manufacturing and Materials Processing, 5(4), 458-481 (2018).

Sacadura, J.-F. Measurement techniques for thermal radiation properties, Proceedings of the Nineth International Heat Transfer Conference, 1990, pp. 207–222.

Volpp, J., & Vollertsen, F. (2016). Keyhole stability during laser welding—part I: modeling and evaluation. Production Engineering, 10, 443-457.

Zaitsev, A. V., Ermolaev, G. V., Polyanskiy, T. A., Gurin, A. M. Study of absorption coefficient in laser cutting of metal. AIP Conference Proceedings, Vol. 2027, No. 1, p. 030146, AIP Publishing LLC (2018).