Applied Surface Science 258 (2012) 3354–3363

Contents lists available at SciVerse ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

# Fresnel absorption of 1 μm- and 10 μm-laser beams at the keyhole wall during laser beam welding: Comparison between smooth and wavy surfaces

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ARTICLE INFO

*Article history:*
Received 8 May 2011
Received in revised form 15 August 2011
Accepted 22 August 2011
Available online 27 August 2011

*Keywords:*
Laser welding
Keyhole
Model
Wave
Hump
Fresnel absorption
Absorptance

ABSTRACT

The angle-dependent absorption of laser beams at metal surfaces is described by the Fresnel-equations. During keyhole laser welding the essential interaction takes place at very striping angles of incidence of the order of 1–8 degrees at the front of the vapour capillary, called the keyhole. For a smooth vapour capillary, laser beams with a wavelength of about 1 μm operate in a Fresnel-regime where the absorptance increases with the angle of incidence at the wall, towards the weak Brewster-angle maximum. In contrast, for 10 μm-lasers high absorptance around the more pronounced Brewster-angle peak takes place. From high speed imaging keyhole surface waves were observed. Mathematical modelling of the laser-keyhole interaction demonstrates that already relatively little waviness of the melt surface at the keyhole strongly modulates the angles of incidence and in turn the Fresnel-absorption due to varying angles of incidence, soon also leading to shadow zones. Due to this local variation of the angle of incidence the absorptance tends towards the angle-averaged value, with the consequence that for 1 μm-lasers the direct absorptance and in turn the penetration depth increases, particularly at low welding speed, while for 10 μm-lasers it generally decreases.



## 1. Introduction

High power laser beams can be applied for materials processing such as laser welding, cutting, surface treatment, rapid manufacturing or micromachining. Most common are the $CO_2$-lasers (wavelength $\lambda = 10.64\,\mu m$) and Nd:YAG rod-laser types ($\lambda = 1.064\,\mu m$); moreover recently Yb:fibre-lasers ($\lambda = 1.070\,\mu m$), Nd:YAG disc-lasers ($\lambda = 1.030\,\mu m$) and diode-lasers ($\lambda = 808\ldots980$ nm) emerged in the cw (continuous wave) multi kW-power range. The focused laser beam is the essential manufacturing tool that determines the process performance and the resulting quality. During deep penetration laser welding, owing to its high power density (typically $I > 10^6\,W/cm^2$ required) the laser beam evaporates material and drills a vapour capillary, the keyhole. The keyhole is the governing interaction zone. It redistributes the optical energy of the laser beam geometrically into depth and converts it by absorption to heat. In the presented work the direct laser beam absorption (i.e. not the contribution after multiple wall scattering or from plasma absorption) during laser welding is studied for wavy keyhole surfaces compared to smooth surfaces.

From the keyhole surface the heat flows by conduction and convection into the workpiece. Hence, the keyhole permanently absorbs part of the laser beam, generating heat. Simultaneously, it permanently evaporates a relatively small portion of metal that keeps the keyhole open and that redirects (by local ablation/recoil pressure) the upstreaming melt (driven by the welding speed of the workpiece relative to the beam) from the front to the rear of the keyhole and melt pool where it resolidifies to form the weld. During cw-laser welding a stable process operates in quasi-steady state conditions, in contrast to transient phenomena that can cause instabilities and poor quality, e.g. by the ejection of spatter. Fig. 1(a) shows a high speed image of the top surface of the weld pool, including the keyhole opening. A longitudinal section of the weld pool and keyhole into depth is illustrated in Fig. 1(b), here for a capillary closed at the bottom, despite welding (melting) through. Note that mainly the front part of the keyhole redistributes the energy and governs the process [1], particularly the higher the welding speed $v$ (or Péclet number $Pe = vw/\kappa$, where $w$ is the beam spot radius and $\kappa$ is the thermal diffusivity). The evaporating material flows out of the keyhole, interacting with the shielding gas flow. For the new high brilliance lasers of excellent beam quality, the impact of the correspondingly more extreme beam properties (power density, beam spot size, and Rayleigh length) on the welding process is of particular importance and has therefore been studied recently [2–5]. In particular, quality issues like heavy spatter formation were observed [6,7].

While the keyhole opening is well visible during high speed imaging of the (top or root) surface, the three-dimensional shape of the keyhole is difficult to observe and to measure. For thin sheets

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doi:10.1016/j.apsusc.2011.08.086

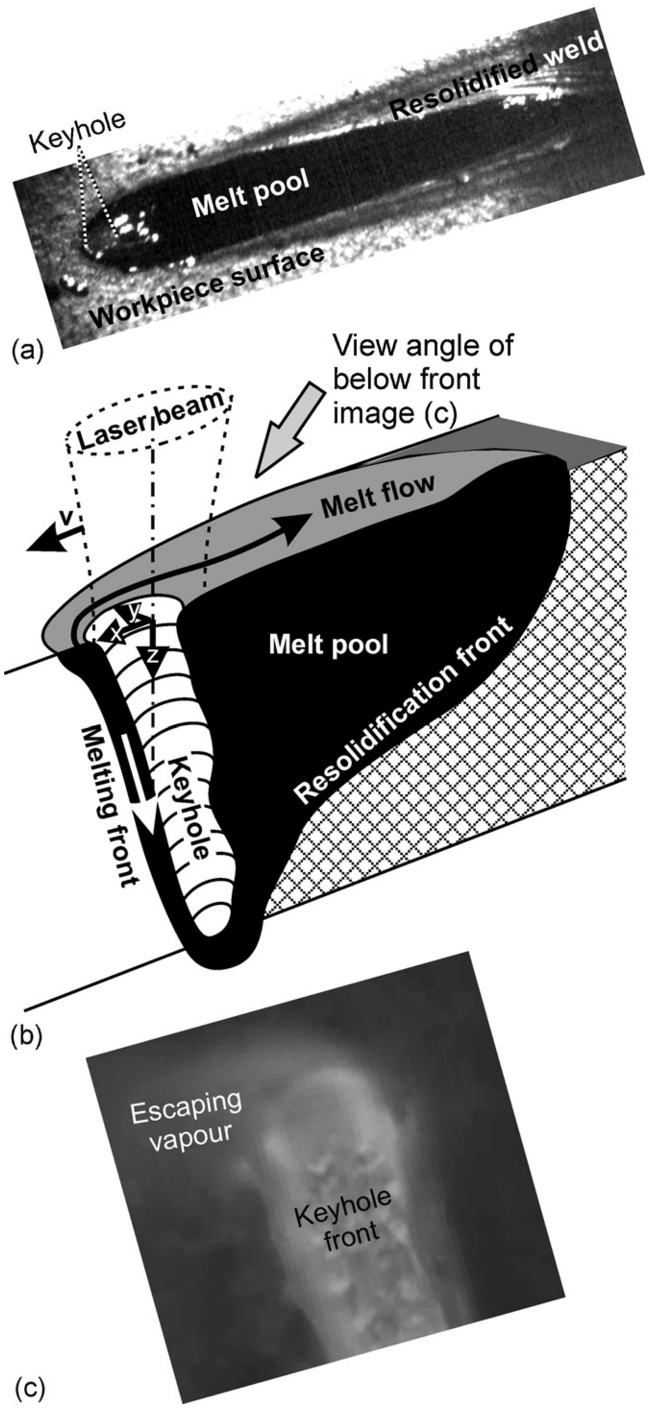


**Fig. 1.** Process of keyhole laser welding: (a) high speed image of the top surface (tilted view from the side), (b) sketch of a vertical *xz*-section of the melt pool and keyhole, and (c) high speed image of the keyhole front surface waves (upper part, by tilted view from the rear side).

also the bottom orifice of the keyhole is visible from the top during imaging [8]. The only research team that has facilities to observe the keyhole shape is Osaka University (just recently also the University of Stuttgart) by X-ray high speed imaging from the side, for narrow samples [9]. This provides a very interesting information, but the resolution of the method is limited to tens of microns, except for a basic experiment where the keyhole was drilled into a larger liquid Zn-pool, thus without constraining solid surrounding, where a magnified keyhole enabled a factor of 3–5 better shape resolution [10]. Recently, suitably adjusted ultra-high speed imaging enabled to observe part of the keyhole front, see Fig. 1(c), at which downstreaming of many humps was observed (over a wide range of parameters) [11].

Occasionally the keyhole was studied by mathematical modelling of the process. Despite several simplifications, e.g. neglecting the weld pool flow, in the 90s semi-analytical models provided suitable calculation of e.g. the keyhole geometry but also of absorption and vapour flow [1,12,13]. The sufficiently high computer performances achieved nowadays have enabled to compute the entire three-dimensional and time-dependent flow field of the melt pool and to some extent of the keyhole vapour in reasonable time, both for laser welding [8,14–17] and even for hybrid laser-arc welding [18]. However, even these powerful computations have still limitations by uncertainties in the boundary conditions, material properties and sub-phenomena of the highly complex overall process. The power density redistribution of the laser beam by multi-scattering was calculated for prescribed keyhole shapes that were obtained from transmission imaging of laser welding of glass [19,20]. The overall absorption during laser welding was estimated by different research groups, with the tendency to very high absorption at low welding speed, particularly due to enhanced multiple scattering, while the direct absorption studied here is difficult to extract experimentally.

The present study aims to calculate the keyhole shape in the *xz*-plane as the essential interaction phenomenon, disregarding most of the complex accompanying mechanisms. Although this causes (anyhow unavoidable) inaccuracies in the hypothesis that the fundamental dependency and trends of the keyhole shape on the focused laser beam and its profile still can be estimated in a qualitatively realistic manner to identify trends and draw fundamental conclusions. We would like to distinguish between the direct interaction of the laser beam with the keyhole wall (first Fresnel absorption), that can be regarded as the controllable contribution of the laser beam, and multiple scattering (second and higher order Fresnel absorption or even plasma absorption [1]) in a stochastic, hardly controllable manner, to be excluded here (although it can be of significant amount, it is mainly a superimposed noise contribution).

The difference between smooth and wavy keyhole (i.e. melt) surfaces is the key aspect of the study. Bergström recently carried out comprehensive experimental [21,22] and theoretical [23,24] studies of the interaction of a laser beam (wavelength 532 nm and 1064 nm) with solid technical metal surfaces (Al, Cu, Ti, etc.). Important was to define the surface topography not by the standardized roughness properties, like $R_a$ or $R_z$, but by the average or rms slope, because the slope distribution determines the Fresnel absorption. For the same roughness the slope distribution can vary significantly depending on the periodicity. In the following, surfaces where the average slope is high are denominated rough or wavy surfaces, in contrast to smooth surfaces. From the ray tracing simulations it became clear that inclined incidence of the laser beam on wavy surfaces modulates the Fresnel absorption such that the dependence of the absorptance on the angle of incidence strongly deviates quantitatively but also in its characteristics from the Fresnel-absorptivity function for a smooth surface. One has to bear in mind that one-dimensional studies along a surface profile [23] consider more vertical inclination angles than the two-dimensional surfaces [24] statistically contribute with, shifting the overall absorptance curve. From the simulations was concluded that rough surfaces differ from smooth surfaces by the modulation of the angle of incidence accompanied by multiple scattering. Moreover, beyond a certain angle of incidence shadowing takes place. Basically, all the findings for solid surfaces are also of importance for the present study, despite the difference that the keyhole surface is liquid, at elevated temperature and time-dependent.