

Relationship between the keyhole laser welding and the plasma

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Abstract. In this paper we investigated the behaviours of the laser beam keyhole welding with different laser beam sources, CO₂ and a solid state Nd: YAG. We showed the differences between the types of laser welding, the geometry and method. Today the most used laser welding technology is the laser beam keyhole welding. In our research we investigated the heating effect of photons and the absorption method on the substrate surface. The photons can significantly absorbed better in case of 10⁶ W/cm² or more because of the plasma state in the welding material. The quality of the keyhole plasma depend on the free electrons of the materials and working medium. A theory of the creation of plasma phase and cloud were investigated. There is a difference working inside the metal vapour and working gas plasma cloud using CO₂ and Nd: YAG. The solid state laser beam source shows better quality of the joint in keyhole welding.

1. Introduction

1.1. The behaviours of laser keyhole welding

The opportunity of optimizing bonds done with laser beam welding has become a decisive research area in today's developing industry, since it is a prevailing and frequent type of bonds both in machine and vehicle industry. Welded bonds must suit the increasingly strict quality requirements, all the welding structures must be specified. There are two types of heating "modes" used to describe the resulting melting of the metal during laser welding (figure 1).

These are called "conduction mode" and "keyhole mode" heating. These modes of heating are created by different power densities and produce different results. Power density is defined as the power of the laser beam divided by the area the focused laser spot. In conduction mode heating, the power density is great enough to cause the metal to melt. Weld penetration is achieved by the heat of the laser conducting down into the metal from the surface. An example would be pulsed laser welding in the millisecond pulse length range. The depth of the weld penetration is controlled in part by the length of the pulse. The longer the pulse the more time heat has to "conduct" into the part. In conduction mode heating the welds are typically wider than they are deep [1-3].

Keyhole mode heating achieves its weld penetration in a different way. During keyhole mode welding the power density is great enough that the metal goes beyond just melting. It vaporizes. The vaporizing metal creates expanding gas that pushes outward. This creates a keyhole or tunnel from the surface down to the depths of the weld. As the laser beam is moved across the surface, the keyhole



follows and creates a typically deep and narrow weld. As long as the laser power is great enough and the travel speed is not excessive, this keyhole will remain open [2-4].

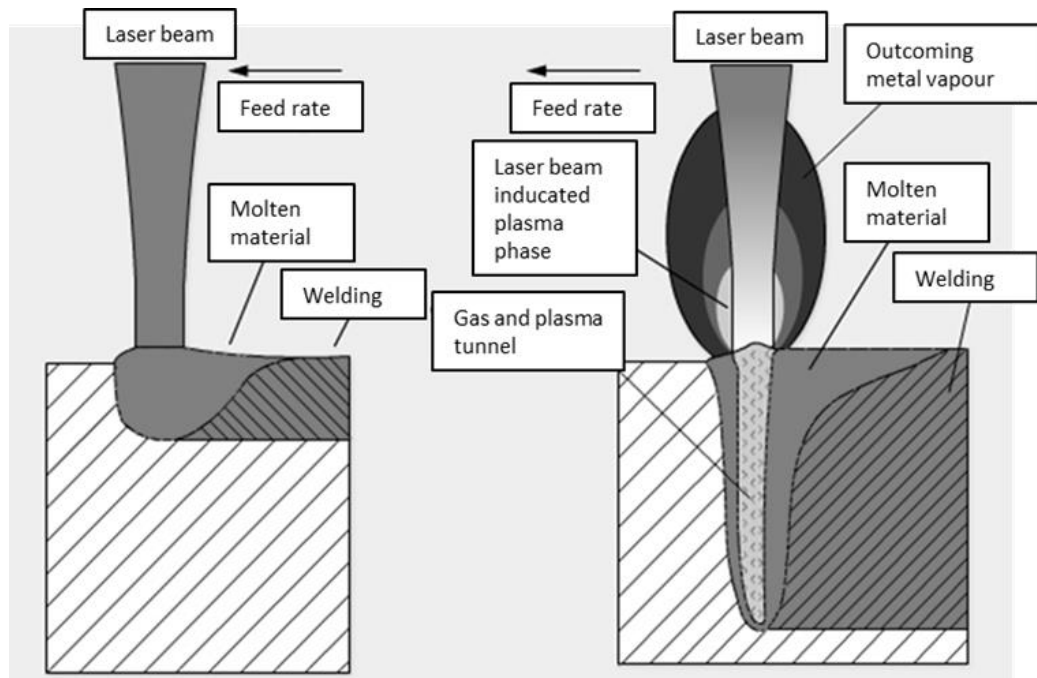


Figure 1. Conduction and keyhole laser welding [2].

Beyond this limit –due to another physical process- the technological procedure is controlled by the conditions of keyhole welding. As an aspect of technology and quality assurance it is important how different welding parameters have effects on different joint geometry. These parameters are the power of the laser beam, the velocity of welding, the position of focus spot, use of working gas and the excitation mode of the laser beam (CW, pulsating). All changes in these parameters have an essential effect on the joint geometry and the behavior of the plasma. Despite the diversity we must stick to the technical requirements and geometric specifications. Typical parameters of joint geometry are the following: depth of penetration, weld width, weld height, root weld with and the height of reinforcement [5].

1.2. Difference between traditional(MIG) and laser welding

Technically laser welding is similar to MIG welding only without the shielding gas. Laser welding fuses the metal by pulses of intense light and heat melting the members together while TIG welding fuses the members by heat created from an electric arc. MIG welding and TIG welding are similar in that they both use electricity to melt the material but MIG welding uses a filler material (usually a wire of the same type of material fed through the electrode).

New advancements in laser welding called "metal deposition laser welding" are similar to MIG in that they introduce a filler material by concentrating a cone of powdered metal into the laser's focus point [6]. This will help to solve one of laser welding's biggest obstacles: part fit up. Since the laser can only create enough heat to melt the metal in a small focus point it doesn't weld consistently well when part fit up varies. Any gap between the 2 members will cause an inconsistent weld. For this reason the most common form of welding (at least in a production environment) is MIG, because MIG welding is currently the most consistent and easiest at welding inconsistent fit up of parts because of the filler material. The geometry differentiation can be seen in figure 2.

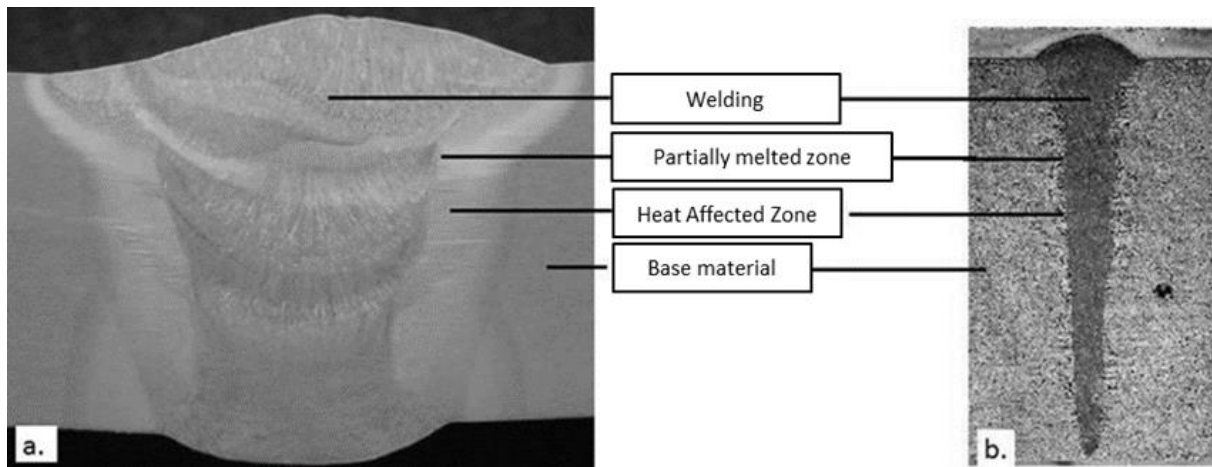


Figure 2. Geometry differentiation between traditional welding (a.) and laser keyhole welding (b.)

In case of laser welding the heat only absorbed where the joint will be so the heat affected zone is much smaller than the traditional welding method. During the laser keyhole welding a plasma tunnel created so the slenderness of the welded joint could be high. The aspect ratio (depth of welding divide with the width) can be 10 or more. The base material has lower inner stress because of the lower and focused heat input.

2. The method of photon heating

The energy of the photon (E) depends on the Planck constants (h), the speed of light (c) and the wavelength of the photon (λ).

$$E = h * \frac{c}{\lambda} \quad (1)$$

, where $h = 6.626 \times 10^{-34}$ Js, $c = 299\,792\,458$ m/s and the λ depends on the type and the material of the laser beam source.

From the 1. equation we can calculate how many photons we need to generate 1 kW laser beam power per second. In case of Nd: YAG (neodymium-doped yttrium aluminium garnet) laser beam source 5.35×10^{18} photon need, using Yb: YAG (Ytterbium-doped yttrium aluminium garnet) 5.18×10^{18} and in case of CO₂ laser beam source 5.33×10^{19} photon required.

These photons have high energy, when they collision with the atoms in the welding base material, the material's atoms energy will increase and the heat will grow. But the photons are only capable of transmitting their energies and interacting to free electrons of the base materials' atoms. So the photon - material interact is more precise if we call it to photon – free electron interact. The electrons can transmit energy to each other, but according only to the thermodynamics II.

When laser irradiation (in the form of electromagnetic waves or photons) impinges on the surface of a workpiece, a fraction of the energy is reflected at the surface, and a part penetrates of the energy is reflected at the surface, and a part penetrates into the substrate. A surface cannot absorb or emit photons. Attenuation takes place inside the solid, as does emission of radiative energy (and some of the emitted energy escapes through the surface into the adjacent medium).

In practical system the thickness of the surface layer over which absorption of irradiation from a laser beam occurs is very small compared with the overall dimensions of a workpiece – usually a few nanometres for metals and a few micrometres for most non-metals. The same may be said about emission from within the solid that escapes into the adjacent medium. In case of opaque materials it is customary to speak of absorption by and emission from “surface”, although a thin surface layer is implied. Consider thermal radiation impinging on a medium of finite thickness, some of the irradiation will be reflected away from the medium, a fraction will be absorbed inside the layer, and the rest will

be transmitted through the slab. Not that all three of these properties are nondimensional and may vary in magnitude between the values 0 and 1.

3. Investigation of plasma phase during the keyhole welding with different wavelength of laser beams

Transition to keyhole laser welding occurs at about 10^6 W/cm² due to the enhancement of metal vaporization. In this case the absorption on the surface of the workpiece is drastically change, the absorption of laser beam is nearly 0.9 (Figure 3).

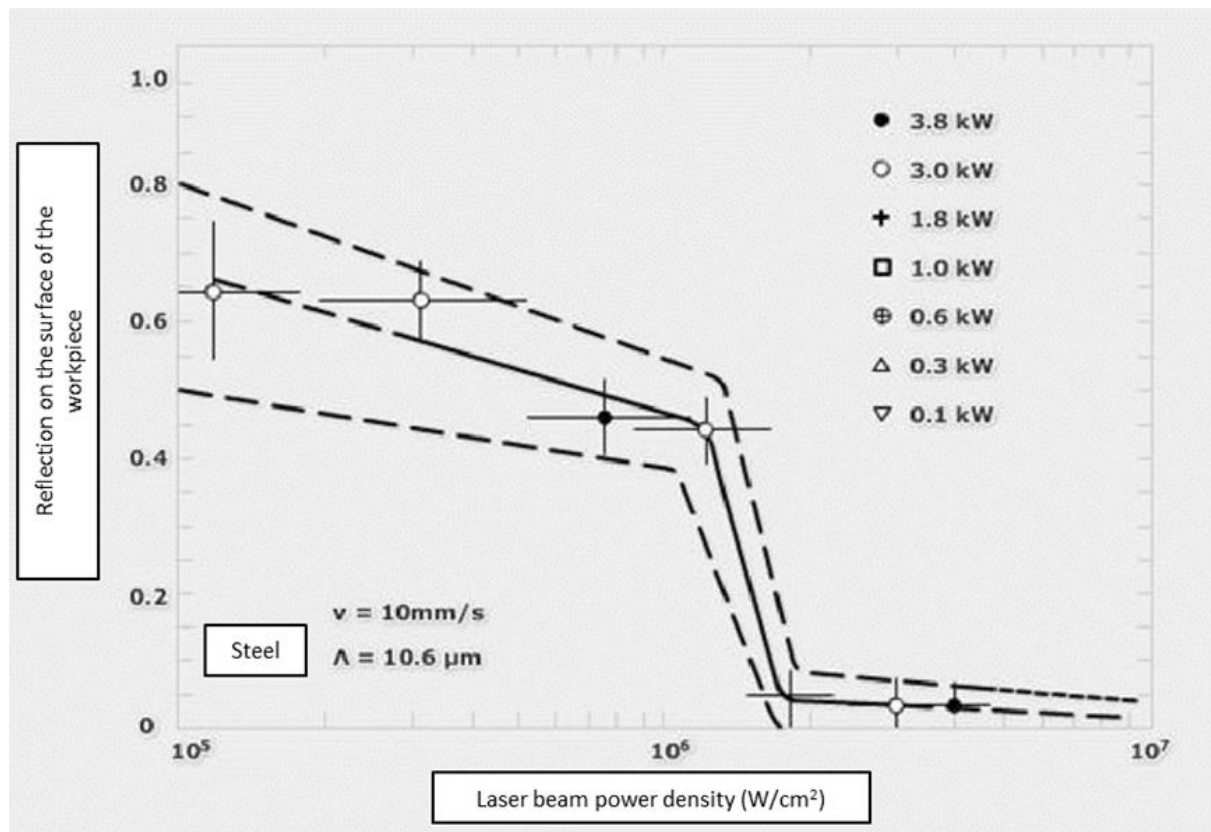


Figure 3. Absorption level changing depending on the laser beam power density [2].

The intense vaporization distinguishes keyhole laser welding from other conventional joining methods. It causes a large increase in vapour pressure (recoil pressure) that drills a depression in the melted metal, forming a long and narrow cavity or keyhole. The laser beam can then penetrate deeper into the metal through the cavity and be refracted and damped while traveling through the vapour. As the beam rays reach the keyhole surface, beam energy is partially absorbed on the surface and partially reflected towards a new point of interaction. The free electrons absorb a part of the photons. This succession of absorption/reflection (or multiple Fresnel absorption/reflection) increases the overall energy absorption (up to 90% in the present example). The keyhole cavity is filled with metal vapour that partly absorbs the incoming laser light. The charged particles present in the vapour can gain kinetic energy from the beam photons. When the gain is significant it results in beam damping, further ionization of the metal vapour (plasma) by the highly energetic electrons, increase of the plasma temperature. There is a high electron density and temperature in the plasma phase compared to the wavelength of the laser beam, also there is a rise in the plasma cloud's radiation energy loss. The optical densities of the plasma is changing, the reflective index is increasing. With these effects less photons can reach the plasma tunnel.

Figure 4 and 5 shows when the laser beam source is CO₂ during the keyhole welding. In this case the laser beam heat the plasma cloud too much, and it can be overheated. The plasma reflection rate increase and, the keyhole plasma tunnel shutdown and it goes to heat convection welding. The unstable plasma can cause cracks in the welding because of the high rate of density of the heat input [10].

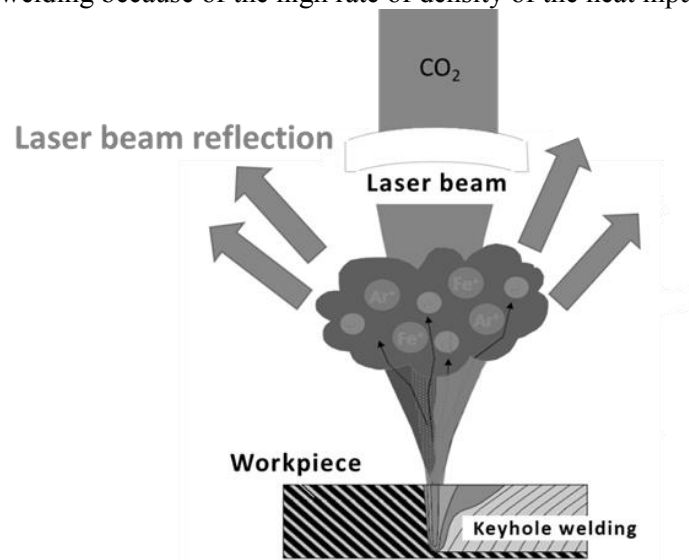


Figure 4. Behaviour of the plasma cloud in case of using CO₂ laser beam source.

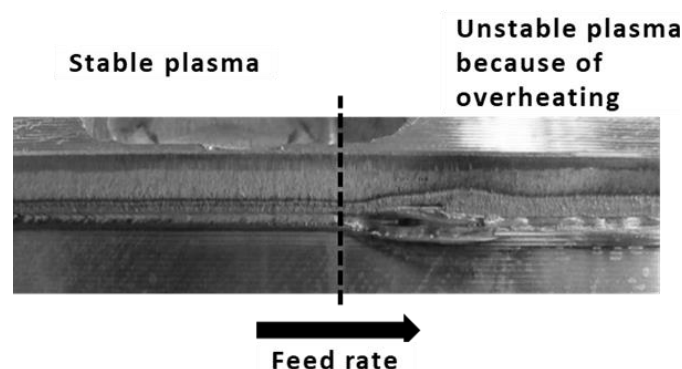


Figure 5. : Stable and unstable plasma using CO₂ laser beam during the keyhole welding.

Using a solid state laser beam source, for example Nd: YAG the laser beam wavelength is much shorter, and it has different effect when interact with the plasma cloud during the keyhole welding process.

Figure 6. and 7. shows the effect of a solid state laser beam source to the plasma cloud. Because of the different wavelength just a few part of photons absorbe in the plasma cloud, the most part of it reach the keyhole welding. This type of plasma cloud can be overheated too, in this case the metal vapour with the working gas overheat and has high rate of infrared irradiation. This cloud goes trough on the welding and the top of the keyhole welding geometry will be wider because of the overheating of infrared irradiation.

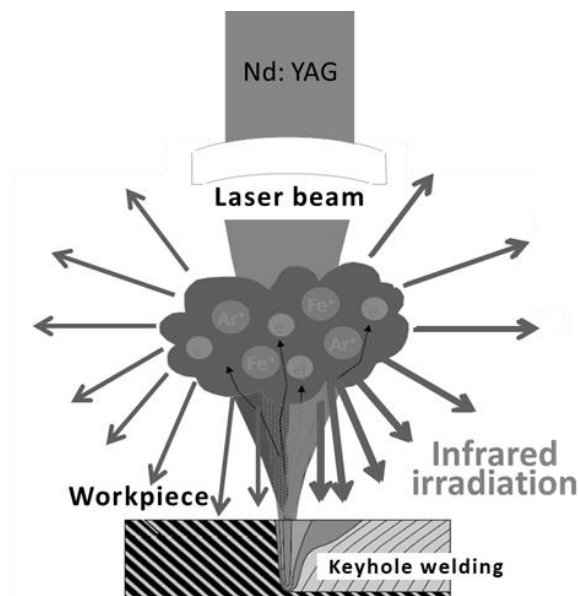


Figure 6. : Behaviour of the plasma cloud using a solid state laser beam heating.

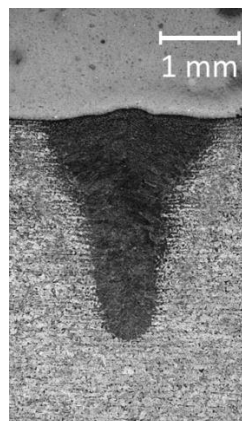


Figure 7. : Effect of the overheated plasma cloud and the infrared irradiation.

Summary Figure 8 shows the connection between the free electron density and the wavelength in the plasma cloud. The dotted lines shows the change between the reflection or transmission behaviors of the plasma cloud.

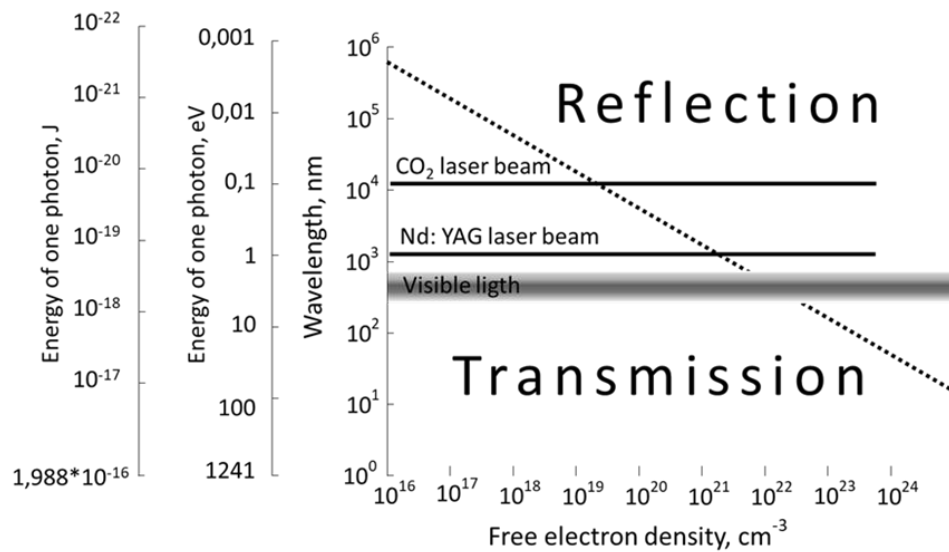


Figure 8. Effect of the laser beam wavelength, photon energy and the electron density in the plasma cloud [2].

The figure shows the wavelength of the CO₂ laser beam 10600 nm and the Nd: YAG 1064 nm. In case of CO₂ laser beam welding the plasma cloud will reflect the incoming photons because the free electron density level is smaller during the overheating. In case of solid state Nd: YAG laser beam the plasma cloud can reach about 3 magnitude higher electron density, and the photons can reach the keyhole welding.

The plasma has then a positive role: it can protect the keyhole cavity from cooling by the surrounding atmosphere and plasma radiation can strengthen vaporization at the keyhole surface. This effect also can support the plasma state using laser beam cutting [11]. Above the critical temperature damping becomes dominant and vaporization vanishes.

There is different type of plasma mediums and the plasma state quality depend on the quality and the free electron density of the mediums (Figure 9.).

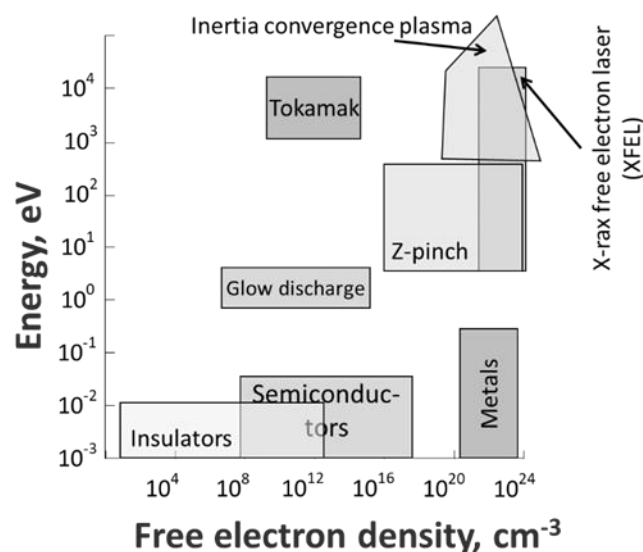


Figure 9. Different plasma mediums depending on the free electron density [8].

Metals have high density of free electrons but the energy of the plasma “lower”. Z-pinch, Tokamak, X-ray free electron laser and Inertia convergence plasma is an innovative research areas in the energy industry [7-9].

4. Summary

The major conclusions are summarized in the followings:

- The accelerated photons can only interact and capable of transmitting energy to the medium's free electrons.
- The behavior of the plasma cloud during laser keyhole welding depend on the type of the laser beam source. Nd: YAG beam source shows better tolerance with overheating because of the free electron density can be higher than using CO₂ laser beam.
- The quality and the composition of the plasma medium define the quality of the plasma cloud and the welding geometry.
- In case of CO₂ laser beam the plasma cloud be overheated, the reflection rate increase and the plasma became unstable.
- In case of solid state laser beam the plasma cloud has infrared irradiation during the overheating and it causes the wider top of the welding geometry.

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Acknowledgement

The publication of the work reported herein has been supported by NTP-NFTÖ-17-B-0514, National Talent Programme, Ministry of Human Capacities, Human Capacities Grant Management Office (EMET).