Pulsed Laser Welding

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1. Introduction

Metal joining by means of components heating to the melting temperatures was known thousands years ago in old age Greece. Heat sources have been developed from forging furnace to modern methods of plasma arc welding, electric resistance welding, oxy-fuel welding or laser welding. Laser, as a source of intensive light beam, starts to be implemented into industrial welding systems due to its advantages in comparison with classic methods, for example narrow heat affected zone, deep penetration, flexibility and many others. Besides the welding of compatible metals it is also possible to weld plastics.

The principle of "light" welding is the same for all suitable laser wavelengths. The absorption of laser radiation in thin work piece surface layer leads to the temperature rise to the melting or vaporization point. Due to the conduction of generated heat to the surrounding material volume sufficient weld pool is melted. However heat conduction also causes essential energy losses.

Laser welding important processing parameters are laser beam properties (power, beam quality and diameter, wavelength, focusing lens length), weld conditions (focus position towards the material surface, relative motion of the work piece towards the laser spot, weld type, processing gas) and physical properties of welded material and work piece dimensions. Typical power densities applied in laser welding lie between 10^5 – 10^7 W.cm^{-2}.

Lasers with active media formed by CO_2, semiconductors, Yb:YAG, Nd:YAG crystals or Ytterbium doped fibres can be used in industry for various components welding. High power gaseous continual CO_2 laser with wavelength 10 600 nm and wall-plug efficiency about 10 % has excellent beam quality, near Gaussian mode and high depth of focus, thus it is suitable for deep penetration welding. Far infrared radiation of this laser type cannot be transferred by means of optical fibre. Therefore typical CO_2 laser welding system is equipped with fixed processing head and work piece positioning mechanism. A mixture of helium and nitrogen is recommended as a processing gas to suppress plasma shielding effect.

Solid state pulsed Nd:YAG laser's wavelength 1 064 nm is suitable for fibre guiding from resonator to the processing head, fixed on a robot arm. This allows welding few meters far from the laser source which is especially suitable for large or in shape complicated components. Laser beam has a multimode profile with quality 20 – 30 mm.mrad, wall – plug efficiency of the flash-lamp pumped Nd:YAG lasers reaches only about 3%. In recent years new and much more efficient laser types were developed – diode lasers with beam quality up to 30 mm.mrad, diode pumped disc Yb:YAG lasers and Ytterbium doped fibre lasers with excellent beam quality, both in near infrared region. With more compact design, higher efficiency 30 % (fibre laser) to 50 % (diode laser) and lower running costs these systems are going to replace above mentioned Nd:YAG and CO_2 lasers (Němeček & Mužík, 2009).

Nevertheless many pulsed laser welders are already installed in small and middle enterprises and various materials are being processed. Processing parameters optimization is a goal of many research projects to improve productivity and decrease occurrence of defects that results in lower production costs.

2. Processing parameters optimization

To achieve fully penetrated high quality weld it is necessary to set optimal combination of processing parameters. They involved three different groups: laser beam properties (wavelength, power, diameter, divergence) material properties (density, thermal conductivity, specific heat, latent heat of melting and vaporization, thickness, joint configuration) and very important interaction parameters (welding speed, focusing element length, focus plane position towards the material surface, shielding gas direction and flow, absorptivity of material surface) (Duley, 1998). At room temperature almost all metals have absorptivity about 10 % - 20 %. It increases during material heating and leaps to 80 % - 90% when metal melting point is reached.

Heat Q necessary to melt material mass m is given by the well known equation

$$Q = m[c(T_m - T_0) + L_m] \tag{1}$$

where c is specific heat, T_m melting temperature, T_0 initial temperature and L_m latent heat of melting. In the case of continual laser welding this equation can be transformed to the following form

$$\frac{Q}{t} = \rho D h v[c(T_m - T_0) + L_m] \tag{2}$$

where Q/t represents power required for melting, ρ volume density, D spot diameter, h penetration depth and v welding speed. Then, penetration depth can be expressed as follows

$$h = \frac{\frac{Q}{t}}{\rho D v[c(T_m - T_0) + L_m]}. \tag{3}$$

Including surface absorption and heat conduction losses, penetration depth can be roughly estimated

$$h = K\frac{P}{Dv} \tag{4}$$

where P is laser power and K constant resulting from material physical characteristics including surface reflectivity and other energy losses. Thus, penetration depth is proportional to the applied laser power and inversely proportional to the spot diameter and welding speed.

P/v ratio defines the heat input to a unit length. Melted area cross section linearly rises with the heat input (Ghaini et al., 2007). In the case of continual laser welding processing parameters like laser power and welding speed are simply entered into the welding device control system pursuant to the material thickness and physical properties. Much more complicated setting of pulsed laser parameters is outlined in paragraph 2.1.

Surface power density or laser beam intensity is defined as a portion of laser power and laser spot area on material surface. Three welding modes are used in praxis, heat conduction mode, penetration mode and deep penetration (keyhole) mode.

Heat conduction welding is characterized by power density in the interval 10^4 – 10^6 W.cm^{-2} that causes only surface melting up to 1 mm. The weld is wide and shallow with aspects ratio about 2:1. Only laser beam without sharp intensity peak can be used, or the focal plane must be shifted some millimetres above the material surface. In the case of pulsed laser, pulse length 1 ms – 10 ms is used. When power density balances around the critical point 10^6 W.cm^{-2}, produced welds are deeper than in the case of the conduction welding. Aspect ratio is about 1:1 that indicates penetration mode welding (Lapšanská et al., 2010).

Keyhole welding mode starts when energy density exceeds 10^6 W.cm^{-2}. Laser beam is focused on the material surface and the fusion zone rapidly heats up to the boiling point. Melted material begins to vaporize at the centre of the weld spot and creates a blind hole (keyhole) in the centre of the weld line (Fig. 1). The pressure of hot metal vapour keeps the hole open during the welding. Presence of the keyhole allows the laser energy to reach deeper into the fusion zone and consequently to achieve deeper weld with lower aspect ratio (Kannatey-Asibu Jr., 2009). Keyhole mode welding is a typical application of high power continuous lasers or high energy pulsed lasers.

During the deep penetration laser welding plasma can be generated above the keyhole. Ionised metal vapour and shielding gas absorb laser light, change its direction and cause lower process efficiency. Inert gases such as argon, nitrogen, helium and their special mixtures are used for plasma reduction. On the other hand, thanks to the plasma plume presence, welding process can be controlled by means of plasma intensity measurement (Aalderink et al., 2005).

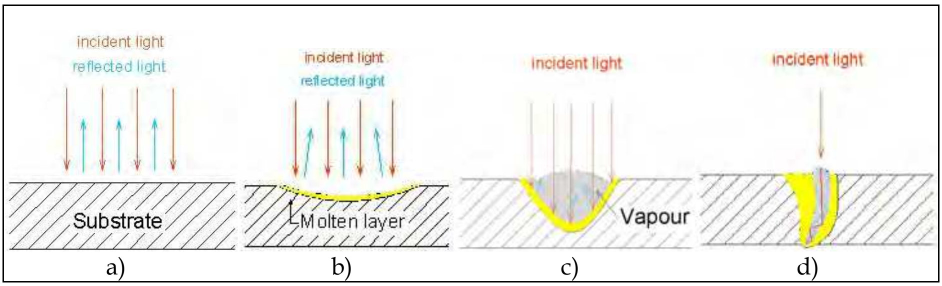


Fig. 1. Keyhole formation, a) surface irradiation, b) surface melting, c) vaporisation and cavity formation and d) light absorption inside the keyhole.

2.1 Pulsed laser welding parameters

In the case of pulsed laser, more parameters are involved. Three basic parameters that must be set at laser source control panel are frequency f (Hz), pulse length t (ms) and flash lamp charging voltage U (V). These parameters define actual pulse energy E (J). Peak power P_{peak} (kW) is defined as a portion of energy and pulse length

$$P_{peak} = \frac{E}{t} . \tag{5}$$

Peak power determines interaction intensity of laser beam with material for given spot size. According to the material thickness and welding mode peak power values 0.2 kW to 5 kW are recommended in the operation manuals of laser welders.

Laser average power P (W) is given as a product of actual energy and pulse frequency

$$P = Ef \tag{6}$$

and determines the welding speed.

There are two possible welding methods using pulsed laser. The first and simpler one is a spot welding which often replaces resistance welding nowadays. One or more pulses land material surface to reach required penetration depth in spot welding. No mutual motion between the processing head and material is applied. Spot welding is also often used for rough fastening of components to be subsequently seam welded using either pulsed or continual laser. This procedure reduces final distortions resulting from high thermal gradients corresponding to high value of applied power densities.

To achieve continuous tight welds using a pulsed laser, pulse overlap must be applied. This is realized using suitable combination of processing parameters. Pulse overlap PO is defined as follows

$$PO = 1 - \frac{v}{Df} \tag{7}$$

To achieve hermetic tight joints pulse overlap is recommended to be 80 %.

In comparison with conventional welding methods and continual laser welding, higher peak power densities in laser pulse mode causes higher heating and cooling rates which can result in weld defects and inhomogeneous microstructure. Many experimental works have been realised to optimise pulsed laser welding parameters for different kind of metals with goal to eliminate defects. For instance (Ghaini and al., 2006) studied overlap bead on plate welding of low carbon steel, (Tzeng, 1999) made successful welds without gas formed porosity in lap joints of zinc-coated steel. Another important parameter was introduced in these studies which is effective peak power density.

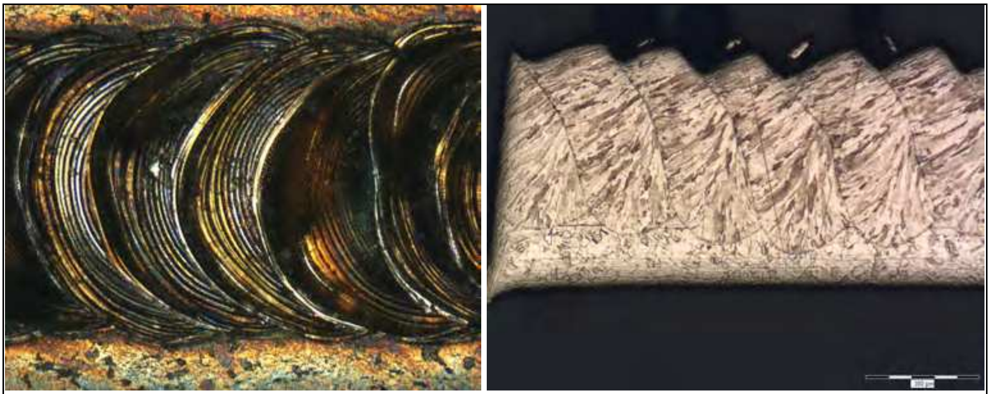
Effective peak power density $EPPD$ is defined as a product of peak power density PPD and pulse overlapping index F

$$EPPD = F \times PPD \tag{8}$$

where

$$F = \frac{1}{1 - PO}. \quad (9)$$

This parameter was introduced to better formulate the real power reaching material surface. When seem welding is required more pulses land material surface (Fig. 2) and their contribution adds. Thus the effective peak power density can be used to compare energy requirements of welds accomplished with different pulse overlap.



a) b)

Fig. 2. Top view and longitudinal weld cross section.

2.2 Experimental work

Pulsed Nd:YAG laser system LASAG KLS 246 – 102 with maximal average power 150 W and beam parameter product 22 mm.mrad was used to carry out experiments focused on the study of the effect of processing parameters on weld dimensions and its surface character. Material to be welded was 0.6 mm thick stainless steel AISI 304.

So as the results were not affected by an accidental misalignment of components to be butt joined, by possible contamination or presence of surface defects of contact areas, or other unsuitable initial conditions influencing weld properties, it was decided not to join two sheets but to make a deep remelting of one sheet, which is, in fact, bead-on-plate welding. This strategy ensures that only the effect of energy changes will be studied. Laser welding is very demanding on pieces to be welded preparation, especially when narrow laser beam is used in near focal position. Therefore, highly precise prepared edges and minimal gap between the components to be joined are always supposed, which are conditions that need to be fulfilled in every precise butt joint laser welding application to prepare a high-quality weld. Then, the results of bead-on-plate experiments can be applied to the real sheet welding at conditions suitable for a high-quality weld joint preparation. This simplification can be used for the effect of processing parameter changes study in different laser applications.

Welding itself was realized 4 mm under the focal plane to ensure the sufficient beam diameter on the specimen which was 0.85 mm. Focussing lens with 100 mm focal length was used. Cleaned degreased weld pieces were clamped in a mounting jig. Pure argon gas at coaxial 8 $l.min^{-1}$ flow rate was used to protect the weld pool against its oxidation. In each set of experiments, only one parameter was changed keeping all the other parameters constant to be able to identify the effect of the one examined parameter. Table 1 presents processing parameters of each set of experiments.

series	*E* (J)	*P* (W)	P_{peak} (kW)	*t* (ms)	*v* ($mm.s^{-1}$)	*f* (Hz)
1	3.5	45.5	1.59 – 0.8	2.2 – 4.4	4.0	13.0
2	3.5 – 6.5	45.5 – 80.6	1.03 – 1.82	3.4	4.0	13.0
3	5.0	45.5	1.47	3.4	1.5 – 6.0	13.0
4	5.0	15.0 – 35.0	1.47	3.4	4.0	3.0 – 7.0
5	1.8 – 6.2	23.4 – 80.6	1.2	1.5 – 5.1	4.0	13.0

Table 1. An overview of processing parameters of realised experiments

2.2.1 Pulse length effect

The first set of experiments was focused on the effect of pulse length which was changed in the interval from 2.2 ms to 4.4 ms. To keep constant beam energy 3.5 J charging voltage had to be decreased when pulse length was increased (Fig. 3). Thus the average power remained constant and peak power decreased (Fig. 4).

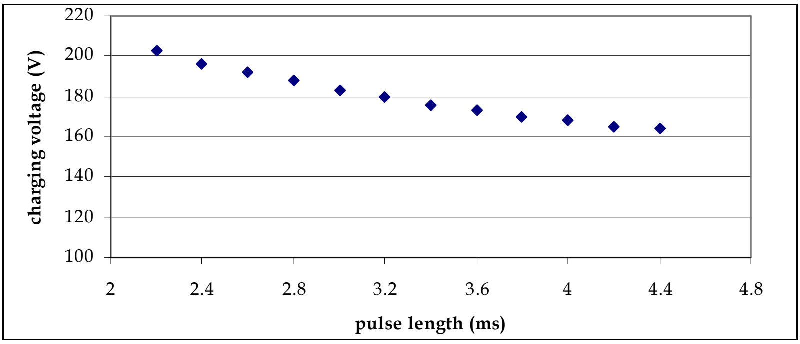


Fig. 3. Charging voltage vs. pulse length keeping constant pulse energy.

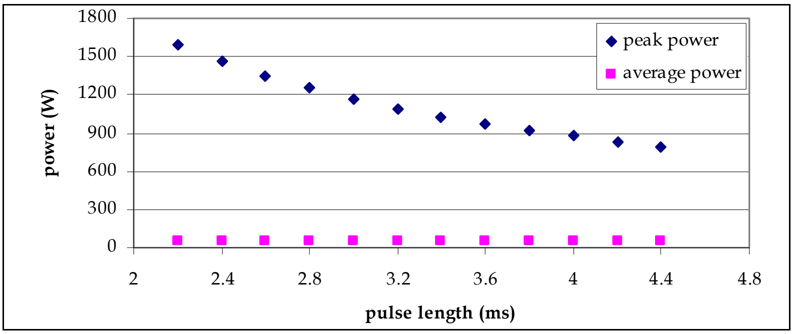


Fig. 4. Average and peak power vs. pulse length keeping constant pulse energy.

Pulse length increase led to the decrease of penetration depth (Fig. 5) that corresponds to the decrease of peak power which seems to be a critical parameter.

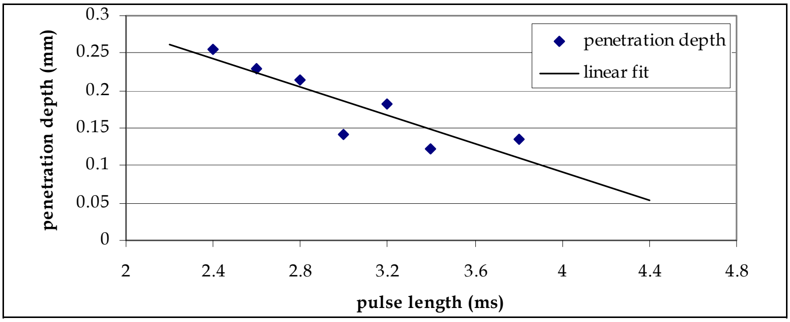


Fig. 5. Penetration depth vs. pulse length.

These results also showed that applied parameters were not sufficient for the full penetration of 0.6 mm metal sheet (Fig. 6). However the effect of pulse length is evident.

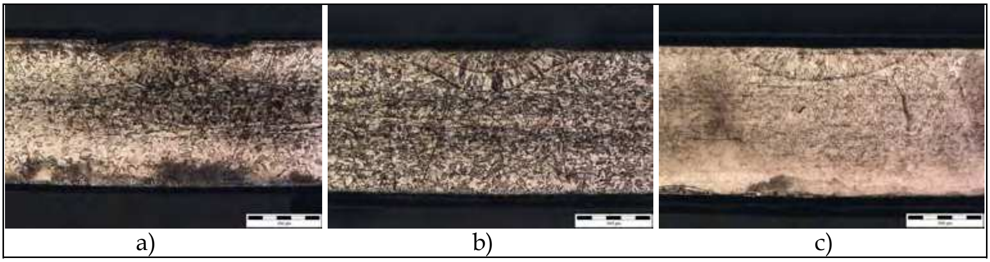


Fig. 6. Perpendicular cross sections of welds at a) 2.8 ms, b) 3.2 ms and c) 3.8 ms.

Laser scanning confocal microscope LEXT OLS 3100 was used to image and analyse laser weld surfaces. Spot diameter varied in the interval from 0.704 mm to 0.759 mm and its slightly decreasing tendency with increasing pulse length was detected (Fig. 7). Average value of spot diameter reached 0.73 mm. According to the 0.025 mm deviations measured within the each sample, no definite relationship between spot diameter and pulse length can be determined in the investigated region.

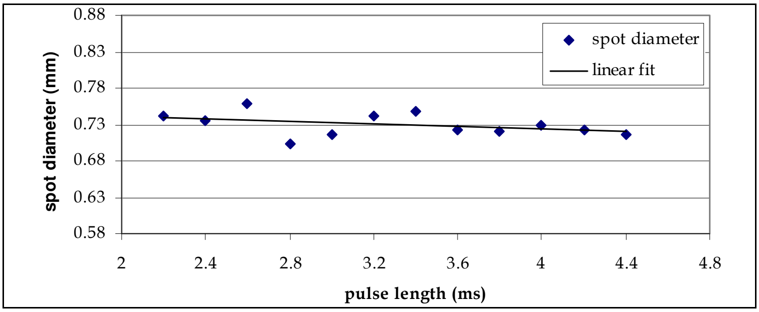


Fig. 7. Spot diameter vs. pulse length.

Fig. 8 presents an example of surface longitudinal central profile. In technical practise, strict claims on weld surface quality are often posed. Suitable combination of welding parameters can minimise post processing mechanical treatment. Fig. 9 presents surface images of selected samples. Pulse overlap 63 % remained constant during all the experiments of this set.

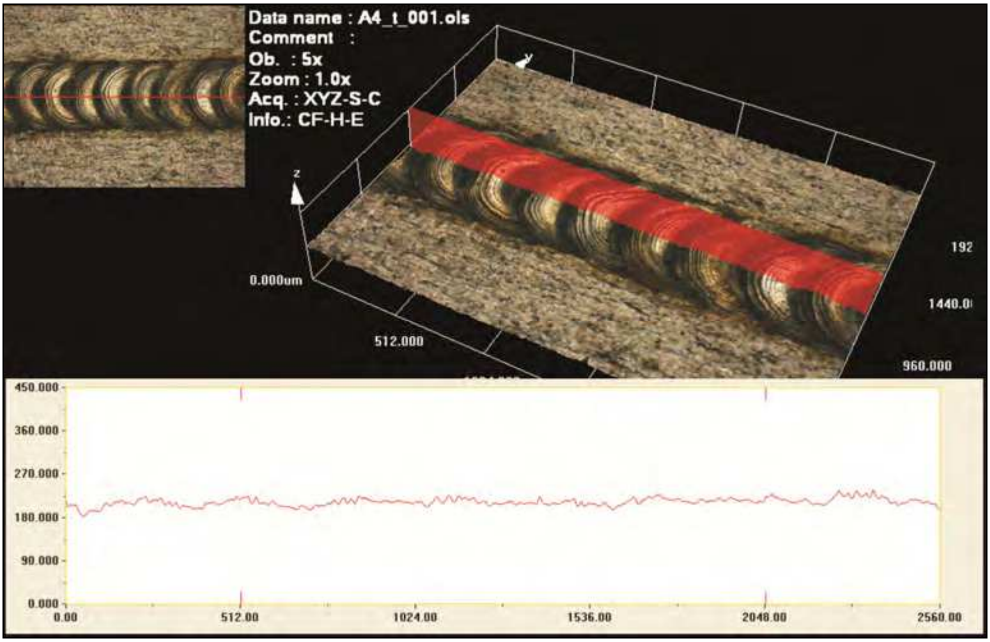


Fig. 8. 3D surface reconstruction and central profile of the weld realised at 3.8 ms.

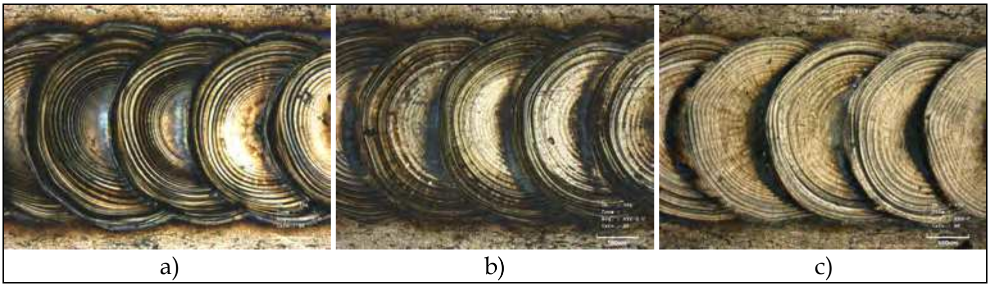


Fig. 9. Weld surface in case of pulse length a) 2.6 ms, b) 3.4 ms and c) 4.4 ms.

2.2.2 Pulse energy effect

The second series of experiments studied the effect of pulse energy which was set in the interval from 3.5 J to 6.5 J via charging flash lamp voltage changes (Fig. 10). Increasing energy naturally increases average as well as peak power (Fig. 11).

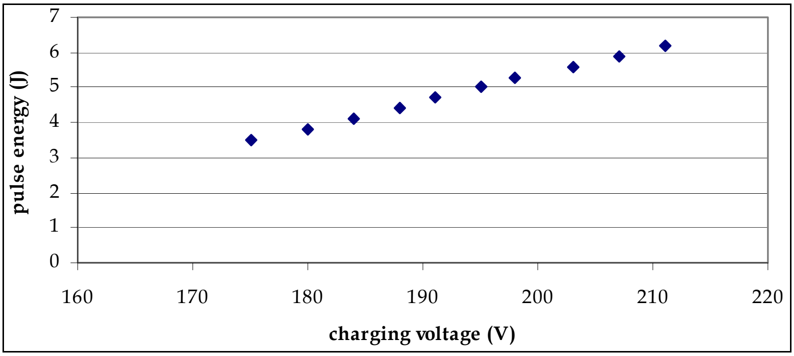


Fig. 10. Pulse energy vs. charging voltage.

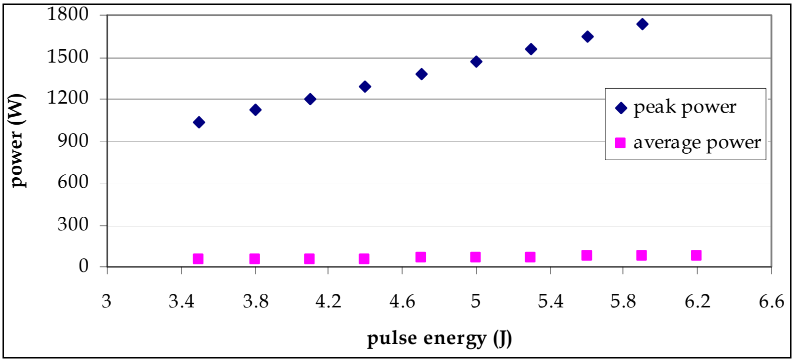


Fig. 11. Average and peak power vs. pulse energy.

Higher laser power leads to the deeper penetration which corresponds to the higher applied power resulting in higher heat input. Nevertheless penetration depth evolution is not linear (Fig. 12).

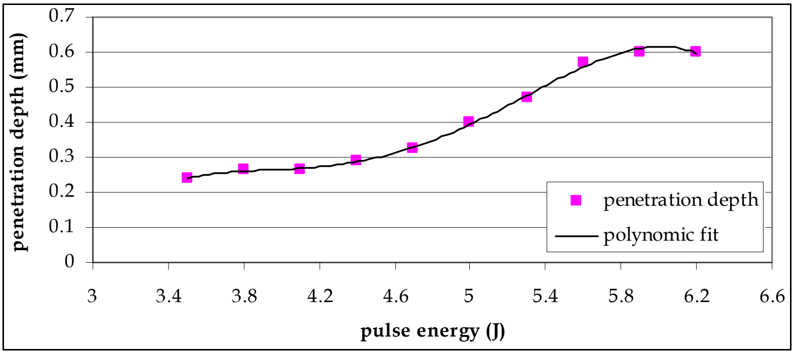


Fig. 12. Penetration depth vs. pulse energy.

Fig. 13 presents reached aspect ratios (penetration depth to weld width) as a function of effective peak power density. In this case pulse overlap 63 % was applied. Thus pulse overlapping index was 2.7. It means that power really touching a unit of material surface is 2.7 times higher in comparison with laser output power assuming no energy losses between laser output and material surface.

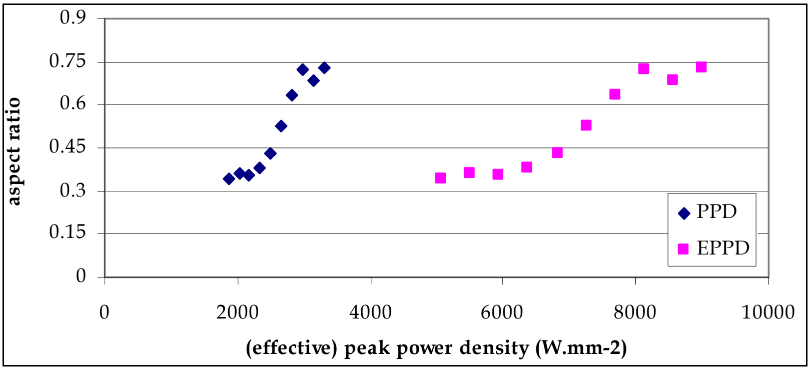


Fig. 13. Aspect ratio vs. effective peak power density.

Penetration depth slightly increases with pulse energy until about one half of the sheet thickness is penetrated. Then, when the formation of the keyhole starts (4.7 J), it increases steeply until the full penetration is reached at 5.9 J (1.7 kW). Keyhole formed at lower peak powers is not stable enough to establish true keyhole welding, and penetration welding mode can be observed (Fig. 14).

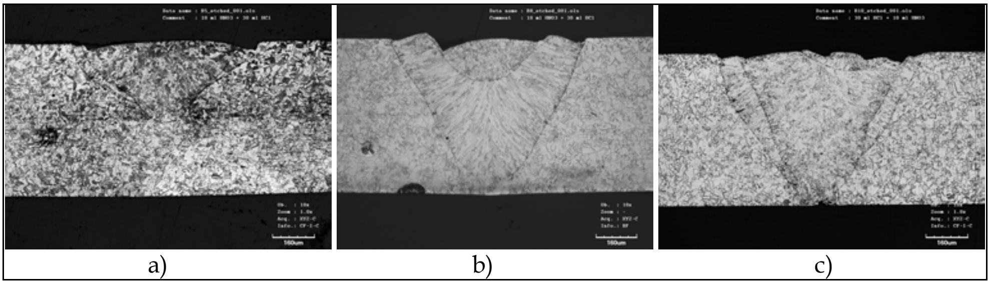


Fig. 14. Perpendicular cross sections of welds at a) 3.8 J, b) 4.7 J and c) 6.2 J.

Aspect ratio increases with increasing effective peak power density until the full penetration is reached at about 8.6 kW.mm^{-2}. At the moment of full penetration spot diameter is maximal, and aspect ratio decreases. Once the full penetration has been achieved, increasing effective peak power density does not lead to another weld width grow. Rather, conversely, the width decreases because the beam can escape from the melt pool because of the full penetration and because less energy is absorbed. That is why the aspect ratio increases again. These data corresponds to the weld cross-section fusion area measurement (Fig. 15).

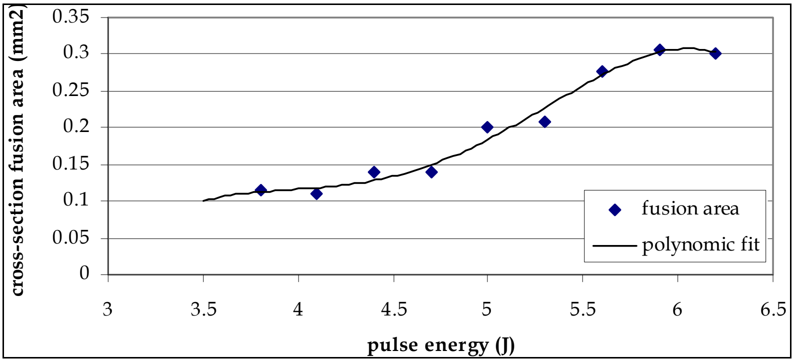


Fig. 15. Cross-section fusion area vs. pulse energy.

Fig. 16 presents the effect of beam energy on spot diameter. Beam diameter on the specimen was 0.84 mm for all carried out experiments. Spot diameter does not reach this value for almost all spots. This fact corresponds to the relative low energy application, non-uniform heat distribution, resulting from characteristic profile of beam intensity, and is supported by relatively low thermal conductivity of welded material.

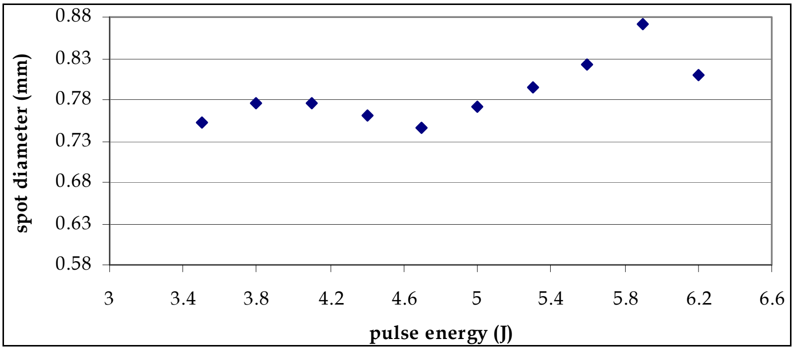


Fig. 16. Spot diameter vs. pulse energy.

Spot shape is also very demanding on pulse energy. The volume of melted material is higher at higher energies which leads to the higher deformation of the spot shape (Fig. 17).

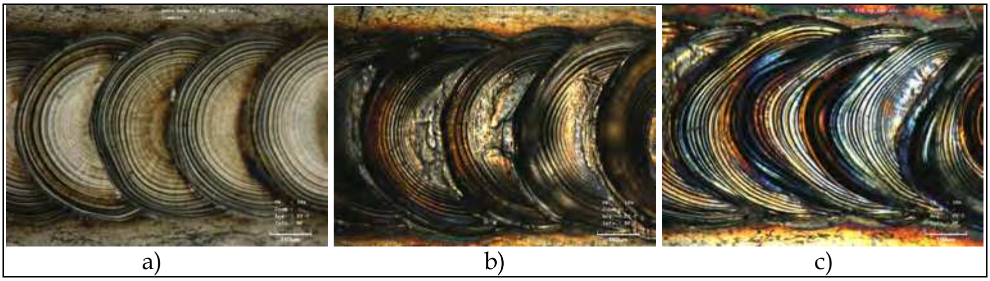


Fig. 17. Weld surface in case of pulse energy a) 3.5 J, b) 5 J and c) 6.2 J.

2.2.3 Welding speed effect

The third experiment was focused on the effect of welding speed. Welding speed was changed from 1.5 $mm.s^{-1}$ to 6 $mm.s^{-1}$.

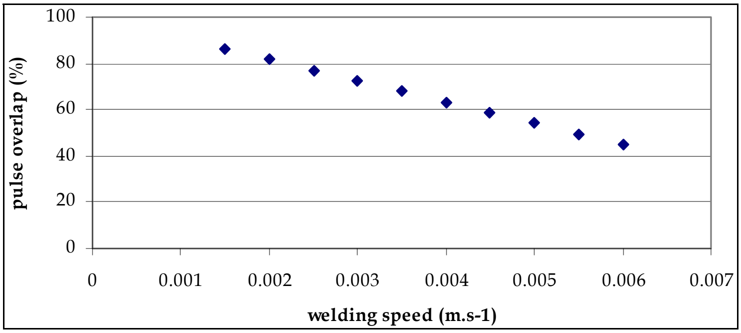


Fig. 18. Pulse overlap vs. welding speed.

Speed changes correspond to the pulse overlap change from 86 % to 40 % (Fig. 18, Fig. 19).

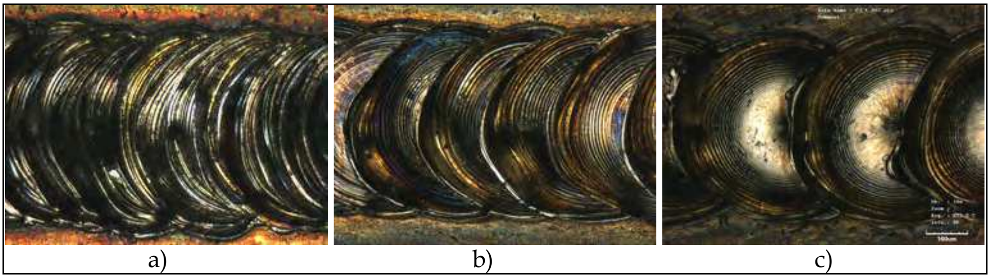


Fig. 19. Weld surface in case of welding speed a) 1.5 $mm.s^{-1}$, b) 3.5 $mm.s^{-1}$ and c) 6 $mm.s^{-1}$.

These experiments did not prove any significant change in penetration depth (Fig. 20). On the other hand, weld width decreased with increasing welding speed (Fig. 21). These give us positive information that slight required changes of pulse overlap via welding speed do not significantly influence penetration depth.

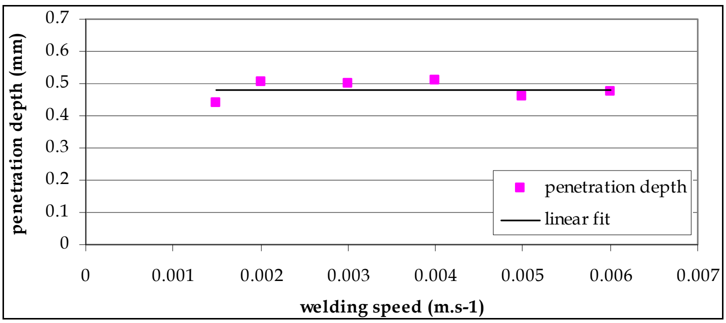


Fig. 20. Penetration depth vs. welding speed.

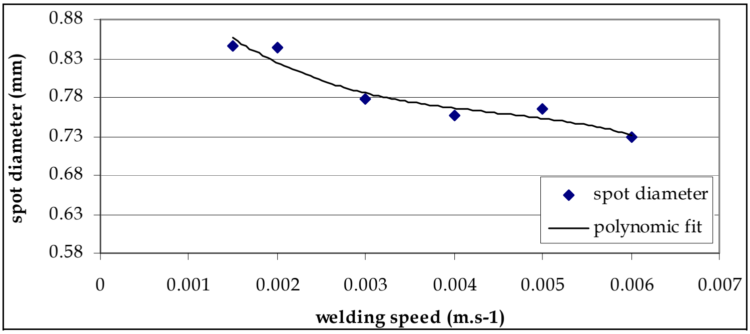


Fig. 21. Spot diameter vs. welding speed.

2.2.4 Pulse frequency effect

Another experiment concerned with pulse frequency effect. Pulse frequency was changed from 9 Hz to 17 Hz. In this case peak power remained constant, while the average power increased (Fig. 22).

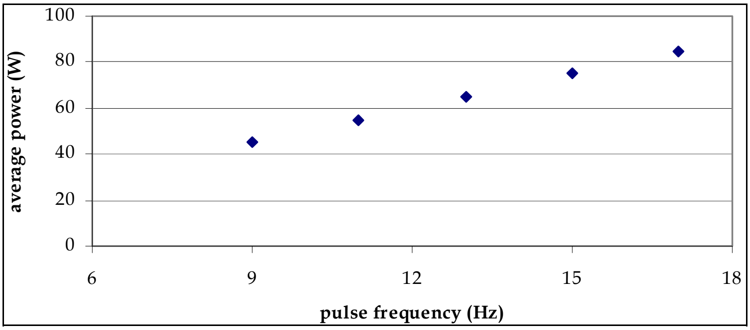


Fig. 22. Average power vs. pulse frequency.

Frequency increase naturally increases pulse overlap (Fig. 23, Fig. 24). Pulse overlap must be high enough so as also bottom side of the sheet is continuously penetrated (Fig. 25).

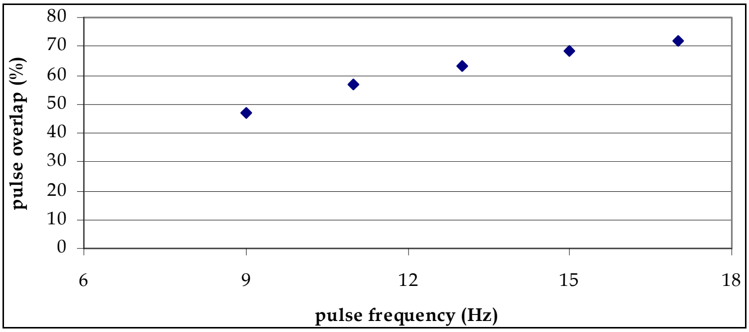


Fig. 23. Pulse overlap vs. pulse frequency.

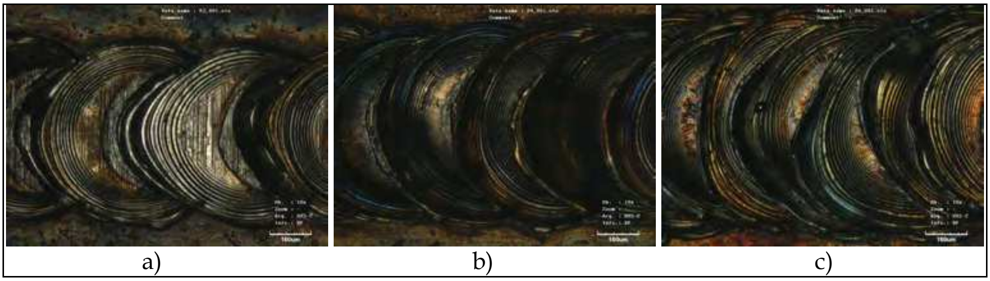


Fig. 24. Weld surface in case of frequency a) 9 Hz, b) 13 Hz and c) 17 Hz.

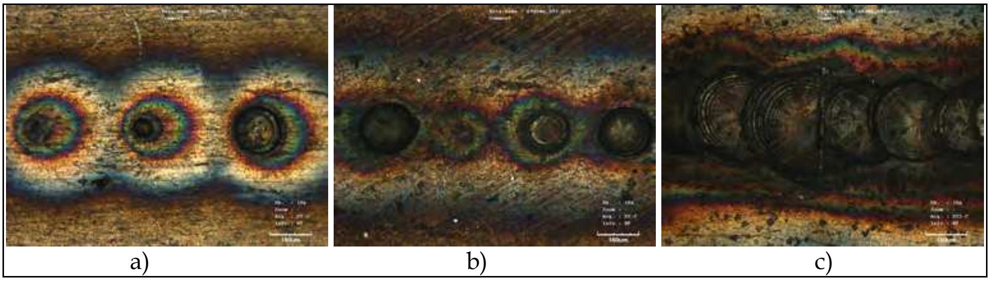


Fig. 25. Weld bottom side in case of frequency a) 9 Hz, b) 13 Hz and c) 17 Hz.

Power increase led to the increase of penetration depth (Fig. 26) as well as the weld width. Frequency 11 Hz was sufficient for the full penetration. Spot diameter slowly increases with increasing frequency (Fig. 27).

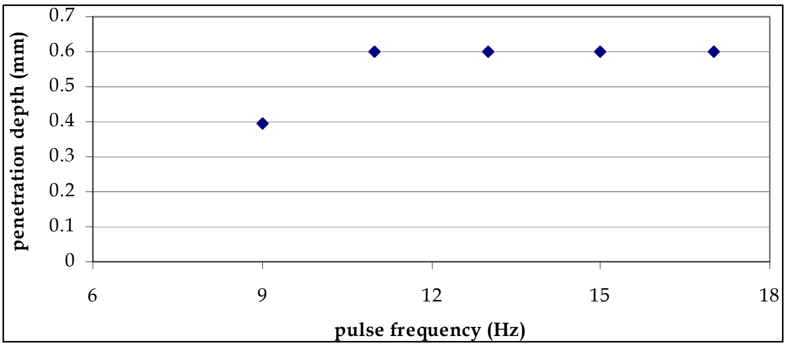


Fig. 26. Penetration depth vs. pulse frequency.

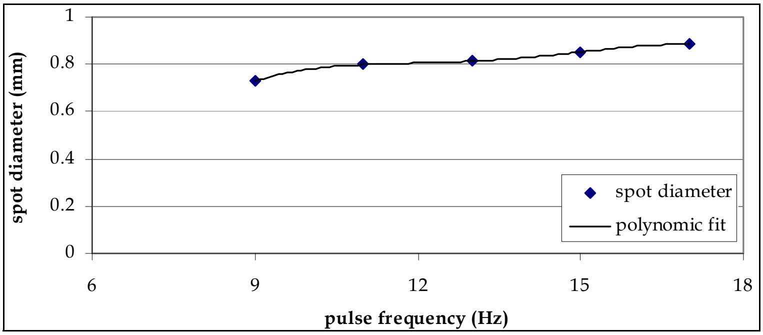


Fig. 27. Spot diameter vs. pulse frequency.

2.2.5 Combination of pulse energy and pulse length effect

In the last experiment beam energy and pulse length were changed simultaneously to keep constant peak power (Fig. 28). Although the peak power is still the same average power increases (Fig. 29).

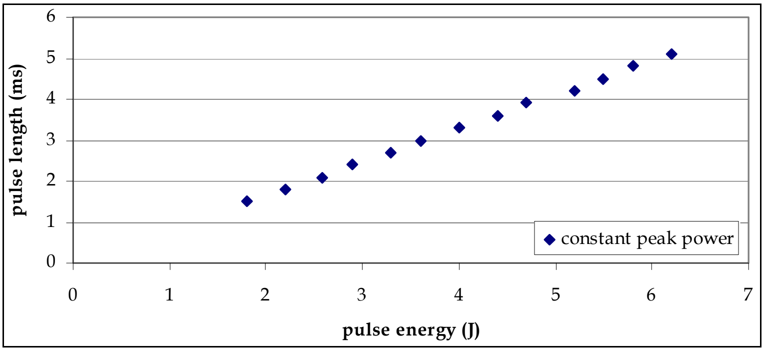


Fig. 28. Pulse length vs. pulse energy keeping constant peak power.

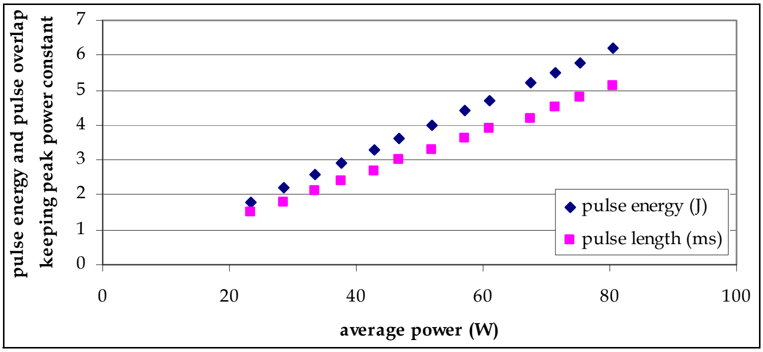


Fig. 29. Combination of pulse energy and pulse length (keeping constant peak power) vs. average power.

The higher energy and pulse length the deeper penetration depth (Fig. 30). This result points out the fact that even peak power can not be used as a definite indicator of penetration depth in pulsed laser welding.

Fig. 31 presents a comparison of these results with results of the effect of pulse energy (chapter 2.2.2). It is obvious that pulse energy is a critical parameter since it defines the volume of melted material.

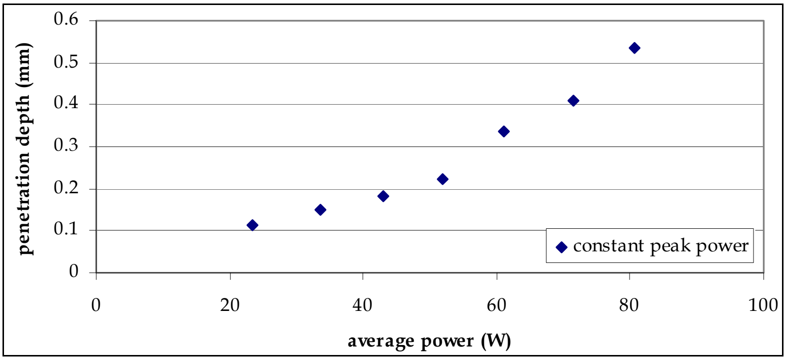


Fig. 30. Penetration depth vs. average power keeping constant peak power.

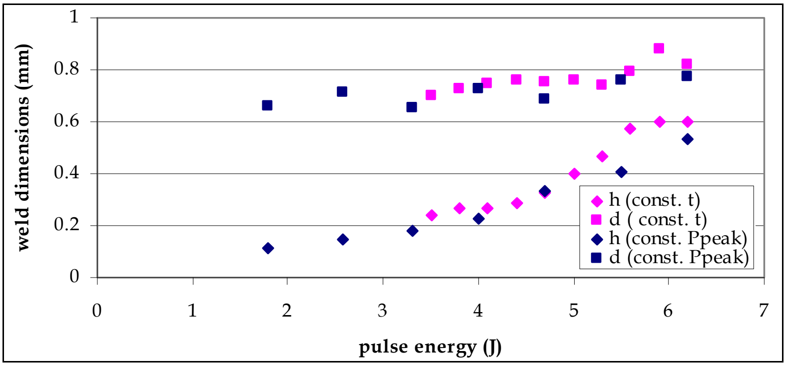


Fig. 31. Weld width *d* and penetration depth *h* vs. pulse energy for constant and variable pulse length.

3. Conclusion

High power Nd:YAG lasers with millisecond pulses are used in industry for spot or overlap welding. Many research papers reporting on pulsed laser welding parameters optimisation leading to the production of sufficiently deep welds without defects have been published. Usually more parameters were simultaneously changed in such optimisation processes. The aim of our research work was to identify the effect of each parameter separately.

Pulsed overlap bead-on-plate welding of 0.6 mm thick AISI 304 stainless steel was realised in our laboratory. Flash lamp pumped pulsed Nd:YAG laser KLS 246-102 with multimode beam profile was used for five series of welding experiments. The influence of different process parameters – pulse length, pulse energy, welding speed, pulse frequency and combination of pulse energy and pulse length on weld dimensions was examined in five separate experiments. Weld cross sections and laser spots overlap on samples surfaces were observed and measured by means of laser scanning confocal microscope LEXT OLS 3100. The effect of penetration depth and surface spot diameter on applied parameters was outlined.

Following from the above mentioned results, each processing parameter more or less influences weld characteristics. It is obvious that the knowledge of only one parameter, for example beam energy or average power, is not sufficient for the prediction of weld dimensions in pulsed laser seam welding. Peak power, pulse length and frequency in combination with processing speed are also very important. Suitable combination of processing parameters must be always found.

Experiments with flash lamp pumped solid state laser with very low efficiency will be followed by new studies on modern laser systems – diode and fibre lasers.

4. Acknowledgment

The Academy of Sciences of the Czech Republic supports this work under the project no. KAN301370701.

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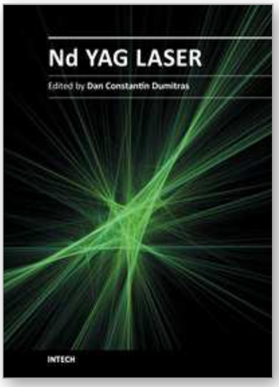

Nd YAG Laser
Edited by Dr. Dan C. Dumitras

ISBN 978-953-51-0105-5
Hard cover, 318 pages
Publisher InTech
Published online 09, March, 2012
Published in print edition March, 2012

Discovered almost fifty years ago at Bell Labs (1964), the Nd:YAG laser has undergone an enormous evolution in the years, being now widely used in both basic research and technological applications. Nd:YAG Laser covers a wide range of topics, from new systems (diode pumping, short pulse generation) and components (a new semiorganic nonlinear crystal) to applications in material processing (coating, welding, polishing, drilling, processing of metallic thin films), medicine (treatment, drug administration) and other various fields (semiconductor nanotechnology, plasma spectroscopy, laser induced breakdown spectroscopy).

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

Hana Chmelíčková and Hana Šebestová (2012). Pulsed Laser Welding, Nd YAG Laser, Dr. Dan C. Dumitras (Ed.), ISBN: 978-953-51-0105-5, InTech, Available from: http://www.intechopen.com/books/nd-yag-laser/pulsed-laser-welding

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