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Selection and Precise Application of Operating Parameters of Nd: YAG and Other Laser Sources for Material Processing

Jayanthi A[1], Kumar KS[2]* and Venkatraman K[3]

[1]Jeppiaar Institute of Technology, Chennai, India
[2]P.T. Lee Chengalvaraya Naicker College of Engineering, Kanchipuram, India
[3]SCSVMV University, Kanchipuram, India

Abstract

Nd: YAG laser has been a versatile tool for variety of material processing in the modern manufacturing industries. Apart from the easy manipulation and robustness of Nd: YAG laser beam, its wavelength absorbed by wide range of materials. Therefore, the possibility of controlling and précised values for prominent operating parameters such as average peak power, average peak power density (APPD), mean power, pulse duration, pulse energy, pulse repetition rate, interaction, pulse overlap theory and its mathematical relationships were discussed for pulsed and continuous wave. Hence, the selection of satisfactory combinations of associated parameters to produce efficient and effective material processing with reduced defects.

Keywords: Nd: YAG laser; Pulsed laser; Continuous laser; Operating parameters; Material processing

Introduction

Recently, laser welding has received much attention as a promising joining technology because it encompasses high quality, precision, performance, and speed with good flexibility and low distortion. In addition, it allows robotic linkages, reduced work force, full automation, and systematization. The theoretical and experimental study of laser material processing began in 1962, Since then, the use of laser welding has grown swiftly, as the new manufacturing possibilities became better understood [1]. In comparison of Nd: YAG laser and CO_2 laser, wavelength, 10.6 µm in case of a CO_2 laser and 1.06 µm for Nd: YAG laser beam. This means a difference in absorption of the laser beam by the materials. On other hand, Nd: YAG laser beam can deliver via an optical fiber almost without loss, while transfer of a CO_2 laser beam handled through an optical mirror system [2]. The other importance of Nd-YAG laser are, being more user-friendly, rigid and compact oscillator, low reflectivity to cu, Al and their alloys [3]. In surface cleaning of Ti alloys, Nd: YAG shows domination over CO_2 laser by heat conduction into the contaminant from the surface. In terms of weldability for metallic materials, the application of Nd: YAG laser to weld metallic materials is steadily being increased [4]. Therefore, the application of Nd: YAG laser steadily being increased; it has been widely implemented in industrial applications. However, a common problem that has been faced by the manufactures during laser material processing is, there are more parameters (a multi input and multi output process) to control of the process quality. Hence, it is necessary to understand and precise the operating parameter for the various material processing. The present paper is to discuss about the selection and précised application of the prominent operating parameters for various laser-assisted material processing using Nd: YAG laser.

Process Parameters Governing Pulsed Nd: YAG Laser Welding

The construction and function of Nd: YAG is same for output characteristics of the two different modes such as continuous and pulsed wave [5]. Schematic diagram of the laser power output for a series of constant energy pulses in a self-designed shape as shown in Figure 1.

Nd: YAG laser pulse parameters are defined below:

$$\text{Average Peak Power } (P_p) = \frac{pulse\,energy(J)}{pulse\,duration(ms)}\ (W) \quad (1)$$

$$\text{Average Peak Power Density } (P_D) = \frac{average\ peak\ power(kW)}{spot\ area(mm^2)}\ (W/mm^2) \quad (2)$$

$$\text{Mean Power } (P_M) = \{\text{Pulse energy (J) x Pulse Repetition Rate (Hz)}\}\ (W) \quad (3)$$

Where P_p is average peak power (W), P_D is average peak power density (APPD) (W/mm²), P_M is mean power (W), T_P is the pulse duration (mS), E_P is the pulse energy (J), PRR is the pulse repetition rate (s^{-1}), T_F the pulse to-pulse time (mS), and C_D (duty cycle)=T_P/T_F.

Mathematical relationships between the pulsed laser parameters

The mathematical relationships between the pulsed laser parameters can be formulated into various equations [5]:

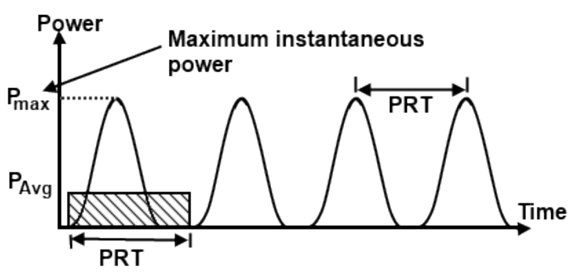

Figure 1: Schematic diagram of the input pulses in a self-designed shape.

***Corresponding author:** Kumar KS, P.T. Lee Chengalvaraya Naicker College of Engineering, Kanchipuram, India, Tel: 09791451493; E-mail: lectsuresh25@gmail.com

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$$P_M = E_P \times PRR = \frac{E_P}{T_P} \times \frac{T_P}{T_F} \text{ (W)} \tag{4}$$

$$P_M = P_P \times C_D = \frac{E_P}{T_P \times D} \times D \times \frac{T_P}{T_F} \text{ (W)} \tag{5}$$

$$P_M = \frac{E_P}{T_P \times D} \times D \times \frac{T_P}{T_F} \text{ (W)} \tag{6}$$

$$P_M = P_P \times D \times T_P \times PRR \quad \text{(W)} \tag{7}$$

Where D is a constant spot area (mm), P_P is the average peak power (W), E_P is the pulse energy (J), T_P is the pulse duration (mS), P_D is the average peak power density (W/mm^2), P_M is the mean power (W), PRR is the pulse repetition rate (Hz), T_F is the pulse-to-pulse time (mS), and C_D is a duty cycle.

It is observed from Eqns. (4) – (7) for a given laser power P_M, there are various combinations of pulsed laser parameters, which indicates both the flexibility and the complexity in the selection of pulsed laser parameters. Therefore, the satisfactory combinations of associated parameters to produce enable efficient and effective material processing with good corrosion resistance, reduced defects.

Overlap theory for pulsed laser for material processing

The cladding, alloying, welding, and cutting produced by the pulsed laser is actually by a series of overlapping. The formation and the quality of the process depend on the set-up of the various parameters. To express the mathematical relationship of the overlap theory, relevant equations are as follows [6]:

In case of welding, if the percentage of overlap, assuming one-dimensional overlapping, P_{ER}, in the x-axis direction

$$Overlap\ \%, P_{ER} = \frac{[S - S']}{S} \times 100\% = \left[1 - \frac{S'}{S}\right] \times 100\% \tag{8}$$

Where

$$S' = V \times T_F \text{ (mm)}, \quad S' = W + V \times T_P \text{ (mm)} \tag{9}$$

Where, V is the travel speed, W the minor diameter of the spot weld, S the major diameter of spot weld formed from a laser spot plus movement during a pulse, and S' is the length in a single spot not overlapped by successive welding spots.

Substituting the expressions for S' and S into Eqn. (8), the overlap percentage is

$$P_{ER} = \left[1 - \frac{V \times T_F}{W + V \times T_P}\right] \quad (\times 100\%) \tag{10}$$

It can understand from Eqn. (10) that overlapping depends upon the selection of pulse duration (T_p), pulse-to-pulse time (T_F), and traverse speed (V) for a given mean power (P_M) and spot size. For further understanding the relationship between traverse speed and overlapping, Eqn. (10) can rearranged as

$$\frac{W}{V} = \frac{T_F}{(1 - P_{ER})} - T_P \tag{11}$$

For pulsed laser applications, the constraint $0 < P_{ER} < 1$ exists, except for when (=1), there is relative motion between the pulsed laser beam and the work piece. Therefore, the traverse speed for pulsed laser seam welding applications is subject to the following mathematical relationship:

$$0 < V \le \frac{W}{T_F - T_P} \tag{12}$$

Parametric analysis in the pulsed laser material processing

For material processing using pulsed laser beam, there are more main parameters than for both pulsed and continuous wave (CW), as described below [6]:

The average peak power density (P_D) for pulsed laser, which correlated directly to the average power density for spot and continuous wave welding;

$$\frac{P_M}{D} = P_D\left(= \frac{E_P}{T_P \times D}\right) \times C_D \text{ (W/mm}^2\text{)} \tag{13}$$

The interaction time (T_{IN}) for pulsed laser with target material

$$T_{IN} = \frac{ds}{V} \times C_D\left(= \frac{T_P}{T_F}\right) \text{ (mS)} \tag{14}$$

The specific energy (E_{avg})

$$E_{av} = \frac{P_P \times T_P \times PRR}{ds \times V} = \frac{P_P \times C_D}{ds \times V} = \frac{E_P}{ds \times V \times T_F}$$

$$= \frac{P_M}{ds \times V} = \frac{(P_P \times T_I N)}{d_S^2} = (\frac{\Pi}{4}) \times P_D \times T_{IN}(J) \tag{15}$$

The pulse overlapping rate (P_{ER})

$$P_{ER} = \left[1 - \frac{V \times T_F}{W + V \times T_P}\right]$$

$$= \left[1 - \frac{1}{((W \times ds \times E_{av}) / E_P) + T_P / T_F}\right]$$

$$= \left[1 - \frac{1}{((W \times ds \times E_{av}) / E_P) + C_D}\right]$$

$$= \left[1 - \frac{1}{((W \times T_{IN}) / (ds \times T_P)) + C_D}\right] \tag{16}$$

Effects of pulse duration (T_P) on heat flow

In case of welding, an overall heat balance on the melt pool, assuming that all the incident energy used only in the melting of weld ingot could ideally state as follows:

$$E_P \times \eta = \frac{dW(W + T_P \times V)}{4} \pi \times \rho \times (C_P \Delta T + L_m) \tag{17}$$

where Z is the coupling efficiency, W the bead width (mm), d the weld penetration (mm), V the traverse speed (mm/s), ρ the density of workpiece (kg/m^3), C_p the specific heat (J/kg K), ΔT the temperature rise to cause melting (K), and L_m the latent heat of fusion (J/kg).

According to Eq. (17), the weld ingot volume W d (W+ V x T_p) x π/4 is directly proportional to "W" as "d" is constant and V x T_p << W. Thus, the entire trend of the heat flow increasing with the average peak power density (P_D) and the pulse duration (T_p) can be justified.

Selection of Laser Output Mode for Compatibility of Materials Processing

Selection of suitable output mode (pulsed or continuous wave

(CW)) for compatibility in laser material processing are given as follows [7]:

Minimum heat input

Pulsed Nd: YAG laser is the choice. wherever the components have metallurgical constraints on heat input or there are heat-sensitive components nearby such as glass-to-metal seals or O-rings, the pulsed YAG can be set up to achieve the required processing rate at a heat input low enough not to damage the components.

Speed

Whether cutting or welding, CW Nd: YAG laser is the best choice by processing the component with a CW beam there is no need to overlap pulses or to re-establish the keyhole. Simply adjust power and speed along with the focus spot size to achieve the desired penetration.

Welding reflective materials

Joining of low absorption and high reflectivity such as copper and precious metals is usually pulsed Nd: YAG laser, because that has the peak power to break down the reflectivity. Hence, pulsed Nd: YAG lasers is the best choice whereas high average power required for CW Nd: YAG lasers.

Heat treating/cladding

Usually CW Nd: YAG lasers are preferred due to its high average power tends to be the limit to speed, case depth, or remelt thickness. Pulsed Nd: YAG lasers can do the job but their lower average power ratings rule them out except for small devices.

Spot welding

Proper selection pulse parameters Nd: YAG pulsed lasers used for the fastest and most repeatable spot weld. However, if large diameter pieces were required, CW laser will be considered.

Low penetration welding

CW laser will weld very quickly and produce parts with high throughput. Pulsed lasers might have sufficient speed also and have the benefit of dealing with material changes or spot welding requirements.

Welding crack-sensitive alloys

CW Nd: YAG laser is the best choice unless there are other constraints such as heat input. The slower cooling rate of the CW laser usually reduces cracking tendencies in steel alloys containing sulphur, phosphorus, lead, and/or selenium.

Conclusion

Nd: YAG laser has been a versatile tool for variety of material processing in the modern manufacturing due to its wavelength absorbed by wide range of materials. Therefore, the possibility of controlling prominent operating parameters of pulsed and continuous waves such as average peak power (P_P), average peak power density (P_D), mean power (P_M), pulse duration (T_P), pulse energy (E_P), pulse repetition rate, interaction time, pulse overlap theory and its mathematical relationships were discussed. Hence, the selection of suitable combinations of associated parameters helps us to produce efficient and controlled material processing with reduced defects.

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