Evaluation of Nd: YAG Laser Welding Efficiencies for 304L Stainless Steel

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Abstract

The laser material interaction, controlling of process parameters and their effect on melting, solidification and process efficiency are critical to understand the behavior of the weld joints. This paper aims to study the effect of welding speed on different process efficiencies in 304L Stainless Steel. The bead on 304L austenitic stainless steel plate is created by varying welding speed. A novel semi-empirical method based on weld pool volume measured from experimental results is used to predict the melting efficiency of Nd: YAG laser welding process. The dimensionless parameter models are used to estimate various types of measurable controlling parameters. These parameters have good agreement with the various available models in literature.

Keywords: Electron microscope: Nd: YAG laser; Stainless steel; Laser welding; Weld pool Volume; Process Efficiency

1. Introduction

The Nd: YAG laser welding process is being used for welding of micro industrial products. The fundamental aspects of welding are process efficiency and heat affected zone. The performance of the laser welding process depends on energy absorbed by the substrate material. It is affected by factors such as process parameters, type of
Nomenclature

| Symbol | Description                               |
|--------|-------------------------------------------|
| $E_{cal}$ | Total energy absorbed by the work piece (J) |
| $\eta_e$ | Energy transfer efficiency                |
| $\eta_m$ | Melting efficiency                        |
| $\eta_c$ | Coupling efficiency                       |
| $\eta_p$ | Process efficiency                        |
| $t$     | Laser on time (ms)                        |
| $P$     | Laser output power (W)                    |
| $r_k$   | Radius of cone (mm)                       |
| $d$     | Depth of the penetration (mm)             |
| $n$     | Number of reflections                     |
| $q_i$   | Heat input (W)                            |
| $q_o$   | Laser output power (W)                    |
| $\alpha$ | Thermal diffusivity (mm$^2$/s)            |
| $\delta h$ | Enthalpy of melting (J/mm$^3$)           |
| $A$     | Weld cross sectional area (mm$^2$)        |
| $w$     | Weld width (mm)                           |
| $P_i$   | Power delivered to the metal (W)          |
| $v$     | Welding speed (mm/s)                      |
| $P_{ab}$ | Laser power absorbed by the metal (W)     |
| $k$     | Thermal conductivity (W/m K)              |
| $T_m$   | Melting temperature (K)                   |
| $N_s$   | Normalized speed                          |
| $N_p$   | Normalized power                          |
| $\Delta H_f$ | Latent heat of fusion (J/mm$^2$)       |
| $V$     | Volume of the weld pool (mm$^3$)          |

During laser welding process, the laser beam energy is maintained below the vaporization temperature of the work piece. The efficiency of the laser welding process is based on the amount of heat utilized for melting the substrate material. The different types of efficiency in laser welding process are considered as a function of controllable process variables namely laser energy transfer efficiency, melting efficiency, coupling efficiency and process efficiency. The laser power and welding speed are significant process parameters however the amount of power absorbed by the substrate material depends on welding speed.

Lankapalli (1996) developed mathematical 2D conduction and conical key hole model based on heat input to the substrate material to predict depth of penetration. Khan et. al. (2011) has carried out investigation to study the effect of process parameters on weld bead geometry, weld depth / width ratio. Norris et.al.(2010) has carried out investigation to study the effect of process parameters on weld bead geometry. Tadamalle et. al. (2013) revealed from the investigations that laser power, weld time and welding speed are significantly affecting parameters. The depth of penetration and bead width decreases with increase in welding speed. The bead width dimensions are more sensitive to the peak power input up to 1700W and less sensitive beyond 1700W. The weld pool geometry, hardness, strength and microstructure of welds have been measured and analyzed by Walsh (2000) as a function of laser power, welding time and speed.

Feurschbach and Richard (1999) proposed dimensional parameter model to estimate melting efficiency. Masouumi (2010) characterized the phenomenon of keyhole formation and developed the relationship between energy transfer efficiency and weld bead geometry. The analytical equation proposed by Feurschbach (1995) to connect the keyhole cavity dimensions with the energy transfer efficiency and estimated the energy transfer efficiency for various weld pool depths and different thick materials using calorimeter. The dimensionless parameters Raykal (1951) and
Christensen et al. (1965) first time introduced the dimensionless parameters $C_h$ and $R_y$ for computing melting efficiency of the arc and CO$_2$ laser welding process. The author Richard and Feurschbach (1996) developed MATLAB based code modules for predicting optimal weld schedules and regulating weld parameters. Feurschbach and Richard (2003) developed optimization software for laser welding by considering energy transfer efficiency and melting efficiency. The application enables the user to input desired weld shape dimensions, select the material to be welded, and to constrain the search problem to meet the application requirements. The dimensionless parameter model has been proposed by Nath et al. (2002) using energy balance equations to estimate melting and coupling efficiency. Unocic and DuPont (2004) investigated three main process efficiencies of Laser engineered net shaping process for tool steel and copper powder material deposits.

The literature review reveals that the efficiency of the arc, gas tungsten arc welding and CO$_2$ laser welding process are analyzed for independent efficiency computation of the process by varying process parameters. The main objective of this investigation is to study the effect of welding speed on different efficiencies of Nd: YAG laser welding process and also to verify the applicability of dimensionless parameter equations developed for other welding process to the Nd: YAG laser welding process.

2. Estimation of Process Efficiencies

The characteristics of a laser welding process depends upon welding speed, laser power, pulse duration, beam angle, size of the weld pool geometry, thermal properties, process efficiencies and others. The efficiency of the welding process can be improved by fully utilizing the power supplied to melt the substrate material.

2.1 Energy Transfer Efficiency

The energy transfer efficiency is a significant factor which is defined as the ratio of heat absorbed by the work piece to the incident laser energy. The fraction of laser energy supplied to the work piece is utilized for melting the work piece. The measurement of energy transfer efficiency in CO$_2$ laser welding process has been carried out experimentally by means of calorimetric technique. However, limited studies have been reported in the literature that directly measures energy transfer efficiency. The total energy absorbed by the substrate ($E_{cal}$) is determined by plotting output voltage verses time signal. The area under the curve can be determined by integration and then it will be multiplied by the calorimeter calibration constant (0.598 W/V). The equation (1) proposed by Unocic (2004) is used to compute energy transfer efficiency.

$$\eta_e = \frac{E_{cal}}{P_0 t}$$

The energy absorbed in laser welding process depends on the weld pool cavity and the net energy transferred to the substrate. The energy transfer to the substrate material is the difference between laser energy absorbed and heat loss to the surroundings. The energy absorbed by the material depends upon multiple internal reflections of laser rays and weld pool shape. The shallow welds absorbs small fraction of laser energy and deep welds absorb greater energy when the weld penetration approaches to a greater depths as shown in Fig.1.
The relationship between energy transfer efficiency and weld penetration presented in equation (2) proposed by Feurschbach and McCollum (1995) in terms of laser beam absorption, keyhole dimensions, and incident laser beam angle. In this approach, keyhole dimensions are considered as constant and bead dimensions variations considered as per Tadamalle et. al.(2013) with respect to welding speed and laser power.

\[
\eta_e = 0.9 \left( 1 - R \frac{1}{\tan \left( \frac{\pi \Phi}{2} \right)} \right)^2
\]  

(2)

The melting efficiency of the welding process can be predicted by using material independent model suggested by Feurschbach (1996) given in equation (3).

\[
C_y = \eta \frac{R_y}{C_h} \left[ 0.48 - 0.29 \exp \left( \frac{\eta R_y}{0.68} \right) - 0.17 \exp \left( \frac{\eta R_y}{59} \right) \right]
\]

Where \( C_h = \frac{A^2}{c^2} \) and \( R_y = \frac{\eta}{a^2 \Delta h} \)

The unknown quantities in equation (3) can be computed using Christensen and Gajendramundsen (1995) are used to estimate energy transfer efficiency and weld bead cross sectional area. The weld bead cross sectional area can be determined from experimental results obtained from the specimens prepared for metallographic inspection.

### 2.2 Melting Efficiency

The second measurable parameter of the welding process is melting efficiency. It is defined as the amount of energy that is used to create molten pool from energy delivered to the work piece. A small portion of the energy is used for melting the substrate material and rest of the energy is dissipated to the surrounding area by different modes of heat transfer. The melting efficiency is significantly affected by process parameters, heat flow geometry and thermo physical properties. The dimensionless parameters \( R_y \) and \( C_h \) are used to estimate melting efficiency of arc, gas tungsten arc welding and CO\(_2\) laser welding process. Melting efficiency is the ratio of dimensionless parameters \( C_h \) and \( R_y \) is proposed by Feurschbach (1999) presented in equation (6).

\[
\eta_m = \frac{\eta \Delta h}{\eta_e q_o}
\]

(4)

The dimensionless parameter \( R_y \) is effective in estimating the melting efficiency of welding process and it is a nonlinear function of heat input and welding speed. The amount of energy that is transferred to the work piece can be found out by knowing the quantity of energy required to melt the work piece. A semi-empirical equation (5) suggested by Unocic and DuPont(2004) is used to predict the melting efficiency based on heat input to melt the material in gas metal arc welding process.

\[
\eta_m = \frac{\sqrt{T_0 T} (c_p(T) \Delta T) + \Delta H_f}{\eta_e q_o}
\]

(5)

The conditions suggested for two dimensional (Okoda (1977)) and three dimensional (Wells(1952)) heat flow analysis in arc welding process for predicting the melting efficiency are presented in equation (6) and (7) respectively.

\[
\eta_m = \frac{1}{\left( 1 + \frac{10.4 \sigma^2}{\sqrt{\nu w^2}} \right)^2}
\]

(6)
The melting efficiency in arc welding process proposed by Okoda and DuPont (2002) can also be estimated by means of power delivered to the substrate material which is given in equation (8).

$$\eta_m = \exp \left( - \left( 1 + \frac{\Delta H_m x^2}{1.14 P_{j\alpha}} \right) \right)$$  

(8)

In equation (8), $q_i$ is replaced by the product of energy transfer efficiency, voltage and current. The relationship between $C_h$ and $R_y$ obtained from the best fit curve is given in equation (9) proposed by the author.

$$\eta_m = 0.65 + 0.016 \left( \frac{\Delta H_m x^2}{\alpha e P_{j\alpha}} \right)$$  

(9)

The semi empirical equation (9) is used for predicting the melting efficiency of Nd: YAG laser welding process. The processing parameters, heat flow geometry and base metal thermo physical properties have significant influence on melting efficiency.

### 2.3 Coupling Efficiency

The coupling efficiency is a dimensionless term used to describe the efficiency of heat source to make the weld joint. It can be defined as the ratio of energy absorbed by the weld to energy output from the laser source. The energy absorbed by the weld can be measured by calorimeter, thermocouples and measuring weld pool areas. The dimensionless parameters, normalized speed ($N_s$) and normalized power ($N_p$) are suggested by Nath et. al.(2002) is used to estimate the coupling efficiency is given in equation (10). It is defined on the basis of power absorbed by the metal for characterizing the conduction welding process.

$$N_s = \frac{v b_1}{a} \quad \text{and} \quad N_p = \frac{P_{ab}}{t k T_m}$$  

(10)

The power absorbed by the material is computed by considering all types of losses and energy balance equation. The relationship between dimensionless parameters in CO$_2$ welding process is given in equation (11).

$$\eta_c = \frac{v w t T_m}{P_{ab}}$$  

(11)

The coupling efficiency and power absorbed by the substrate material is computed by substituting thermo physical properties, welding speed and weld width.

### 2.4 Process Efficiency

The process efficiency is the main measurable parameter in any welding process. It describes the total amount of energy utilized to create a molten weld pool from the energy delivered to the work piece. The process efficiency is defined by Unocic et. al.(2004) as the product of energy transfer efficiency and melting efficiency as given in equation (12).

$$\eta_p = \eta_e \eta_m$$  

(12)

The process efficiency depends on weld bead dimensions, type of laser source, thermo physical properties and material properties.
3. Experimental Procedure

The 304L austenitic stainless steel has been selected for the investigation of different efficiencies in Nd: YAG laser welding process. The thermo physical properties of the material and process parameters used during experimentation are given in Table 1 and Table 2 respectively.

| Parameters                  | Values       | Parameters     | Values       |
|-----------------------------|--------------|----------------|--------------|
| Density                     | 8030 Kg/m³   | Poisons Ratio  | 0.29         |
| Elastic modulus             | 193 G Pa     | Melting point  | 1217K        |
| Mean coefficient of Expansion | 18.4 μm/m°C | Refractive index | 3.81Fe        |
| Thermal conductivity        | 20 W/m K     | Enthalpy       | 8.7 J/mm³    |
| Specific Heat               | 500 J/Kg K   | Diffusivity    | 5.7 mm²/s    |

Table 1: Thermo physical properties of the 304L stainless steel

| C    | Mn  | Ni   | Cr   | Si   | V    | N    |
|------|-----|------|------|------|------|------|
| 0.3  | 2.0 | 8-12 | 18-20| 0.75 | 0.07 | 0.1  |

Table 2: Process parameter, Chemical and mechanical properties of the material

| Parameters                  | Values       | Parameters     | Values       |
|-----------------------------|--------------|----------------|--------------|
| Gas flow rate               | 7 lit/min    | Pulse energy   | 2.76 J       |
| Pulse duration              | 2 ms         | Spot focus diameter | 0.8 mm     |
| Frequency                   | 25 Hz        | Focal distance | 150 mm       |
| Beam angle                  | 90±5º        | Proof Stress   | 170 M Pa     |
| Yield Strength              | 485 M Pa     | Elongation     | 40%          |

The samples are cut into rectangular specimens of 30 mm x 50 mm by using wire cut electric discharge machine to avoid distortion. The bead on plate is created on 0.5 mm thick sheet by varying the welding speed from 2 mm/s to 10 mm/s. The experimental setup is shown in Fig. 2.
The weld samples were cut into transverse directions and the cross-sectional surface has been prepared for metallographic inspection. The electrolytic etching technique is used to observe the microstructure of the weld joint. The samples prepared for metallographic inspection are as shown in Fig. 3(a) and Fig 3(b). The weld bead geometry dimensions are measured by using an optical microscope and image analyzer. The physical observation of samples prepared for metallographic inspection reveals that the depth of penetration decreases with increase in welding speed. The full depth of penetration occurs at a welding speed of 10 mm/s.

4. Result and Discussion

Fig. 4 shows the effect of welding speed on power absorbed by the substrate material. The total power absorbed by the material increases with increasing welding speed. A large amount of heat is utilized to create and maintain the molten pool. This is due to large amount of power is absorbed to melt material beyond the welding speed of 7 mm/s and less than 4 milliseconds is available to transfer energy by means of conduction process. The Nd: YAG laser beam source is highly reflective to the metallic materials at a wavelength of 1.064 μm [14]. The reflectivity of the polished stainless steel surface is about 98% at room temperature and it reduces as the temperature of the surface rises. The molten pool of 304L stainless steel material has reflectivity of 85% when laser rays are parallel to the depth of penetration [10].

The heat loss to the surroundings is assumed to be 10% of the absorbed laser energy. The energy transfer efficiency obtained by considering calorimetrically measured values of laser output is 87% [15]. The material independent model and laser reflection methods are employed to calculate energy transfer efficiency with respect to welding speed. A variation of 13% and 28% is observed from the material independent model and laser reflection method respectively. The results obtained from these two models are presented in Fig. 5. Since the variation in energy transfer efficiency is significant, the melting efficiency is computed based on models suggested by different researchers and the results obtained are shown in Fig. 6.

The estimated melting efficiency by using different values of weld pool dimensions obtained from image analyzer shows higher value than all other models. The estimation based on the heat input is directly proportional to the product of energy supplied, energy transfer efficiency and pulse frequency. The melting efficiency increases nonlinearly with decreasing welding speed. This is due to the selection of process parameters such as heat input, thermal diffusivity, sheet thickness, weld bead geometry and enthalpy for the computation of melting efficiency.

The theoretical maximum heat transfer efficiency values for gas tungsten arc welding, arc welding and plasma arc welding processes are 37%, 44% and 48% respectively. The maximum and minimum value of melting efficiency obtained from semi empirical method using Nd: YAG laser welding process is 37% and 68% respectively. It is
evident from the above observations that the melting efficiency based on weld pool volume increases with increase in welding speed. The substrate material melting is more at higher speeds since less time is available for transporting heat away from the localized melted region. This is due to larger amount of energy is utilized to create and maintain molten weld pool. In laser welding, the beam coupling with substrate material is highly dependent on material properties because of different value of optical reflectivity for different materials. The coupling efficiency for high and low speed Co2 laser welding is estimated by using equation (6). The Fig. 7 reveals that welding speed plays significant role in laser welding process, because coupling efficiency increases with increase in welding speed. The coupling efficiencies in conduction and keyhole CO2 laser welding process are 15% to 65% respectively [12].

The coupling efficiency of Nd: YAG laser welding process obtained from the experimental results is 38% to 55%. The efficiency assessed by using normalized speed and power parameters in Nd: YAG laser welding lies within the permissible range as obtained in CO2 laser welding. The coupling efficiency can be increased by accelerating photon density level and welding speed, peak power at the beginning of the pulse and improving the surface conditions related to the absorptivity.

The process efficiencies are computed based on material independent model and reflection method. The maximum process efficiency obtained from reflection method and material independent model is 9.05% and 47.68% respectively. The results shown in Fig. 8 and Fig. 9 depicts that the process efficiency increases with increase in welding speed. The reflection method depicts reasonably lower efficiency than that of material independent model. It is due to multiple reflections of laser rays within the material which is used for melting the substrate material. The material independent model is developed by considering thermo mechanical and material properties, whereas reflection method is based on number of internal reflections and depth of keyhole. The results obtained from reflection method depicts that the shallow weld zone absorbs small fraction of energy and deep welds absorbs greater energy when the weld penetration approaches to a depth more than 1 mm. It has been revealed from the study that the process efficiency increases with increase in welding speed in case of semi empirical method whereas in case of reflection method it is inversely proportional.
5. Conclusions

The important measurable parameter in welding process is process efficiency. It depends upon processing and operating parameters, thermo mechanical and chemical properties of the material, surface conditions and laser power source. The welding speed is significantly affecting on all types of efficiencies. It has been found that the amount of power required for melting the material is higher and heat carried away by conduction is lower at a welding speed of 7mm/s and above. The semi empirical method presented in this work predicts higher efficiency than all other models. The efficiency obtained by using the model based on reflection gives significantly lower value than the material-independent model. The defect free welds have been observed within the range of selected welding speeds. The effect of pulse duration, gas flow rate and focal position on process efficiency can also be tried and effective methods can be devised to measure efficiencies.

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