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Influence of welding speed on the melting efficiency of Nd:YAG laser welding

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A B S T R A C T

Melting efficiency is one of the more important measurable parameters in laser welding when assessing the performance of a process. This paper aims to study the effects of speed on the melting efficiency and energy transfer efficiency of Nd:YAG laser welding process. The weld bead on a 304L austenitic stainless steel sheet is created by varying the welding speed. The weld samples are cut in the transverse direction by using electric discharge machining, and the cross-section is prepared for metallographic inspection. The cross-sectional dimensions and beads length are measured by using an optical microscope and image analyzer. A methodology is proposed for estimating the weld pool volume from experimental data and a generalised equation for predicting the melting efficiency and energy transfer efficiency is developed. The results obtained by the proposed method have reasonably good agreement with the models proposed by various researchers. The outcome of the result shows the significant influence of welding speed on melting efficiency and energy transfer efficiency in welding of austenitic stainless steel thin sheets. It will be seen from results that one can select appropriate welding speed and processing conditions to obtain desired melting efficiency.

A R T I C L E I N F O

Keywords:
Nd:YAG laser welding
Melting efficiency
Weld pool volume
Energy transfer efficiency
Heat affected zone

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1. Introduction

The Nd:YAG laser welding process is extensively used in modern industrial applications due to increase in demand for micro products. It is very essential to understand the behavior of laser material interaction, controlling of process parameters and their effect on melting, solidification and efficiency. The fundamental figures of merits for the laser welding process can be expressed in terms of melting efficiency, coupling efficiency, process efficiency, and energy transfer efficiency. The other figures of merits considered are fusion zone size, tolerance, and changing base metal temperature. The melting efficiency quantifies the fraction of net heat input to the work piece that is used to produce the weld pool. The absorption of heat by the material is affected by many factors like process parameters, type of laser, incident power density, and base metal surface condition. The optimum melting efficiency and weld strength of the joint depend upon vaporization temperature of the work piece material. The functional characteristics of laser welding process depends upon welding speed, laser power, size of the weld pool geometry, thermal and process efficiencies. The welding efficiency can be improved by fully utilizing the power supplied to melt the unit volume of material.

In literature it has been reported that the effect of very high welding speed on melting efficiency and depth of penetration has been studied [1-2]. The authors discussed the effect of welding speed on weld bead geometry, and performance parameters such as variation of weld bead diameter from pulse to pulse, duty cycle, and effective pulse energy [3]. The present research work is the continuation of this research on development of new analytical equations to predict the melting efficiency. The experimental and analytical prediction shows that there is a strong dependence of energy absorption on laser power, beam size, and welding efficiency [4-5]. The dimensionless parameters Rykalin (R_y) and Christensen (C_h) are used for computing the melting efficiency of arc and CO_2 laser welding. The melting efficiency of the laser welding process is determined by using experimental results, dimensionless parameter models and energy balance equations. Several researchers have formulated analytical equations to predict the melting efficiency in arc welding process [6-10]. The dimensionless parameter model is very valuable in characterizing partial penetration in laser beam welding process. The material independent model reveals that the variation in laser power and focus spot size is insensitive to the energy transfer efficiency in continuous wave laser beam welding process. A dimensionless parameter model developed for evaluating the melting efficiency in CO_2 laser beam welding has been applied in gas tungsten arc welding (GTAW), plasma arc welding (PAW), and autogenous arc welding processes [11-14].

The energy transfer efficiency of arc and laser welding process is estimated by using calorimetric method and thermal expansion measurement techniques for thin sheets and the results obtained are correlated with the reflection method. The process efficiencies of laser engineered net shaping process is estimated for the tool steel and copper powder material deposits [15-19]. Transient 3D numerical model was developed to study the temperature field and molten pool shape during laser welding and volume of fluid method was employed in the calculations [18]. The influence of welding process parameters, preheating and heat absorption on different laser welding efficiencies is investigated [19-21]. It was found that the global efficiency of the laser welding process decreases slightly by varying the welding speed from 10 mm/s to 2 mm/s, but drops significantly below 1 mm/s [22]. The preheating of weld samples has an effect on absorption efficiency and other efficiencies in the beginning of the process and in the formation of the keyhole [23, 24]. The absorption efficiency and keyhole coupling efficiency are determined by using laser energy reflected from molten pool and by considering plasma effect studied under steady state condition [25].

This paper aims to study the effect of process parameters on melting efficiency (η_m) of Nd:YAG laser weld joints. A semi empirical equation is proposed to estimate the weld pool volume from experimental data, a dimensionless parametric equation to estimate melting efficiency. The section 2 deals with the models proposed by various researchers to evaluate the melting efficiency in different welding process, and section 3 enumerate the experimental procedure adopted. The equations proposed for prediction of weld pool volume and melting efficiency are presented in section 4 and section 5 respectively. The results and discussions are illustrated in section 6 and the conclusions of present work are given in section 7.

2. Melting efficiency

Melting efficiency is defined as the ratio of energy required to create a molten pool from heat energy supplied to the energy absorbed by the work piece. A small percentage of the total energy is used for melting the fusion zone and rest of the energy is dissipated to the surroundings by means of various modes of heat transfer. The literature review reveals that processing parameters, heat flow pattern and thermo-physical properties have significant influence on melting efficiency. A dimensionless parameter model can be used to determine the actual heat input to the metal and the melting efficiency. The dimensionless parameters R_y and C_h are derived from the Rosenthal heat flow solutions. These parameters can be evaluated by using the Eq. 1 developed for the arc welding and CO_2 laser welding process [9]. The Rosenthal heat flow solution model ignores mass additions to the melt pool. Hence modifications are required in the heat flow equations that can incorporate mass addition to the Rosenthal heat flow solution model. However, a semi empirical model can provide reasonable estimates of melting efficiency for both the arc welding and CO_2 laser welding process.

$$C_h = \frac{s^{2} A}{\alpha^2} \text{ and } R_y = \frac{P_i s}{\alpha^2 \delta h} \tag{1}$$

where P_i is the heat input to the substrate (W), α is the thermal diffusivity of base metal (mm²/s), δh is the enthalpy of melting (J/mm³), A is the weld cross-sectional area (mm²), s is the welding speed (mm/s). The melting efficiency (η_m) for the arc welding process [10] can also be expressed as the ratio of dimensionless parameters C_h and R_y [8] as given in Eq. 2.

$$\eta_m = \frac{C_h}{R_y} = \frac{s\, A\, \delta h}{\eta_e P_i} \tag{2}$$

The dimensionless parameter R_y play an important role in estimating the melting efficiency and it is a nonlinear function of heat input and welding speed. Several researchers have developed equations to predict the melting efficiency by using 2D and 3D heat flow conditions. The 2D and 3D heat flow conditions are expressed in terms of thermo-physical properties and processing parameters for predicting the melting efficiency. The mathematical models applied for 2D and 3D heat flow conditions in arc welding process are presented in Eq. 3 and Eq. 4, respectively [10].

$$\eta_m = \frac{1}{\left(\left(\frac{8\,\alpha}{5\,s\,w}\right) + 2\right)} \tag{3}$$

$$\eta_m = \frac{1}{1.35\left(1 + \left(1 + \frac{10.4\,\alpha^2}{(s\,w)^2}\right)^{\frac{1}{2}}\right)} \tag{4}$$

where w is the bead width (mm). A model applied for predicting the melting efficiency based on power delivered to the substrate material in arc welding process is given in Eq. 5:

$$\eta_m = exp\left(-\left(1 + \frac{\delta h\, \alpha^2}{1.14\, P_i\, s}\right)\right) \tag{5}$$

In present work, the term power input P_i, supplied by the laser source to the material is replaced by the product of energy transfer efficiency (η_e), voltage (V) and current (I). A semi empirical Eq. 6 is used to predict the melting efficiency based on heat input required to melt the material [7] in GTAW process:

$$\eta_m = \frac{v \int_{T_0}^{T} C_{p(T)} \Delta T + \Delta H_f}{\eta_e t\, P_i} \tag{6}$$

where ΔH_f is the latent heat of fusion (J/mm³), v is the total volume of melted substrate (mm³), T is the temperature of the weld pool (K), T_0 is the initial temperature (K), t is the laser on time (ms), and C_p is the heat capacity (J/mm³K). The experimental procedure adopted in this work for welding of 304L austenitic stainless steel using Nd:YAG laser welding machine is explained in the next section.

3. Experimental procedure

The welding of 304L austenitic stainless steel sheets is carried out by using pulsed Nd:YAG laser welding machine, TruLaser station 5004 (Trumpf), designed to deliver a maximum laser power of 4 kW. The process parameters, thermo-mechanical properties and chemical composition of 304L stainless steel are given in Table 1 and the setup used for experimentation is shown in Fig. 1. The blank sheets are cleaned before welding by 6-8 % NaOH solution followed by 20 % HNO_3 solution. The samples are cut into rectangular specimens of 30 mm by 50 mm with the help of wire cut electric discharge machine to avoid the distortion. The weld quality and aspect ratio of the WBG depends upon welding speed. The threshold value of melting front propagation was found between 1.1-1.4 mm/s and when welding speed is less than 1 mm/s the molten pool irradiates for a longer period of time which results in lower coupling efficiency [22]. The welding speed beyond 10 mm/s does not provide sufficient time to melt the material. Hence, the experiment are planned to conduct on 0.5 mm thick sheet to create a bead on plate by varying the welding speed from 2-10 mm/s in steps of 1 mm/s.

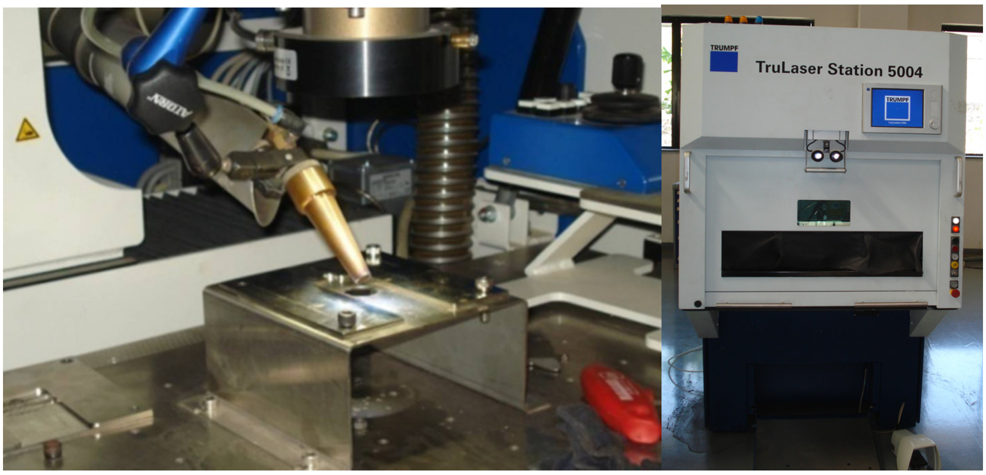


Fig. 1 Specimen mounting arrangement and experimental setup

Table 1 Process parameters and thermo mechanical properties and chemical composition of 304L stainless steel [3]

Process parameters		Thermo mechanical properties of the 304L stainless steel			
Parameters	Values	Parameters	Values	Parameters	Values
Beam diameter	0.4 mm	Density	8030 kg/m^3	Poisons ratio	0.29
Pulse duration	2 ms	Elastic modulus	193 GPa	Melting point	1723 K
Frequency	25 Hz	Mean coefficient of expansion	18.4 µm/m/K	Refractive index	3.81 Fe
Beam angle	90 ± 5 °	Thermal conductivity	20 W/mK	Enthalpy	8.7 J/mm^3
Pulse energy	2.76 J	Specific heat	500 J/kgK	Diffusivity	5.7 mm^2/s

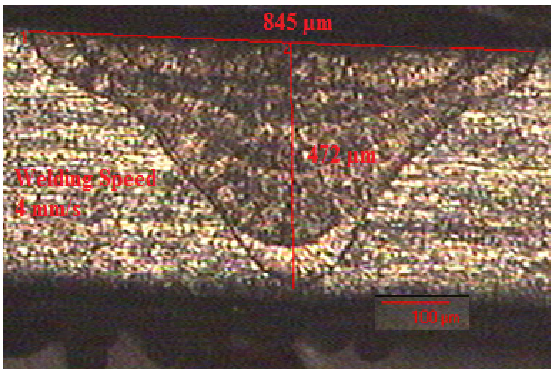
C	Mn	Ni	Cr	Si	V	N	Proof stress	Yield strength	Elongation
0.3	2.0	8-12	18-20	0.75	0.07	0.1	170 MPa	485 MPa	40 %

Table 2 Weld bead geometry dimensions measured from weld samples

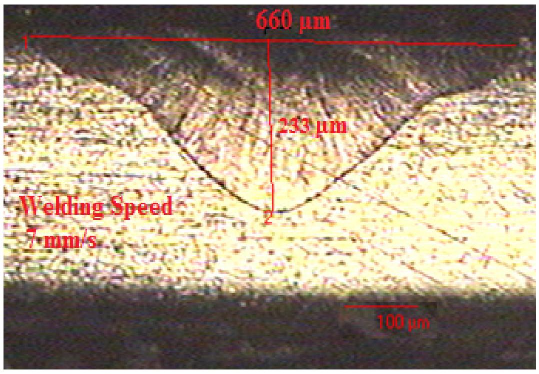
Exp. No.	Welding speed (mm/s)	Bead width (µm)	Bead length (µm)	Depth of penetration (µm)
1	2	895	912	500
2	4	845	845	472
3	5	730	730	375
4	7	691	691	233
5	8	687	687	190
6	9	682	682	189
7	10	610	648	100

4. Estimation of weld pool volume

In laser welding process, the selection of preferred levels of welding speed plays an important role to achieve higher melting efficiency. The experiments are conducted by varying welding speed and by keeping all other process parameters constant. The transverse cross-section area, bead length (BL) and bead width (BW) of the weld bead geometry (WBG) are extracted from the samples prepared for metallographic inspection, Fig. 2(a) to Fig. 2(f). The WBG and HAZ profile dimensions are measured by using Metatech (Hitachi) electron microscope. The digitized data obtained from the HAZ profile is used to generate polynomial equations at different welding speeds. This digitized data is best fitted to obtain the second order polynomial equations. A sample second order polynomial equation and corresponding curve obtained from digitized data at a welding speed of 8 mm/s is shown in Fig. 3. Similarly other second order polynomial equations are derived from experiments conducted at different welding speeds. A generalized second order polynomial equation applicable to the geometry of any heat affected zone profile is given in Eq. 7.



(a)



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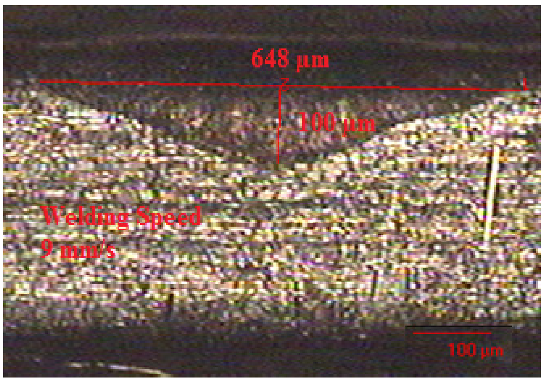

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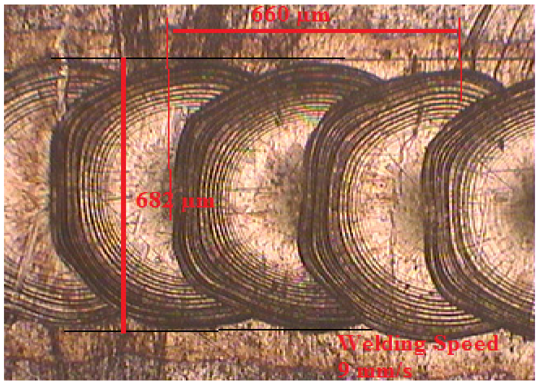

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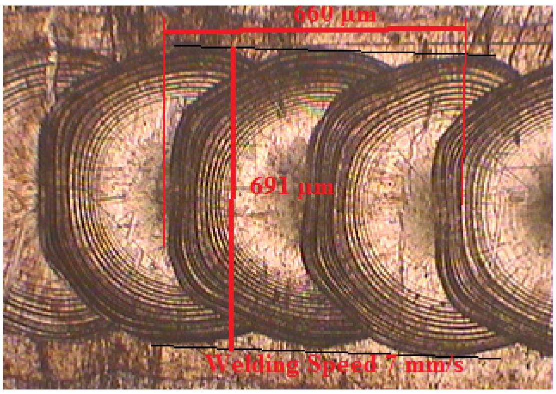

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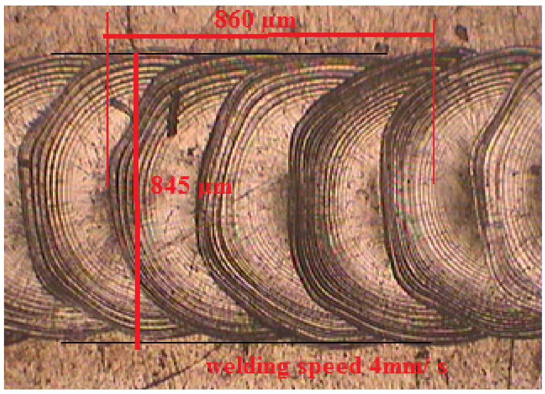

(f)

Fig. 2 Samples prepared for metallographic inspection and measurement of WBG

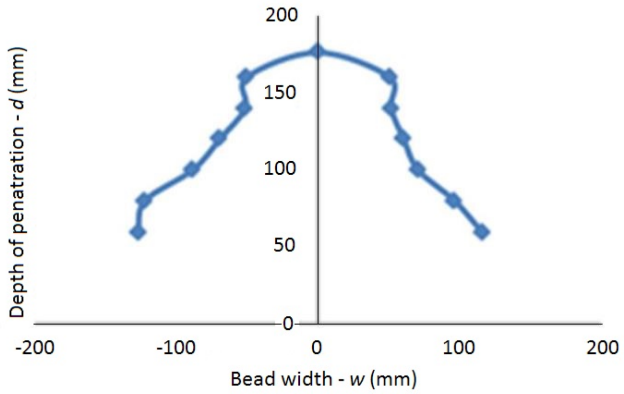

Fig. 3 Digitized data fitted to obtain a second order polynomial equation

$$f(x) = C_1 + C_2x + C_3x^2 \tag{7}$$

The coefficients C_1, C_2, and C_3 are constants which are evaluated by using the polynomial equations derived from digitized HAZ data and the variable x denotes the bead width. This data is measured from the cross-sectional view of the micrographs obtained at different welding speeds shown in Table 2. The digitised data is used to obtain a HAZ profile of the weld pool shown in Fig. 3 and the corresponding second order polynomial equation. The weld pool volume estimated by revolving half section of the polynomial curve about the axis of the laser beam is given in Eq. 8.

$$V = \int_0^d (C_1 + C_2x + C_3x^2)^2 \, dx \tag{8}$$

A generalized equation proposed to evaluate the weld pool volume by using best fit curve obtained from the geometric mean of all corresponding coefficients.

$$V = 0.512 + 0.028x - 0.007x^2 \tag{9}$$

The weld pool volume and its cross-sectional area is a function of depth of penetration, bead length and bead width. The correct measurement of depth of penetration and bead length is difficult, because it requre metallographic preparation to observe cross-sectional view of the WBG. The bead width can be measured with ease hence it is proposed equation to estimate the weld pool volume in terms of bead width as given in Eq. 10.

$$V = 0.512 + 0.028\,w - 0.007w^2 \tag{10}$$

The coefficients given in Eq. 10 are valid in the range of weld speed from 2-10 mm/s. This range is selected because it gives better results in terms of pulse overlapping factor, variation in bead diameter from pulse to pulse and other performance parameters [3] at the specified values of process parameter considered for the study.

5. Prediction of melting efficiency

The dimensionless parameters R_y and C_h can be evaluated by knowing material properties, weld speed, laser power input and weld pool cross-sectional area. The values R_y and C_h are estimated by varying the welding speed and a best fit curve shown in Fig. 4 is obtained by using linear regression analysis technique. The correlation coefficient between C_h and R_y is greater than 0.943 and the relation obtained from the best fit curve is presented in Eq. 11.

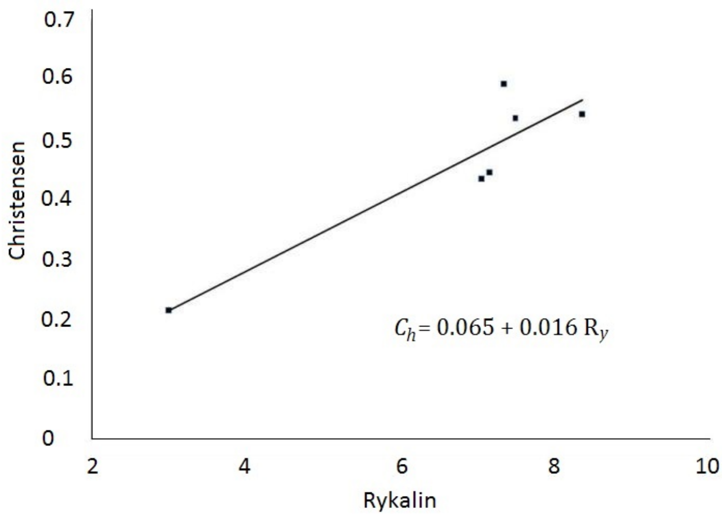

Fig. 4 Relation between Rykalin and Christensen dimensionless parameters

$$C_h = 0.065 + 0.016\ R_y \tag{11}$$

The relationship for melting efficiency (η_m) derived from Eq. 11 is given in Eq. 12:

$$\eta_m = 0.016 + \frac{0.065}{R_y} \qquad \eta_m = 0.065 + 0.016 \left(\frac{\Delta \mathrm{H}_m \alpha^2}{\eta_e \mathrm{P}_i\ \mathrm{s}}\right) \tag{12}$$

The semi empirical Eq. 12 can be used for predicting the melting efficiency of Nd:YAG laser welding process. The melting efficiency is a function of R_y.

The laser beam reflection method is used in this study to estimate energy transfer efficiency. The accurate prediction of weld size is done by considering different values of energy transfer efficiency.

6. Results and discussions

The power absorbed by conduction and melting of the substrate material is more at higher welding speeds. The Fig. 5 reveals that total power absorbed by the substrate material increases with increase in welding speed. This is due to the significant difference in temperature between laser source and work piece material as a result of which more amount of heat is utilized to create and maintain molten weld pool. It is found that the power utilized for melting the material is less than that of power absorbed by conduction up to a welding speed of 7 mm/s. However beyond this limit, power absorbed for creating weld pool is greater than heat carried away by the conduction. This is due to less than 4 ms times is available for transferring heat energy to the substrate material by conduction. The stainless steel material has reflectivity 64 %, whereas for copper, aluminium and nickel it is greater than 74.20 %. Many researchers have determined the melting efficiency in welding by considering energy transfer efficiency constant at 0.37 or 0.48 [7, 10]. In this study, laser beam reflection method is employed to compute energy transfer efficiency.

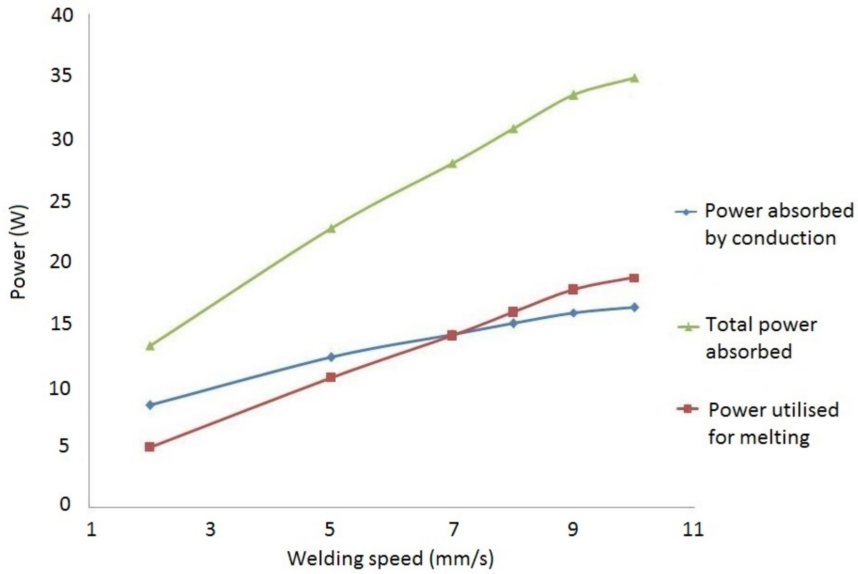

Fig. 5 Effect of welding speed on power absorbed by the specimen

The Fig. 6 shows that there is a significant variation from 10.1-21.2 % in the energy transfer efficiency with respect to welding speed, therefore different values of energy transfer efficiencies are considered instead of a single value.

The heat input to the substrate material is directly proportional to the product of energy supplied, energy transfer efficiency and pulse frequency. The energy transfer efficiency is based on materials properties, laser beam reflection, process parameters, operating conditions and power source. The analytical equations proposed by the researchers to estimate the melting efficiency predict differently for different types of welding processes. A non-linear relationship is observed between the melting efficiency, weld speed, and R_y from the results obtained by different researchers.

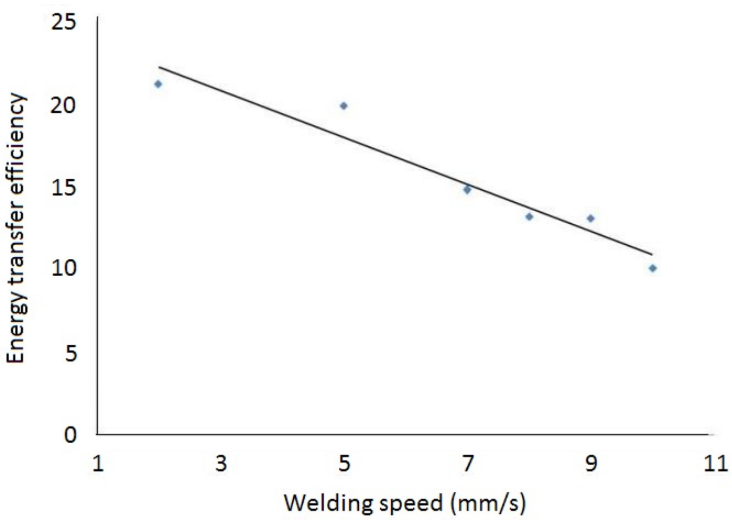

Fig. 6 Correlation between energy transfer efficiency and welding speed

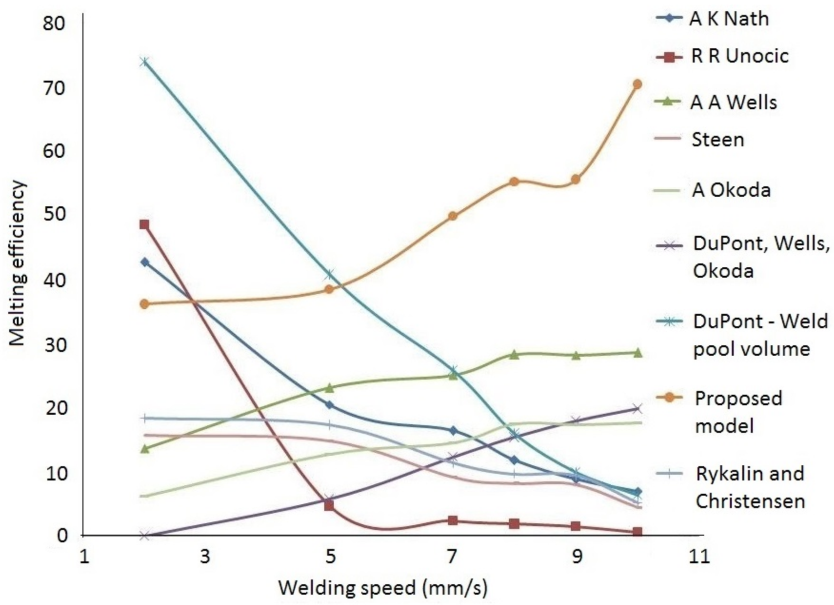

Fig. 7 Comparison of melting efficiencies predicted using proposed models and models presented by different researchers

This is shown in Fig. 7 and Fig. 8. The weld pool volume has been computed by using Eq. 10 and resulting values are substituted to predict melting efficiency. The proposed model predicts higher efficiency than that of other models. This is due to selection of process parameters for dimensionless parameter modeling and the variation in heat energy absorbed by the substrate material with respect to welding speed. It can be seen from Fig. 8: an increase in welding speed leads to increase in melting efficiency. This is because the energy required to melt the substrate material is influenced by welding speed and less time available to transfer heat away from the melt pool region. Hence more amount of energy consumed to create and maintain molten weld pool. The melting efficiency predicted by the proposed models is higher than the other models presented in this paper and are in close agreement [12]. This is due to bead on plate welds belongs to the 3D heat flow whereas the other models are based on 2D heat flow concepts. The maximum melting efficiency estimated by using the proposed weld pool volume equation and melting efficiency model is 74.20 % and 70.56 %, respectively, at the welding speed of 10 mm/s.

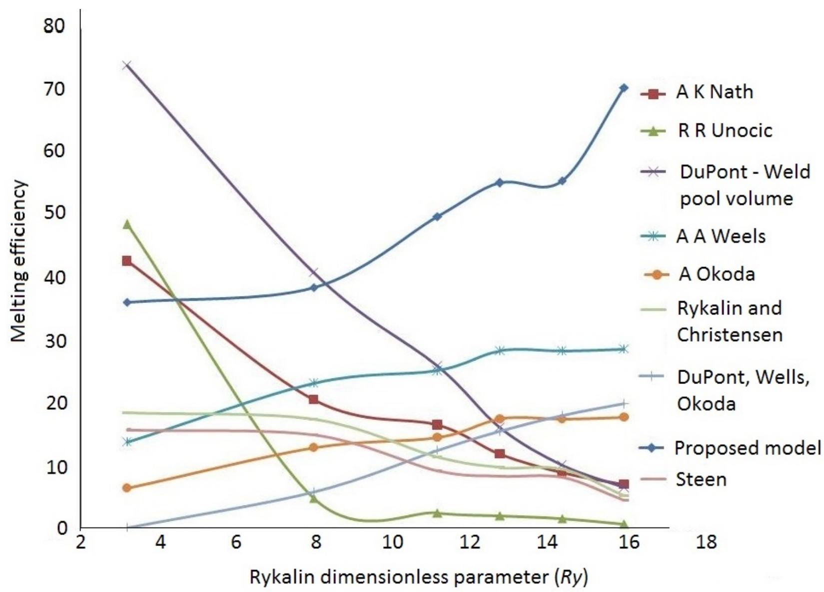

Fig. 8 Comparison of melting efficiencies predicted with respect to Rykalin dimensionless parameter model

7. Conclusion

The melting efficiency of the welding process depends upon processing and operating parameters, thermo mechanical and chemical properties of the material, surface conditions and type of power source. The mathematical model proposed in this work is used to predict weld pool volume by measuring weld bead diameter experimentally and melting efficiency by using dimensionless parameter model. The energy transfer efficiency and melting efficiency are significantly affected by the welding speed. The total power absorbed by the substrate material increases with increasing welding speed. The power utilized for melting the material is less than that of power absorbed by conduction up to a welding speed of 7 mm/s, whereas beyond this limit, power absorbed for creating weld pool is greater than heat carried away by the conduction. The defect free welds have been observed within the range speed selected for welding. The mathematical models presented in this work can be extended for predicting heat flow and solidification modelling studies. The equations developed in this work for estimating melting efficiency predict higher efficiency than the other models. The effect of pulse duration, gas flow rate and focal position on melting efficiency can also be tried. Laser welding at extremely low speeds requires further investigation to explain the reasons behind this drastic change.

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References

[1] Fuerschbach, P.W., Eisler, G.R. (1999). Effect of very high travel speed on melting efficiency in laser beam welding, *SAE International Journal of Materials and Manufacturing*, Vol. 108, No. 5, 824-829, doi: 10.4271/1999-01-0996.

[2] Lankalapalli, K.N., Tu, J.F., Gartner, M. (1996). A model for estimating penetration depth of laser welding processes, *Journal of Physics D: Applied Physics*, Vol. 29, No. 7, 1831-1841, doi: 10.1088/0022-3727/29/7/018.

[3] Tadamalle, A.P., Reddy, Y.P., Ramjee, E. (2013). Influence of laser welding process parameters on weld pool geometry and duty cycle, *Advances in Production Engineering & Management*, Vol. 8, No. 1, 52-60, doi: 10.14743/apem2013.1.153.

[4] Walsh, C.A. (2002). Laser welding – literature review, Materials Science and Metallurgy Department, University of Cambridge, England, from *http://www.msm.cam.ac.uk/phase-trans/2011/laser_Walsh_review.pdf*, accessed August, 21, 2014.

[5] Pépe, N., Egerland, S., Colegrove, P.A., Yapp, D., Leonhartsberger, A., Scotti, A. (2011). Measuring the process efficiency of controlled gas metal arc welding processes, *Science and Technology of Welding & Joining*, Vol. 16, No. 5, 412-417, doi: 10.1179/1362171810Y.0000000029.

[6] Chang, W.S., Na, S.J. (2002). A study on the prediction of the laser weld shape with varying heat source equations and the thermal distortion of a small structure in micro-joining, *Journal of Materials Processing Technology*, Vol. 120, No. 1-3, 208-214, doi: 10.1016/S0924-0136(01)00716-6.

[7] Fuerschbach, P.W., MacCallum, D.O. (1995). Variation of laser energy transfer efficiency with weld pool depth, In: *Proceedings of 14th International Congress on the Applications of Lasers and Electro-Optics*, San Diego, California, USA, 493-497.

[8] Unocic, R.R., DuPont, J.N. (2004). Process efficiency measurements in the laser engineered net shaping process, *Metallurgical and Materials Transactions B*, Vol. 35, No. 1, 143-152. doi: 10.1007/s11663-004-0104-7.

[9] Fuerschbach, P.W. (1995). A dimensionless parameter model for arc welding process, In: *Trends in Welding Research: Proceedings of the 4th International Conference*, Gatlinburg, Tennessee, USA, 493-497.

[10] DuPont, J.N., Marder, A.R. (1995). Thermal efficiency of arc welding processes, Supplement to the Welding Journal, 406-416, from *http://www.aws.org/wj/supplement/WJ_1995_12_s406.pdf*, accessed August 21, 2014.

[11] Fuerschbach, P.W., Eisler, G.R. (2002). Effect of laser spot weld energy and duration on melting absorption, *Science and Technology of Welding and Joining*, Vol. 7, No. 4, 241-246, doi: 10.1179/136217102225004293.

[12] Nath, A.K., Sridhar, R., Ganesh, P., Kaul, R. (2002). Laser power coupling efficiency in conduction and keyhole welding of austenitic stainless steel, *Sadhana*, Vol. 27, No. 3, 383-392, doi: 10.1007/BF02703659.

[13] Tzeng, Y.-F. (2000). Process characterisation of pulsed Nd:YAG laser seam welding, *The International Journal of Advanced Manufacturing and Technology,* Vol. 16, No. 1, 10-18, doi: 10.1007/PL00013126.

[14] Christensen, N., Davies, V. de L., Gjermundsen, K. (1965). Distribution of temperature in arc welding, *British Welding Journal*, Vol. 12, No. 2, 54-75.

[15] Klimpel, A., Rzeźnikiewicz, A., Janik, Ł. (2007). Study of laser welding of copper sheets, *Journal of Achievements in Materials and Manufacturing Engineering*, Vol. 20, No. 1-2, 467-470.

[16] Norris, J.T., Robino, C.V., Perricone, M.J., Hirschfeld, D.A. (2010). Development of a time-resolved energy absorption measurement technique for laser beam spot welds, *Welding Journal*, Vol. 89, No. 4, 75s-81s.

[17] Wang, R., Lei, Y., Shi, Y. (2011). Numerical simulation of transient temperature field during laser keyhole welding of 304 stainless steel sheet, *Optics & Laser Technology*, Vol. 43, No. 4, 870-873, doi: 10.1016/j.optlastec.2010.10.007.

[18] Patschger, A., Bliedtner, J., Bergmann, J.P. (2013). Approaches to increase process efficiency in laser micro welding, *Physics Procedia*, Vol. 41, 592-602, doi: 10.1016/j.phpro.2013.03.121.

[19] Bergmann, J.P., Patschger, A., Bastick, A. (2011). Enhancing process efficiency due to high focusing with high brightness lasers – applicability and constraints, *Physics Procedia*, Vol. 12, Part A, 66-74, doi: 10.1016/j.phpro.2011.03.009.

[20] Mladenov, G., Vutova, K., Wojcicki, S. (1998). Experimental investigation of the weld depth and thermal efficiency during electron beam welding, *Vacuum*, Vol. 51, No. 2, 231-233, doi: 10.1016/S0042-207X(98)00165-1.

[21] Kim, T.H., Albright, C.E., Chiang, S. (1990). The energy transfer efficiency in laser welding process, *Journal of Laser Applications*, Vol. 2, No. 1, 23-28, doi: 10.2351/1.4745249.

[22] Tu, J.F., Paleocrassas, A.G. (2010). Low speed laser welding of aluminium alloys using single-mode fiber lasers, In: Stone, X.A. (ed.), *Laser Welding*, InTech, 47-76, doi: 10.5772/9857.

[23] Forsman, T., Powell, J., Magnusson, C. (2001). Process instability in laser welding of aluminum alloys at the boundary of complete penetration, *Journal of Laser Applications*, Vol. 13, No. 5, 193-198, doi: 10.2351/1.1404414.

[24] Hamadi, O.A., Khashan, K.S. (2008). Modeling of the preheating effect on keyhole laser welding efficiency, *Iraqi Journal of Applied Physics Letters*, Vol. 1, No. 1, 10-15.

[25] Greses, J., Barlow, C.Y., Hilton, P.A., Steen, W.M. (2003). Effects of different gas environments on CO_2 and Nd:YAG laser welding process efficiencies, In: *SPIE Proceedings: First international Symposium on High-Power Laser Macroprocessing,* Osaka, Japan, 257-263, doi: 10.1117/12.486500.