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Effect of Preheating on the Parameters of Laser Keyhole Welding Process: Analytical Study

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Abstract: In this work, results of a mathematical analysis of the role of workpiece preheating in laser keyhole welding were presented. This analysis considered the steady-state welding as well as certain range of boundary conditions over which preheating effect would be indicated. This work is an attempt to interpret the role of preheating to increase welding depth and perform keyhole welding with high quality using physical and thermal properties of steel alloys.

Introduction

Welding with high power lasers is commonly used nowadays in modern industries due to high productivity, flexibility and high quality provided by laser in addition to possibility to carry out advanced and complicated welding processes. Compared to the conventional welding techniques, use of CO_2 and Nd:YAG lasers with precise control of laser beam parameters made it possible to control welding depth as well as detect defects inside the structure of welded region. Also, controlling welding depth makes it possible to carry out such processes without any side effects to the welded regions or surroundings [1]. In laser welding, the affected area is small and localized and welding process is usually fast then the distortion is minimal [2].

As the material being irradiated by a high power laser beam, surface temperature raises rapidly if the laser beam intensity is high enough. Hence, laser energy absorbed by material is increased as more energy being accumulated onto small volume at the surface [3-5]. Continuing irradiating, the surface will melt at beam incidence point then vaporize to form a hole through which most of incident laser energy being absorbed. If the welding required is deep then the Gaussian distribution and divergency of laser beam form a key-shape hole so this type of welding is known as "keyhole welding". In this process, the incident laser beam penetrates material surface completely and moves along the path between two samples wanted to weld. The quality of laser keyhole welding depends on samples alignment and width of working region [6]. Fig.(1) explain laser keyhole welding process.

Laser keyhole welding, and whole industrial processes, is based on the fundamentals of heat transfer from power source (laser beam) to the workpiece. Although this process seems an ordinary thermodynamic process between two media different in temperature, the problem of heat transfer in such processes is often complex due to many variables included [7-10]. Good understanding of laser keyhole welding process requires more models describing such process and presents enough data in order to be studied and analyzed. Each of effects of variables included can also be studied individually or together with others in order to control welding process [11-12].

Several previous works included analyses and mathematical models related to the parameters of laser keyhole welding process as well as thermal properties of the material welded by high power focused beams [13-22]. These works were all based on the source line model (SLM) of workpiece temperature distribution relative to the cross section of welded region in addition to effects of latent heat of fusion [15-19]. According to the analyses presented in these works, preheating effect on the parameters of laser keyhole welding process can be studied and discussed.

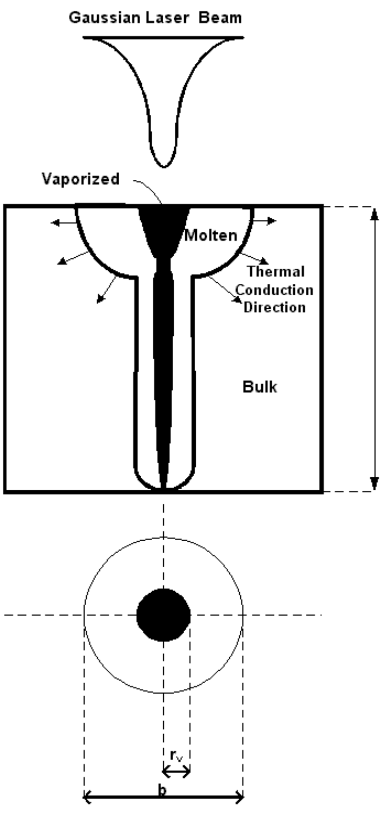

Fig. (1) Principle of laser keyhole welding

The laser power penetrating workpiece through the keyhole formed on workpiece surface is given as:

$$P_{KH} = \eta_a \eta_{KH} P_B \quad (1)$$

Assuming that laser keyhole welding process is carried out under the steady-state condition, as other parameters are constant, the absorption efficiency (η_a) is determined by the reflectivity of the molten, which in turn depends on the effect of plasma present in beam path toward workpiece [23-25]. This efficiency does not depend on preheating temperature since the region surrounding material-beam interaction region is already melted that may cause to absorb all the incident power. Preheating affects the absorption efficiency just in non-steady states such as beginning welding process [24].

The other parameter determining the mount of laser power transferred into workpiece is the efficiency of energy transfer through keyhole (η_{KH}) which represents a function depends precisely on the ratio of keyhole radius on surface (r_v) to incident laser beam radius (r) at the same local [26]. If the value of keyhole radius (r_v) is ($1/e^2$) of that of incident Gaussian beam radius (r), then only (85.5%) of unreflected laser power penetrates the keyhole toward workpiece as the rest dissipates at surface as a heat. As well, if the ratio (r_v/r) is ($1/e$) then (63.2%) of laser power enters the workpiece. This definitely causes temperature distribution to disturb as the welding width (b) increases at surface and this does not match keyhole-welding condition.

Maximum efficiency of energy transfer through keyhole (η_{KH}) is about (95%) [18] that can be considered constant if the parameters of welding process such as workpiece velocity, laser beam power, focal position and preheating are varying. Hence, the loss in the incident energy should not exceed 5%. Then:

$$r_v \geq 1.2 r_{1/e^2} \quad (2)$$

At low laser power, it is very probable that the condition above does not satisfy, so, preheating leads to increase the efficiency (η_{KH}) by increasing value of (r_v) [16]. This is why the preheating being applied to workpiece in order to increase penetration depth at low laser powers. Welding processes are usually performed using high laser powers. If the parameters of welding process mentioned above vary over a definite range and the condition in Eq. (2) is always satisfied, then preheating of workpiece does not affect the efficiency (η_{KH}).

In this study, we discuss effect of workpiece preheating on some parameters of laser keyhole welding process. We also suppose that the condition of Eq. (2) is already satisfied or approached and the value of efficiency (η_{KH}) is known to be unity.

Analysis

The temperature distribution along distance (z, $z+dz$) of melted region surrounding the keyhole is given as:

$$T_{L,z}(x,y) - T_{P,z} = \frac{P_z}{4k}\left(\frac{4N}{vx^2}\right)\exp-\left(\frac{\upsilon\sqrt{x^2+y^2}}{2N}\right) \quad (3)$$

where T_p is the temperature of bulk region at the edge of the molten pool (liquid phase). This equation is valid as the coordinate (z) is localized to welding depth (t), i.e., $0 \le z \le t$ and $T_m \le T_{L,z}(x,y) \le T_v$. It can be applied on surface of workpiece according to the following boundary condition:

$$T(x=0, y=r_v, z=0) = T_v \quad (4)$$

The Gaussian beam has a circular intensity distribution and Eq.(4) represents an elliptical distribution of temperature given in Eq.(3). This distribution corresponds a circle when $T=T_v$ where $r=\pm x^2+y^2$ and $y=\pm r_v$. Knowing that [17]

$$T - T_o = \frac{AP_z}{2\pi k v}\frac{1}{\sqrt{t(t+t_o)}}\exp-\frac{1}{4N}\left[\frac{(z+z_o)^2}{t}+\frac{y^2}{t+t_o}\right] \quad (5a)$$

Also,

$$t_o = \frac{r_B^2}{4N}\ ,\ t = \frac{x^2}{4N} \quad (5b)$$

We obtain the following expression:

$$T - T_o = \frac{(1-R)P_z}{2\pi k v t}\exp-\left(\frac{x^2+y^2}{4Nt}\right) \quad (6)$$

Solving at $y=0$, as the workpiece is moved usually in one direction, then

$$T - T_o = \frac{(1-R)P_z}{2\pi k x}\left(\frac{4N}{vx}\right)\exp-\left(\frac{vx}{4N}\right) \quad (7)$$

We define the temperature difference in term of laser power entering workpiece through keyhole as

$$T_v - T_p = \frac{P_{KH}}{2\pi k_L x}\left(\frac{4N}{vx}\right)\exp-\left(\frac{vx}{4N}\right) \quad (8)$$

When x is too small, then the effect of exponential term is going to be negligible [17], so

$$T_v - T_p = \frac{P_{KH}}{2\pi k_L x}\left(\frac{4N}{vx}\right) \quad (9)$$

The laser power transferred to the workpiece includes a part transferred to the whole bulk of solid (P_z) which in turn includes a part (P'_z) transferred exactly inside the workpiece through melted (liquid phase) volume by convection, then both terms can be defined as follows [27-28]:

$$T_m - T_p = \frac{P_z}{k_L} \quad (10a)$$

$$T_m - T_f = \frac{P'_z}{k_S} \quad (10b)$$

Hence

$$\frac{T_m - T_p}{T_m - T_f} = \frac{P_z}{P'_z}.\frac{k_S}{k_L} \quad (10c)$$

Returning to Eq.(9), we get

$$T_p = T_v - \frac{P_{KH}}{2\pi k_L x}\left(\frac{4N}{vx}\right) \quad (11)$$

Substituting Eq.(10) in Eq.(11), we obtain

$$T_m - T_p = (T_m - T_f)\frac{P_z}{P'_z}.\frac{k_S}{k_L} \quad (12a)$$

$$T_p = T_m - (T_m - T_f)\frac{P_z}{P'_z}.\frac{k_S}{k_L} \quad (12b)$$

Now,

$$T_v - \frac{P_{KH}}{2\pi k_L x}\left(\frac{4N}{vx}\right) = T_m - (T_m - T_f)\left(\frac{P_z}{P'_z}.\frac{k_S}{k_L}\right) \quad (13)$$

Then

$$\frac{T_v}{T_m - T_f} - \frac{P_{KH}}{2\pi k_L x(T_m - T_f)}\left(\frac{4N}{vx}\right) = \frac{T_m}{T_m - T_f} - \left(\frac{P_z}{P'_z}.\frac{k_S}{k_L}\right) \quad (14)$$

and

$$\frac{T_v - T_m}{T_m - T_f} + \frac{P_z}{P_z^{'}}.\frac{k_S}{k_L} = \frac{P_{KH}}{2\pi k_L x(T_m - T_f)}(\frac{4N}{vx}) \qquad (15a)$$

Table (1) Parameters considered in solutions of the present treatment.

Parameter	Value
Melting Temperature	1820°C
Vaporization Temperature	2873°C
Thermal conductivity of solid phase (k_S)	59.5 W/m.K at 0°C 53.2 W/m.K at 100°C
Thermal conductivity of liquid phase (k_L)	0.5 k_S
Thermal Diffusivity (N)	1.69 x 10^{-5} m^2/s
Laser Power (P)	Up to 3 kW
Laser beam radius (r)	0.05-1 mm
Workpiece velocity (v)	0.05-10 mm/s

To express the ratio of power transferred to bulk to that transferred inside, we write

$$\frac{P_z}{P_z^{'}} = \frac{k_L}{k_S}\{\frac{T_m - T_v}{T_m - T_f} + \frac{P_{KH}}{2\pi k_L x(T_m - T_f)}(\frac{4N}{vr})\} \qquad (15b)$$

where $x=r$.

Defining the vaporization parameter (g_v) and preheating parameter (g_m) as follows:

$$g_v = \frac{T_v}{T_m} \quad \text{and} \quad g_m = \frac{T_f}{T_m} \qquad (16)$$

Eq. (15b) can be rewritten as:

$$\frac{P_z}{P_z^{'}} = \frac{k_L}{k_S}\{\frac{1 - g_v}{1 - g_m} + \frac{P_{KH}}{2\pi k_L x(1 - g_m)}(\frac{4N}{vr})\} \qquad (17)$$

and

$$\frac{P_{KH}}{x} = 2\pi k_L (1 - g_m)(\frac{4N}{vr})\{\frac{1 + g_v}{1 - g_m} + \frac{P_z}{P_z^{'}}.\frac{k_S}{k_L}\} \qquad (18)$$

In order to solve the last equation, we have considered thermal and physical properties of low-carbon steel and some parameters of laser beam and workpiece supposed to be used in laser keyhole welding. Even though, this treatment is not necessarily valid for all metallic alloys as the treatment is entirely depends on thermal and physical properties of the workpiece material. Table (1) indicates the values of parameters considered in solutions of this treatment.

Results and Discussion

Fig. (2) shows the effect of laser beam radius on the ratio of power transferred to the bulk through keyhole by conduction to that by convection. As shown, this ratio increases with increasing radius (r) but it is limited by the value of radius at which laser beam intensity being low to carry out thermal process required.

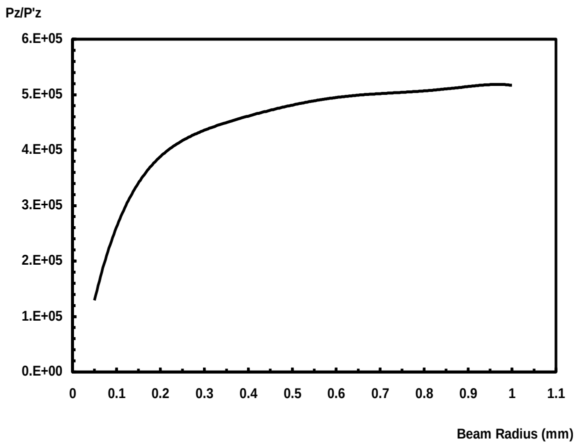

Fig. (2) effect of laser beam radius on the amount of power transferred to the workpiece through keyhole

The optimum case of power transfer to workpiece is achieved when the laser beam radius is nearly equal to radius of vaporized hole then most power will be coupled to the hole, therefore keeping this condition satisfied by control laser beam radius will then control laser keyhole welding process. Furthermore, radius of vaporized region (r_v) relates to welding width, and then it can be increased by decreasing welding width in order to couple more laser power into workpiece through the keyhole as increasing welding width increases absorption of laser power by liquid phase (molten). Since just the central part of laser beam is supporting the vaporization of material, then increasing absorption by molten decreases beam intensity required for vaporization as well as increase welding width more. Larger vaporized region (deeper depth and wider width) corresponds to faster formation of keyhole. Use of focusing optics is the usual effective method to raise laser beam intensity and reduce its radius despite limitations of such procedure. Both procedures, thermodynamic and optical, can support laser keyhole welding process toward better results.

If the workpiece is heated by an external source, then the bulk will deliver optical power lesser than the case without heating. The amount being lost due to thermal conductivity of the bulk will now be consumed to heat interaction region more and more. As interaction region is already melted and/or vaporized, then the additional consumed power will support penetration of laser beam inside workpiece to an optimum value of preheating parameter over which whole workpiece would melt.

Figures (3) and (4) explain the effect of preheating temperature (T_f) and hence preheating parameter (g_m) on the ratio P_z/P'_z. Depending on properties of laser beam and workpiece considered here, heating workpiece to a temperature near to melting point reduces the high laser power needed for welding depth required as well as time of keyhole formation. This is an assumption and the maximum value of preheating parameter (g_m) does not exceed (0.84) in order not to induce any change in the crystalline structure of the bulk [25, 27].

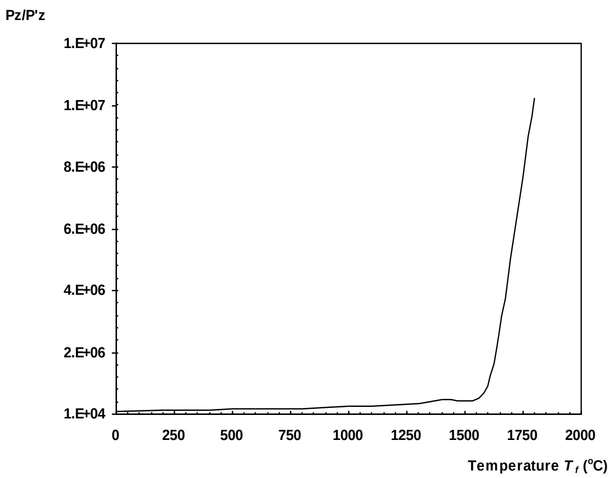

Fig. (3) Effect of preheating temperature on the amount of laser power being transferred to workpiece through keyhole

As shown, initial increasing in preheating temperature leads to rather small increasing in the ratio (P_z/P'_z) as it is limited mainly by thermal conductivity of solid and liquid phases, but at higher temperatures, the ratio (P_z/P'_z) is limited by liquid phase conductivity (k_L) more than that of solid phase (k_S). Also, Fig. (4) confirms the optimum value of preheating parameter (g_m) about (0.84) at which all power transferred to bulk (P_z) is coupled into workpiece.

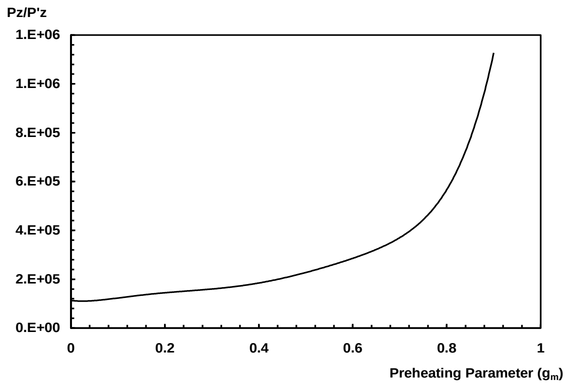

Fig. (4) effect of preheating temperature on the amount of laser power being transferred to workpiece through keyhole

The term *(vr/4N)* represents a coupling parameter controlling the ratio (P_{KH}/x) by laser beam radius (r) and workpiece velocity (v). Fig. (5) explains variation of P_{KH}/x with coupling parameter *(vr/4N)* at different value of preheating parameter (g_m) and the minimum value of ratio (P_z/P'_z).

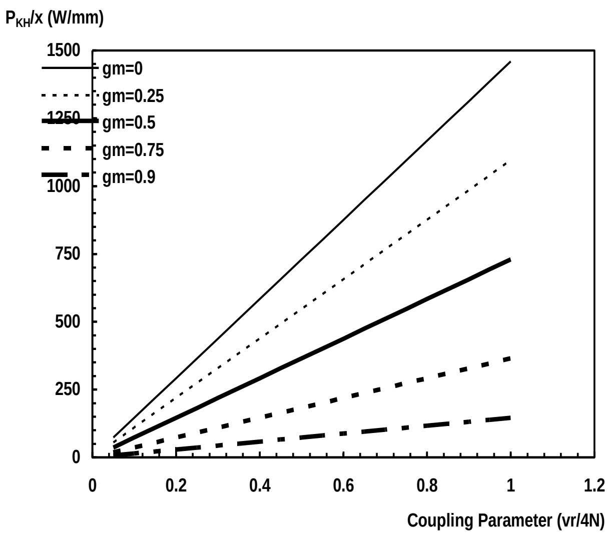

Fig. (5) variation of laser power per transferred through keyhole per unit length with the coupling parameter (*vr/4N*)

From this figure, we can determine a range of minimum and maximum values of parameter *(vr/4N)* over which optimum operation can be achieved, as both workpiece velocity and preheating process are practically limited.

Preheating process is applied overall workpiece bulk, which may cause in some cases to deform the structure of solid. So, preheating can be applied to a limited region exactly in front of laser beam incidence by localized-heating techniques at too short times to prevent heat transfer to bulk.

As confirmed, welding process includes several parameters of importance little than laser power such as workpiece velocity (v), laser beam radius (r), thermal diffusivity (N) and preheating parameter (g_m). so, we can introduce the relation between the coupling parameter (*vr/4N*) and preheating parameter (g_m) at the minimum of P_z/P'_z as shown in Fig. (6).

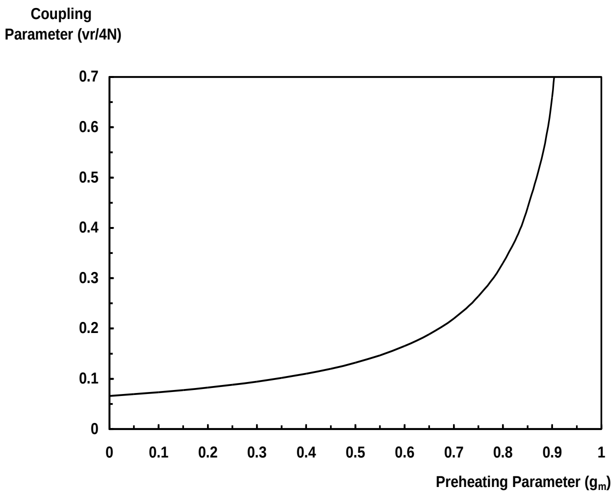

Fig. (6) Variation of coupling parameter *(4N/vr)* with preheating parameter (g_m) at the minimum of ($P_z / P`_z$)

Conclusions

Regarding to results presented in this study, it can be stated that the optimum case of power transfer to workpiece is achieved when the laser beam radius is nearly equal to the radius of vaporized hole then most power will be coupled to hole. Therefore keeping this condition satisfied by control laser beam radius will then control laser keyhole welding process. The optical power is transferred to the bulk by conduction is much higher than that transferred by convection. Depending on properties of laser beam and workpiece, preheating the workpiece to a temperature higher than its initial temperature reduces the laser power needed for the required welding depth as well as time of keyhole formation. Both term *(vr/4N)* and preheating effect (T_f/T_m) control the optical power transferred to bulk through keyhole per unit length by controlling laser beam radius (r), workpiece velocity (v) and preheating parameter (g_m). This study is based on the thermal and physical properties of low-carbon steel and may be not suitable for all metallic or steel alloys. This is because the sensitivity of the treatment and its results to such properties.

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DEFINITIONS

A absorptance
b welding width
g_m preheating parameter
k_L liquid-phase thermal conductivity of workpiece material
k_S solid-phase thermal conductivity of workpiece material
N thermal diffusivity of workpiece material
P_B laser beam power
P_{KH} laser power entering the workpiece through keyhole
P_z optical power per unit length transferred to the solid
P_z' optical power per unit length transferred to the solid by convection
r radius of the incident laser beam
r_B Gaussian beam radius at *1/e* of the intensity at surface
r_v radius of the vaporized region
T_f temperature at a position far from incidence point
T_L liquid-phase temperature
T_m melting temperature
T_o initial temperature of workpiece
T_p temperature of diagnostic probe used for temperature measurement
T_v vaporization temperature
t_o heat transfer time
v welding velocity
x horizontal coordinate of workpiece movement
η_a absorption efficiency
η_{KH} keyhole coupling efficiency

دراسة تحليلية لتأثير التسخين المسبق على معاملات عملية اللحام العميق بالليزر

عدي عطا حمادي و خولة صلاح خشان

وحدة بحوث الليزر ، قسم العلوم التطبيقية ، الجامعة التكنولوجية ، بغداد ، العراق

الخلاصة

في هذا البحث ، تم تقديم نتائج لدراسة وتحليل رياضي لدور التسخين المسبق للعينة في اللحام العميق بالليزر. يأخذ هذا التحليل بنظر الاعتبار الحالة المستقرة لعملية اللحام والشروط الحدودية لمدى من القيم التي يكون تأثير التسخين المسبق للعينة عندها واضحاً. يعد هذا التحليل محاولة لتفسير دور التسخين المسبق في زيادة عمق اللحام وإنجاز اللحام العميق بجودة عالية اعتماداً على الخواص الفيزياوية والحرارية لسبائك الفولاذ .