ESTIMATION DEPTH FOR STAINLESS STEEL OF LASER SPOT WELDING

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Abstract

Penetration depth is one of the most important factors to the quality of a laser weld. In this investigation, two calculations are used to estimate the penetration depth for Stainless Steel 304L of laser spot welding. At laser power of 3500W, the calculations produce 0.0225m and 0.0226m penetration respectively. The power distribution into the material is given by the modified first order of Bessel function. The transmitted power will decrease according to the function, as the power penetrates the material. At the depth of 0.0226m and 0.0225, the power is given 3.9770W and 4.0981 respectively

Keywords: *Laser Welding, Penetration Depth, Stainless Steel*

Introduction

Pulsed lasers continue to replace the resistance spot welding process for joining of small electronic packages and other hardware assemblies. Laser spot welding has an important advantage for these applications because it can deliver a very precise amount of weld energy (0.1 to 50 J) in a very short time (0.1 to 20ms) [1]. Laser welding proved to be the most effective tool for packaging and strong attachments of various components, it also enables producing more and hence reducing the devices cost effectively [2]. The low carbon steels austenitic stainless steel (300 series steel) which has carbon levels of less than 0.1% produce good quality welds and reliable weld performance [3].

Methodology

Figure 1 depicts the power distribution inside the Stainless Steel 304L plate. Meanwhile, the weld nugget dimensions are shown in the Figure 2.

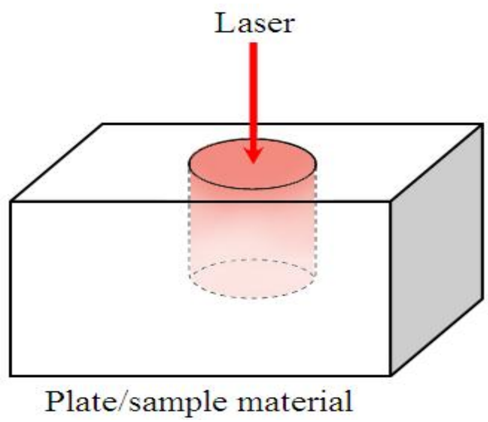

Figure 1:Power distribution inside the plate.

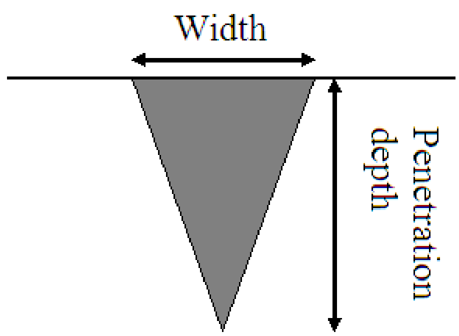

Figure 2: Weld nugget dimensions produced by spot laser welding.

Power distribution in the weld nugget can be estimated using the First Order of Bessel Function [4],

$$P(r,z) = J_0(\lambda r)\left[Ae^{\lambda z} + Be^{-\lambda z}\right] \qquad (1)$$

where *P(r,t)* is the power distribution in radius and penetration direction, J_0 is First Order of Bessel Function, r is radius, λ is assumed as material absorption coefficient, *A* is reflected power and *B* is transmitted power. The diagram will simplify the power distribution.

The SS304L absorption coefficient, λ is 0.3 [5]. The power is assumed fully transmitted through the material, so, the reflected power, *A* is ignored. The equation then become,

$$P(r,z) = J_0(0.3r)[Be^{-0.3z}] \qquad (2)$$

Two calculations for estimating penetration depth of laser welding processes have been compared to find the agreement between them. In the first calculation [2], the general differential equation of heat diffusion is considered,

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{g(r,t)}{\rho c} \qquad (3)$$

where α is thermal diffusivity, $g(r,t)$ is the rate of internal heat generation/absorption at a point in a material, ρ is the material density, c is the specific heat. To determine the penetration depth of the laser spot welds as a function of pulse duration and incident average power per pulse power density, assuming that the energy balance at the laser spot can be expressed as,

$$(1-R)I_0 = \rho L_m \frac{\partial d}{\partial t} - k\left(\frac{\partial T}{\partial z}\right)_{z=0} \qquad (4)$$

Then, the final equation will be,

$$d = \frac{(1-R)Pt}{\pi r^2 \left[L_m + c(T_m - T_0)\right]} \qquad (5)$$

where P is the laser power, R is the material reflectivity, r is the laser beam radius, L_m is the latent heat, c is the specific heat, T_m is the melting temperature and T_0 is the initial temperature.

In the second calculation [6], a quasi-steady state model of deep penetration continuous wave CO_2 laser welding for penetration depth estimation is derived. Assuming that the thermal properties of the medium are constant and that the axis of the cylindrical surface passes through the origin of the coordinate system, the governing differential equations of the temperature distribution is [7],

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{v}{\alpha}\frac{\partial T}{\partial z} = 0 \qquad (6)$$

Where v is the welding speed, α is the thermal diffusivity. The closed-form solution of the above equation in polar coordinates (r,θ) is [7],

$$\frac{T_v - T}{T_v - T_0} = 1 - \exp(-Per^*\cos\theta) \text{ x} \sum_{n=o}^{\infty} \varepsilon_n \frac{I_n(Pe)}{K_n(Pe)} K_n(Per^*)\cos(n\theta) \qquad (7)$$

where $Pe = va/(2\alpha)$ is the Peclet number, $r^*=r/a$ is the normalized radial coordinate, $\varepsilon_n=1$ for $n=0$ and 2 for $n\geq 1$, I_n is a modified Bessel function of the first kind, of order n and K_n is a modified Bessel function of the second kind, of order n.

Finally, the penetration depth can be estimated as,

$$d = \frac{P}{\left[k\left(T_v - T_0\right)\right]} \frac{1}{\sum_{i=1}^{4} \frac{c_i}{i}(Pe_0)^{i=1}} \qquad (8)$$

where P is the power, k is the thermal conductivity, T_v is the boiling point, T_0 is the ambient point, Pe_0 is the Peclet Number ($Pe_0 = vr/2\alpha$; v is the laser scanning velocity, r is the laser beam radius, α is the thermal diffusivity), with C_1=2.1995, C_2= 6.2962, C_3=-0.4994,and C_4=0.0461. Note that this empirical relation is valid only in the range 0-5 of the Peclet Number.

In this investigation, laser radius, r is fixed at 0.25mm and laser power is varied from 0 until 3500W. Since the Equation 5 is considering a stationary pulsed laser source, the pulse duration is firmed at 10ms. For Equation 8, it considerate a moving continuous wave laser source, then Peclet Number is varied between 0 and 5 since Peclet Number is a function of the scanning velocity. Note that in the Equation 8, it is assumed that laser power is fully transmitted, then for Equation 5, the reflectivity of the material, R should be 0 to make the transmitted power identical for the both equations.

The material used in these calculations is Stainless Steel 304L and the physical properties are shown in Table 1.

Table 1: Physical properties of SS304L [5]

Properties	SS304L
Material density,ρ	8000kg/m^3
Latent heat of fusion, L_m	300kJ/kg
Specific heat, c	500J/kg.^{0}C
Ambient temperature, T_0	27^{0}C
Melting temperature, T_m	1400^{0}C
Boiling temperature, T_v	3100^{0}C
Thermal conductivity, k	16.2W/m.^{0}C

Equation 5 only considers 1 Dimensional power penetration with stationary laser source but in Equation 8, power penetration is in 2 Dimensional with moving laser source. So, to make the agreement materialized, scanning velocity of Equation 8 must be small enough and approaching static state. Since the Peclet Number is a function of the scanning velocity, then by controlling it, the velocity approaching static state could be determined.

Results and Discussion

Using Equation 2, power distribution profile can be obtained inside the SS304L weld nugget, as shown in Figure 3. The results of penetration depth versus laser power for Equation 5 and Equation 8 are depicted in Figure 4.

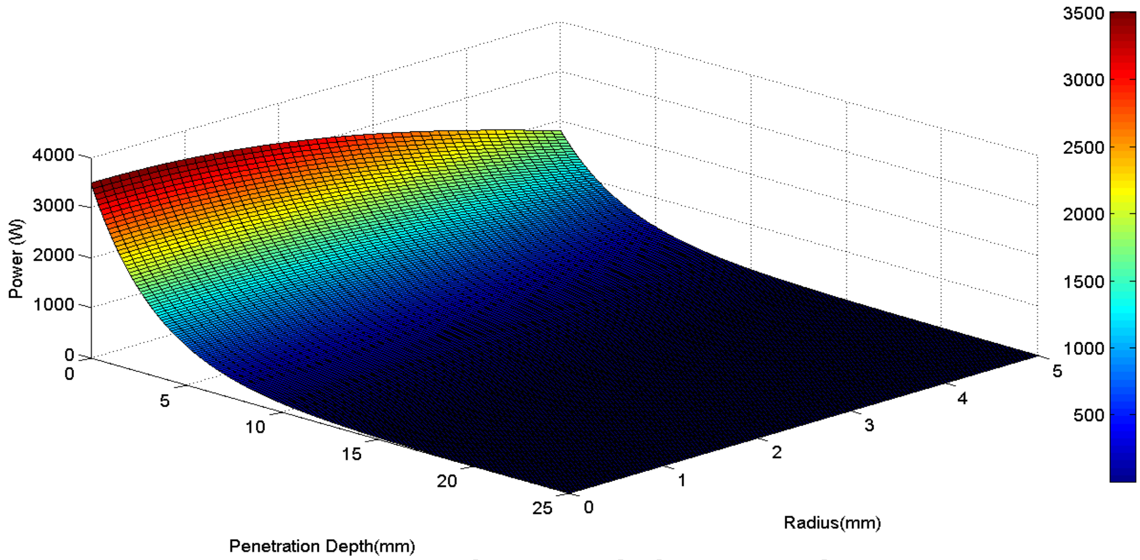

Figure 3:Power Distribution inside the SS304L plate

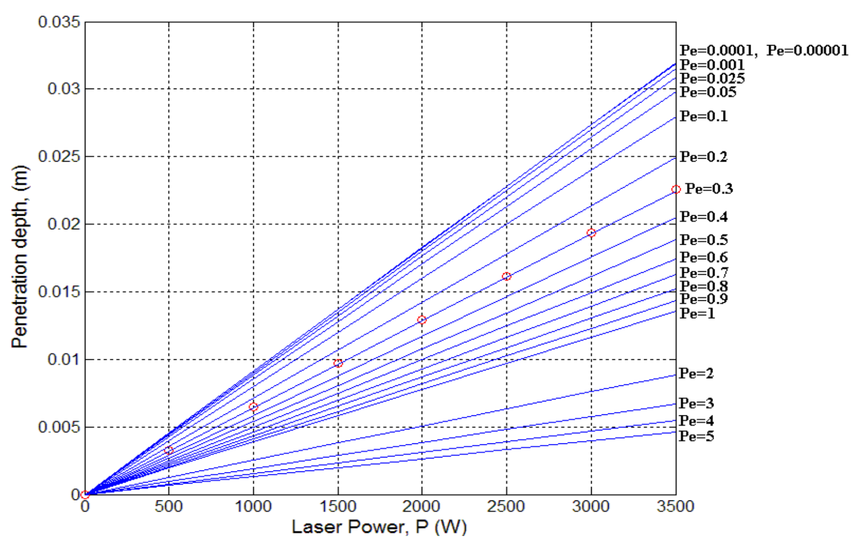

Figure 4: Penetration depth versus laser power

Results from Equation 5 are shown by the red circles, meanwhile results from Equation 8 are shown by the blue lines. The results are given in Table 2.

Table 2 : Results for penetration depth of Model 1 and Model 2 at Pe=0.3

Laser Power (Watt)	Penetration Depth (m)	
	Equation 5	Equation 8; Pe=0.3
0	0.0000	0.0000
500	0.0032	0.0032
1000	0.0064	0.0063
1500	0.0096	0.0097
2000	0.0128	0.0129
2500	0.0160	0.0160
3000	0.0193	0.0194
3500	0.0225	0.0226

For both calculations, the results indicate that the penetration depth has a linear relationship with the laser power. Figure 4 depicts the overlapping values between the both models. These values are obtained when the Peclet Number is fixed at 0.3 for Equation 8. The penetration depth values between the equations are quite similar and the differences are minimal. For example, at laser power of 3500W, Equation 5 and Equation 8 produce 0.0225m and 0.0226m penetration respectively. The difference between the both values only 0.0001m. Furthermore, at certain power such as at laser power of 2500W, the penetration depth for both equations is exactly the same which is 0.0160m. This shows that under certain conditions the agreement between the two calculations can be obtained.

From Figure 4, one can realize that the penetration depth increase exponentially with the linearly increment of Peclet Number. These are indicated when the Peclet Number varied from 5 to 1 and also from 1 to 0.1. The penetration depth difference between Peclet Number 5 and 4 is small but it becomes extremely bigger between 2 and 1. For any power beyond 3500W, the linear relationship between the laser power and the penetration depth is still valid.

Using Equation 2, the power at the certain depth can be attained. In this calculation, the initial power is fixed at 3500W. This power will decrease according to Equation 2 as the power penetrates the material. At the depth of 0.0226m and 0.0225, the power is 3.9770W and 4.0981 respectively. The power profile also can be obtained along the radius or width. At radius 0.001m, the power at the surface is 3421.7W and at the depth of 0.0226m the power is 3.900W.

Conclusion

From this investigation, the two calculations are capable of estimating the penetration depth of power during the laser spot welding. The power profile also can be estimated accurately using the modified first order of Bessel function. For future study, time parameter should be included to obtain the power profile as the lasing takes place.

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References

[1] P. W. Fuerschbach, G. R. Eisler. 2002. Effect of laser spot weld energy and duration on melting and absorption. Science and Technology of Welding and joining. 7:241-246.

[2] M. Fadhali, J. Zainal, Y. Munajat, A. Jalil, R. Rahman. 2007. Reliable pigtailing of photnic devices employing laser microwelding. J. Engineering and Applied Sciences. 2(12):1724-1728.

[3] Jose´ R Berretta, W de Rossi, Maurı´cio D Martins das Neves, Ivan Alves de Almeidab, Nilson Dias Vieira Junior. Pulsed Nd:YAG laser welding of AISI 304 to AISI 420 stainless steels. 2007. J. Optics and Laser in Engineering. 45:960–966.

[4] Murray R Spiegel. 1974. Schaum's Outline of Theory and Problems of Fourier Analysis with Application to Boundary Value Problems, McGraw Hill, USA.

[5] R. Rai, J.W. Elmer, T. A. Palmer, T. DebRoy. 2007. Heat transfer and fluid flow during keyhole mode laser welding of tantalum, Ti-6Al-4V, 304L Stainless steel and vanadium. J. Phys. D: Appl. Phys. 40:5753-5766.

[6] Kishore N. Lankapali, Jay F Tu, Mark

Gartner. 1996. A model for estimating penetration depth of laser welding processes. J. Phys. D: Appl. Phys. 29:1831-1841.
[7] Carslaw H S and Jaeger J C. 1962. Conduction of Heat in Solids 2nd Ed.,Oxford: Clarendon. p 390.