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Optical method of penetration sensing for pulsed Nd:YAG laser welding

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ABSTRACT

The ability to monitor and control the depth of a laser weld in real-time is critical in many laser welding applications. Consequently, we have investigated the use of an optical method to sense weld depth. Welds were generated on kovar samples, using a pulsed Nd:YAG laser. The sensing method uses digital high-speed photography to measure the velocity of the plume of vaporized metal atoms ejected from the metal surface. An energy balance equation is then used to relate the plume velocity to the size of the weld. Numerical solution of the energy balance equation yielded values for weld depth that were within 8% of the actual measured values.

Keywords: Laser welding, penetration sensing, high-speed imaging, nondestructive testing

2. INTRODUCTION

The use of lasers in welding applications has gained widespread use over the last two decades, due largely to the ability to focus large energies onto relatively small areas. This focusing ability provides heating sufficient to melt metals. However, a viable technique for sensing the penetration depth of a blind weld does not exist. In many industrial and military applications of laser welding, test welds are taken from a group of welds produced for a certain laser/metal combination, and a specific set of weld parameters. From cross sections of 5-10 test welds, the penetration depth of an entire sampling of welds (as many as 100) is inferred. The object of this work is to suggest a method for an in-process, nondestructive optical technique for penetration sensing of pulsed Nd:YAG laser spot welds. This technique assumes that keyhole or deep penetration mode welding, as opposed to conduction mode welding, is maintained during the majority of the laser pulse. In conduction mode welding, the mechanisms for heat transfer are (1) conduction of the surface laser energy by electrons trapped in the metal lattice and (2) convection of the molten pool due to surface tension driven flow.¹ In this case vaporization is not achieved. For the case of keyhole welding, the surface intensity is sufficient to promote vaporization. During intense vaporization, a recoil pressure is associated with the momentum change that occurs when a metal atom leaves the surface of the weld pool. This recoil pressure is sufficient to cause a depression of the weld pool surface.^{2,3} As the laser intensity increases this depression forms a void in the weld pool, and allows for further penetration of the incident laser into the metal, leading to deep penetration welding. In this work, keyhole penetration or keyhole welding refers to the regime of laser welding in which a void is formed and maintained in the weld pool during some fraction of the laser pulse.

The technique presented in this work involves measuring (1) the velocity of the plume emitted from the metal surface during the laser pulse and (2) the radius of the weld nugget of the resulting spot weld. The energy balance equation that must necessarily be met to maintain the keyhole is then used to relate these variables to the depth of the weld.

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3. THEORY

In keyhole welding, an energy balance must be maintained between the forces that cause the void to collapse and those that keep the void intact. The forces that cause the liquid to flow back into the void are surface tension and hydrostatic pressure. Those that force fluid outwards are recoil pressure and vapor pressure. Experimental observations have shown that, during the laser pulse, the displaced fluid forms a ring around the weld pool.⁴ The resulting energy balance equation has been described by Nonhof⁵ and is given by

$$V_p P_r = \gamma_b (A_p - A_c) + \gamma_m A_r \quad (1)$$

where V_p is the volume of the molten pool, P_r is the recoil pressure, γ_b and γ_m are the surface tensions at the boiling and melting points, respectively, and A_p , A_c , and A_r are the surface areas of the void, the weld, and the ring, respectively. These variables are functions of the keyhole depth and surface radius.⁵ Assuming a weld pool with a parabolic cross section, a surface radius of R , and a depth h_0 , an equation describing the walls of the void is given by

$$h = f(r) = h_0 \left[\left(\frac{r}{R} \right)^2 - 1 \right] \quad (2)$$

The surface area of the void A_p may be determined from

$$A_p = \int_0^{2\pi} \int_0^R \left(\sqrt{\left(\frac{df}{dr} \right)^2 + 1} \right) r dr d\theta \quad (3)$$

Substituting equation (2) into equation (3),

$$A_p = \int_0^{2\pi} \int_0^R \left(\sqrt{\frac{4h_0^2}{R^4} r^2 + 1} \right) r dr d\theta \quad (4)$$

Evaluating the integral of equation (4) yields

$$A_p = \frac{4}{3} \pi R h_0 \left[\left(\frac{R^2}{4h_0^2} + 1 \right)^{\frac{3}{2}} - \left(\frac{R^2}{4h_0^2} \right)^{\frac{3}{2}} \right] \quad (5)$$

The surface area of the wall of the ring, the area of the nugget, and the volume of the void are given by

$$A_r = \left[\frac{\pi^2 R^3 h_0}{\sqrt{\frac{2h_0}{R} + 2}} \right]^{\frac{1}{2}} \quad (6a)$$

$$A_c = \pi R^2 \quad (6b)$$

$$V_p = \frac{\pi R^2 h_0}{2} \quad (6c)$$

Assuming that the recoil pressure is directly proportional to the kinetic energy of the vapor, one may write

$$\sqrt{\frac{2\gamma_m}{\rho V_p} \left[\frac{\gamma_b}{\gamma_m} (A_p - A_c) + A_r \right]} = f(v) \quad (7)$$

where ρ is the density of the metal vapor, and f gives the functional form of v , the plume velocity. The validity of equation (7) may be examined by measuring the plume velocity and the weld depth and radius from weld cross sections, and plotting the left-hand side of equation (7) versus the plume velocity.

4. EXPERIMENT

The plume velocity was measured by using high-speed digital photography to record the time evolution of the plume. The technique images the broadband radiation emitted by the plume. Figure 1 shows a schematic of the imaging apparatus. The camera is a Kodak Ektapro EM, equipped with an image intensifier, and is run at a recording rate of 6000 frames per second. The processing laser radiation transmitted through mirror M is detected by a photodiode. The photodiode signal is used to trigger the camera processor. The images are stored on VCR tape or on computer disk. The processing laser is a Raytheon SS501 pulsed Nd:YAG laser, operating at a pulse rate of 10 Hz, with an average power ranging from 60 to 120 Watts. Operation within this range of parameters minimizes the variation in intensity from shot to shot. The laser is focused using a 4 inch fused silica plano-convex lens. Bead on plate welds were produced on kovar (Fe-29Ni-17Co) samples. A mechanical shutter is used to irradiate the sample with a single pulse, producing a single spot weld. The weld depth was determined from cross sections of the resulting welds.

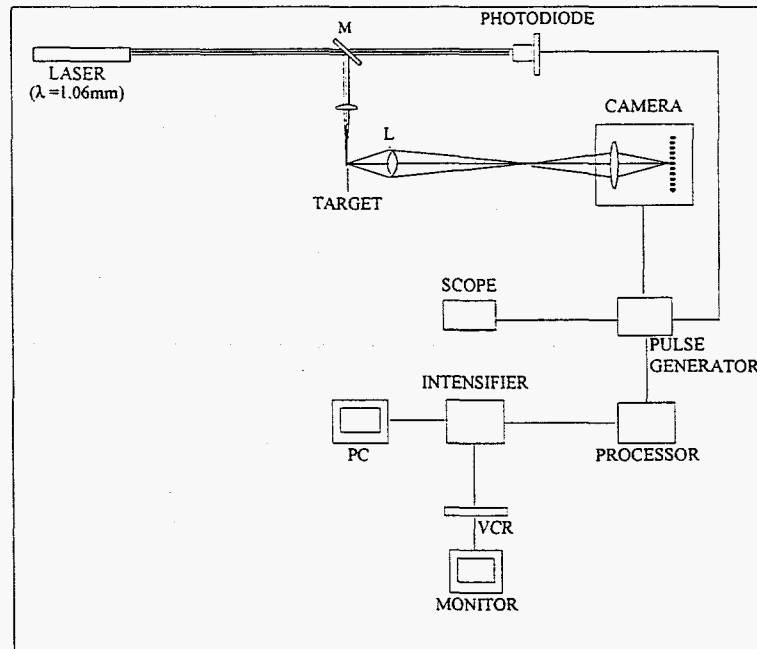


Figure 1. Schematic of the imaging apparatus.

5. RESULTS

Figure 2 shows a typical series of images of the Nd:YAG-produced plume above kovar. This case corresponds to a surface intensity of 1.16 MW/cm^2 . The processing laser is incident from top to bottom. The images show a well defined plume that remains intact as long as 2 milliseconds after the arrival of the laser pulse. Measurements of the plume position for each frame were made. Figure 3 shows a plot of position versus time for five cases, with surface intensities ranging from 0.49 to 1.39 MW/cm^2 . In each case a least squares fit to the equation

$$z = z_0 + v_0 t + \frac{1}{2} a t^2 \quad (8)$$

was performed, where z_0 is the initial height, v_0 the initial velocity, and a the acceleration.

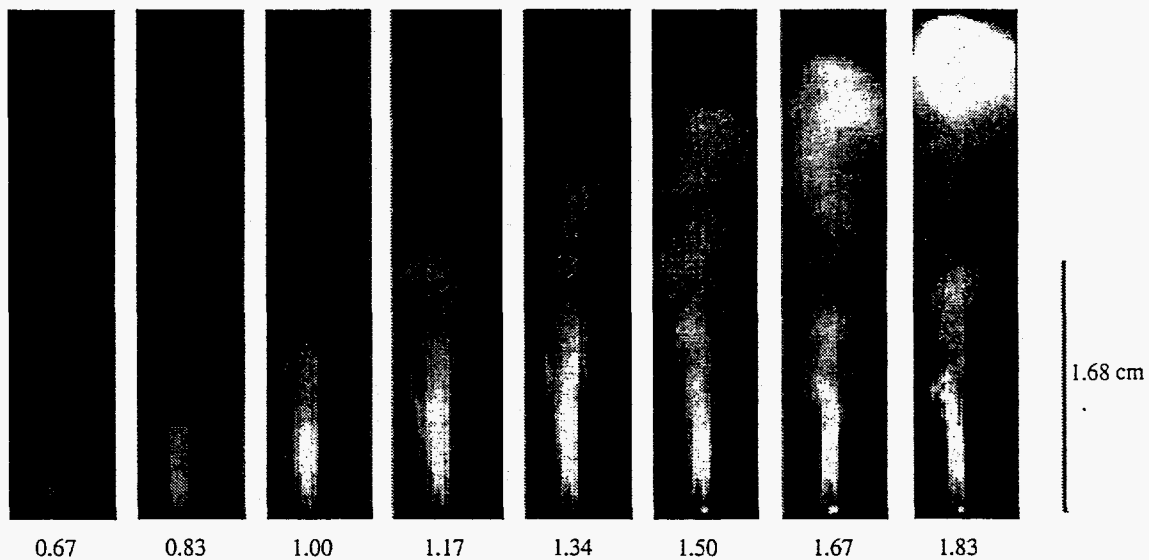


Figure 2. Series of plume images for $I=1.16 \text{ MW/cm}^2$. Times given in milliseconds at the bottom of each frame.

From Figure 3, it can be seen that from approximately 1.0 to 1.5 milliseconds, the speed of the plume is constant and begins to decrease as turbulent mixing occurs. The image of a typical spot weld cross section is shown in Figure 4.

The left-hand side of equation (7) was calculated from the measured weld dimensions R and h_0 , and plotted as a function of the plume velocity. Approximate values for the surface tension of kovar at its melting and boiling temperatures were obtained using values for Fe-29Ni.⁵ The density of the metal vapor was calculated using the ideal gas law equation for iron at its boiling temperature. This analysis makes the assumption that the size of the keyhole is equal to or at least directly proportional to the size of the weld nugget. The results are shown in Figure 5.

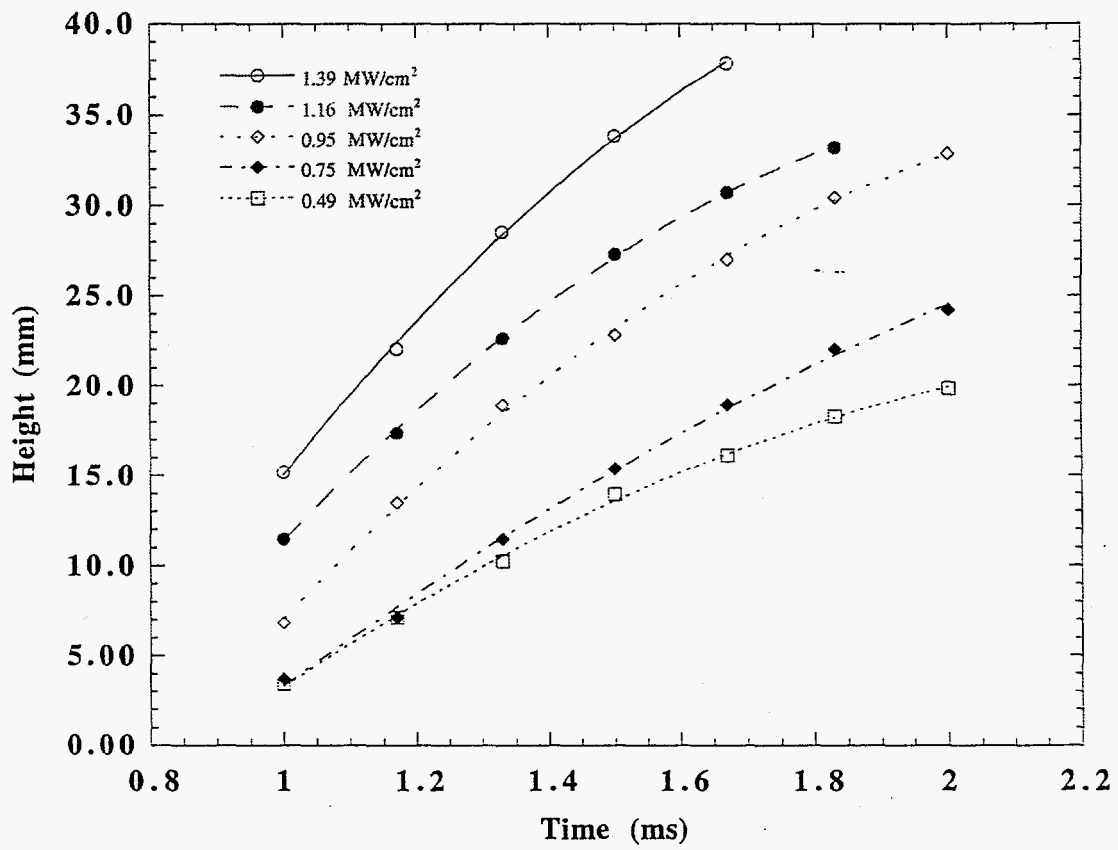


Figure 3. Plume height versus time for 5 Nd:YAG/kovar spot welds.

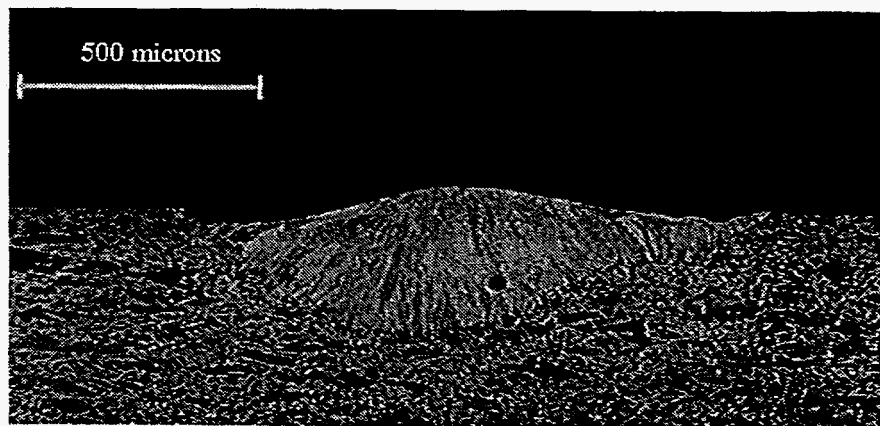


Figure 4. Cross section of kovar weld for $I=0.75 \text{ MW/cm}^2$.

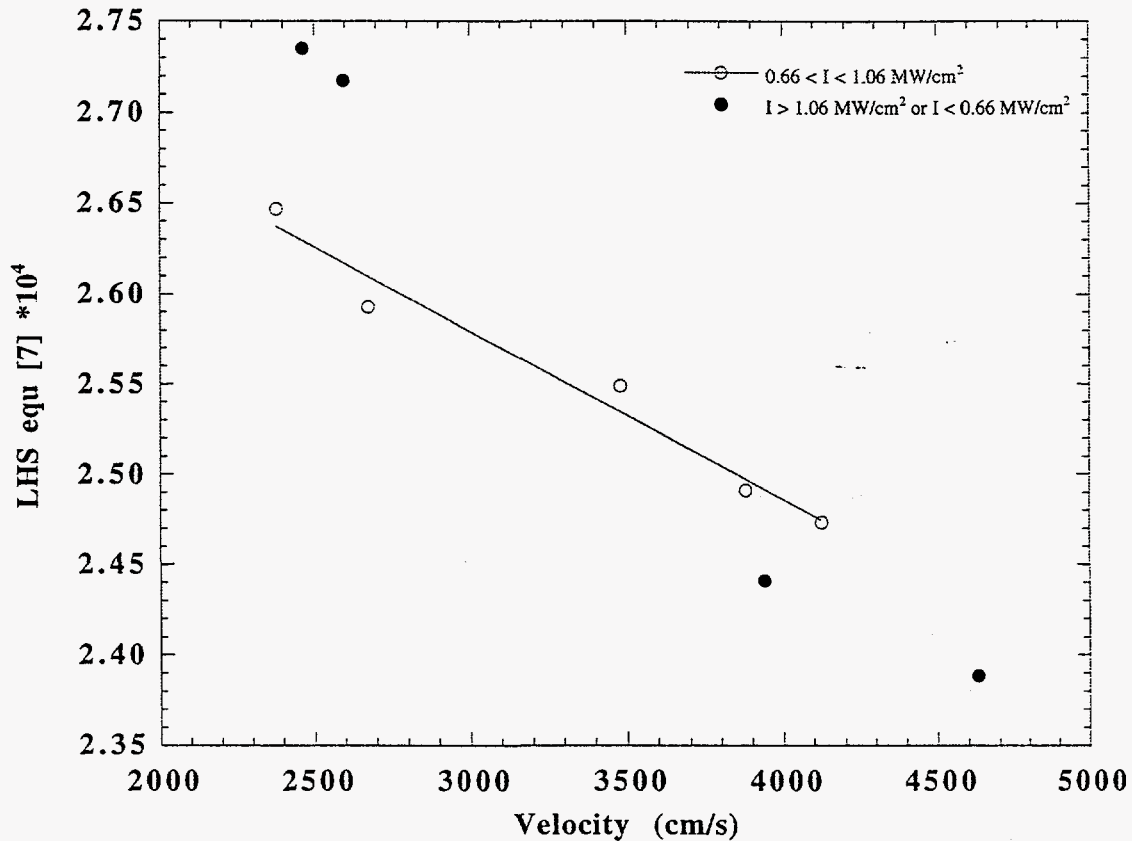


Figure 5. Left-hand side of equation (7) vs. plume speed.

6. DISCUSSION

The plot of the left-hand side of equation [7] versus v shows that the energy balance formulation gives a good approximation of pulsed spot welding of kovar, in the range of laser intensities ranging from 0.49 to 1.39 MW/cm². An equation linear in v and of the form

$$LHSequ[7] = \alpha + \beta v \quad (9)$$

where α and β are constants, was obtained for $0.66 < I < 1.06$ MW/cm². The values of α and β are $2.86 \cdot 10^4$ cm/s and -0.932, respectively. Equation (9) is unique to the case of pulse Nd:YAG spot welding of kovar. Therefore nondestructive penetration measurements can be made by measuring the plume velocity and the radius, and solving equation (9) numerically, to determine h_0 . A test of the fit of equation (9) and of the technique was performed by substituting values for R and v into equation (9), and solving for h_0 numerically. The results are given in Table 1. Spot welds made in the ranges $I > 1.06$ MW/cm² and $I < 0.66$ MW/cm² show a significant departure from equation (9). This may indicate that different regimes of plume dynamics and weld pool dynamics exist in pulsed Nd:YAG welding of kovar, for intensities above 1.06 MW/cm² and below 0.66 MW/cm².

Table 1: Measured and calculated values of weld depth.

Measured Height (mm)	Calculated Height (mm)	Percent Difference
0.26	0.247	5
0.27	0.266	1.5
0.25	0.249	0.40
0.24	0.220	8.3
0.22	0.213	3.1

7. CONCLUSIONS

This work has described pulsed Nd:YAG welding using an energy balance equation and tested the validity of the equation using experimental observations of plume velocity, weld depth, and weld radius. Good agreement was obtained between theory and experiment for intensities ranging from 0.66 to 1.06 MW/cm². Indeed, weld depths were predicted to within 8 percent of the measured values using the derived energy balance equation. This result suggests that the procedure may provide a viable means of performing nondestructive measurements of the weld depth of pulsed Nd:YAG laser spot welds.

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