Title: | MODELING AND DESIGN OF ENERGY CONCENTRATING LASER WELD JOINTS

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# Modeling and Design of Energy Concentrating Laser Weld Joints

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## Abstract

The application of lasers for welding and joining has increased steadily over the past decade with the advent of high powered industrial laser systems. Attributes such as high energy density and precise focusing allow high speed processing of precision assemblies. Other characteristics of the process such as poor coupling of energy due to highly reflective materials and instabilities associated with deep penetration keyhole mode welding remain as process limitations and challenges to be overcome. Reflective loss of laser energy impinging on metal surfaces can in some cases exceed ninety five percent, thus making the process extremely inefficient. Enhanced coupling of the laser beam can occur when high energy densities approach the vaporization point of the materials and form a keyhole feature which can trap laser energy and enhance melting and process efficiency. The extreme temperature, pressure and fluid flow dynamics of the keyhole make control of the process difficult in this melting regime. We design and model weld joints which through reflective propagation and concentration of the laser beam energy significantly enhance the melting process and weld morphology. A three dimensional computer based geometric optical model is used to describe the key laser parameters and joint geometry. Ray tracing is used to compute the location and intensity of energy absorption within the weld joint. Comparison with experimentation shows good correlation of energy concentration within the model to actual weld profiles. The effect of energy concentration within various joint geometry is described. This method for extending the design of the laser system to include the weld joint allows the evaluation and selection of laser parameters such as lens and focal position for process optimization. The design of narrow gap joints which function as energy concentrators is described. The enhanced laser welding of aluminum without keyhole formation has been demonstrated.

## Introduction

The laser welding of metals has increased significantly over the past 20 years in applications where the speed and precision of the process has over come the high cost and complexity of the process. Laser welding which relies on a conduction mode of melting is generally easy to control, resulting in precise welds which may be made at high travel speeds. Reflection of the laser energy can reduce the efficiency to less than 5% of the of the delivered laser energy for highly reflective materials such as aluminum. The low depth to width aspect ratio and generally shallow penetration of conduction mode laser welding limits the applications to thin section welding. Equipment damaging and process disturbing back reflections can be a problem in this mode of welding.

Keyhole mode laser welding has been made possible by the use of high powered industrial lasers in which energy densities sufficient to create vapor cavities and enhanced absorption is possible. Absorption of the incident beam can exceed 60% of the energy delivered. High depth to width aspect ratios and deep penetration welding is made possible with this mode of melting. It is difficult to maintain control of the dynamic balance between vapor pressure and surface tension within the keyhole. This often results on the occurrence of voids, spatter, porosity and surface defects, particularly in partial penetration keyhole welds. Energy absorbing plasmas can be formed which can affect the efficiency and stability of the process.

The reflective propagation of light into a V shaped groove and the concentration of this energy was shown by Mendenhall in 1911 [1]. The reflective propagation of laser energy deep within a

narrow gap weld joint has been demonstrated in various industrial applications [2,3,4]. Multi-pass autogenous electron beam welds made in a narrow gap has demonstrated a method for producing deep, high depth to width aspect ratio beam welds without the defects associated with a keyhole mode of melting [5]. Modeling of the energy transport due to multiple internal reflections has focused primarily on the understanding of laser keyhole mode melting [6], cutting and drilling processes. A two dimensional geometrical optics model has been used to predict the location of energy absorption within a weld joint due to primary reflections [7] using ray tracing. Experimental results showed enhanced melting due to energy trapping and improvements in the depth to width aspect ratio of the resultant welds. Qualitative comparison between simulated energy peak locations and experimental weld locations showed good correspondence[8].

## A Three Dimensional Ray Tracing Model of Laser Weld Joints

A three dimensional model has been constructed to describe the propagation of laser energy into a narrow gap weld joint. The laser beam is presented by a 2D array of point sources spatially distributed to approximate the extent of the focal spot of the laser beam. Rays emanate from these point sources over a solid angle defined by the F number of the laser beam being modeled. The rays carry with them directional information and a unit of energy defined by

$$\varepsilon_{r0} = E_i \ / \ ( \ n_r * n_p \ ) \qquad (1)$$

where:    $E_i$   is the energy of the laser pulse in joules
$n_r$   is the number of rays per point source
$n_p$   is the number of point sources



Figure 1. V-groove and a single ray trace.
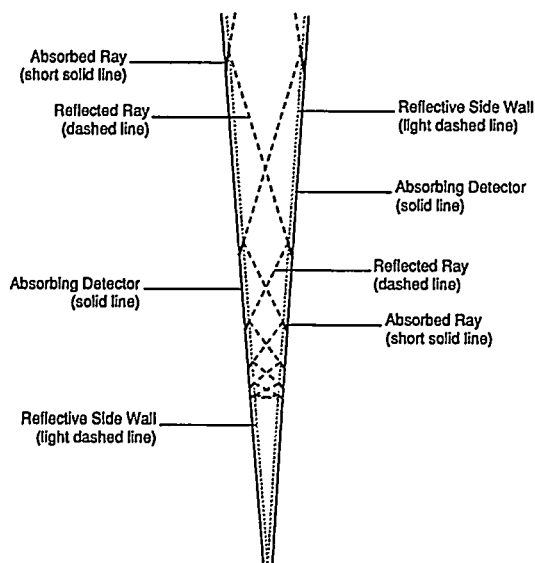
the rays are directed into a geometric representation of the weld joint gap as defined by two partially reflective surfaces which are backed by two arrays of fully absorptive elements. As the rays strike the surfaces, part of the energy is reflected as defined by a constant reflection coefficient and part of the energy passes through the partially reflective surface to be recorded by the absorbing element array. Figure 1. shows a ray being traced into a transverse cross section of a V joint geometry the location of the partially reflective side wall, absorbing detector plane of elements, the reflected and absorbed portion or a traced ray can be seen. Note the increase in angle and frequency of the reflections as a function of depth within the joint.

The energy passing through the partially reflective surface is absorbed by a an element of a two dimensional array of fully absorbing elements. The element absorbing the energy $a_{(x,y)}$, defines the location and records the total

energy accumulated by that element. The energy is accumulated within the surface element as described by the following relationship.

$$\varepsilon_a = \varepsilon_a + (\varepsilon_{rn} * \alpha) \qquad (3)$$

where:  $\alpha$  is the coefficient of absorption
$\varepsilon_{rn}$  is the energy in the ray after n reflections

The reflected ray energy is decremented by each absorption event. The propagation of the ray is halted when less than 1% of the original ray energy remains.

$$\varepsilon_{rn} < \varepsilon_{r0} * 0.01 \qquad (4)$$

The model allows geometric representation of key laser and joint input geometry, calculates total energy absorbed and creates an output file of absorbed energy as a function of location within the weld joint. Plotting of energy intensity as a function of location within the weld joint for a series of simulations allows comparison between cases and optimization of criteria such as energy distribution or peak energy location. A constant coupling coefficient of 0.35 was used for stainless steel simulations and 0.1 for aluminum simulations for Nd:YAG laser welding. The effects of angle dependent absorption, polarization, scattering or temperature dependent absorption were not included in this model.

Simulation Studies

A number of laser welding models were constructed using the OptiCad optical computer aided design program, allowing the definition of laser spot size, F number and focal point location ( x,y,z, tilt x, tilt y ). Definition of the narrow gap joint geometry allowed the specification of V groove angles, straight joints, joint gaps, curved surfaces and the absorption coefficient. Detector plane location, extent and number of array elements were also defined. Nine point sources of light were distributed over a square array to represent the laser light source at the sharp focus waist of the beam. To attain sufficient statistical distribution, 5,000 to 10,000 rays were distributed over this array of point sources. The simulations were run under Microsoft Windows 95 on a Pentium 100 MHz PC. Typical run times were 5 to 10 minutes per simulation. Output files were linked to an EXCEL spreadsheet for plotting and data analysis. Examples of the optical CAD model and output file for a typical V weld joint as shown in Figures 2 and 3.

For comparison of the simulations with experimental data, a 1 kW Nd:YAG laser welding system was used to perform welds with and without an energy concentrating weld joint design. This laser uses three separate pulse lasers combined using fiber optics and lens to deliver up to 1 kW of laser energy to single spot. Three models were constructed corresponding to the three beams of this laser system. The joint geometry of a 28 degree included angle V joint was used to concentrate the laser energy while accommodating the beam spot size and maximum joint depth of 2 mm. A coupling coefficient of 0.1 was used to represent the coupling of 1.06 $\mu$m laser energy to aluminum. The spot size, F number, orientation and location of each beam with respect to the weld joint was modeled. The location and amount of energy absorbed for each laser beam was determined from simulation. These results were combined to predict the increased energy coupling of the laser due to the narrow gap joint geometry.
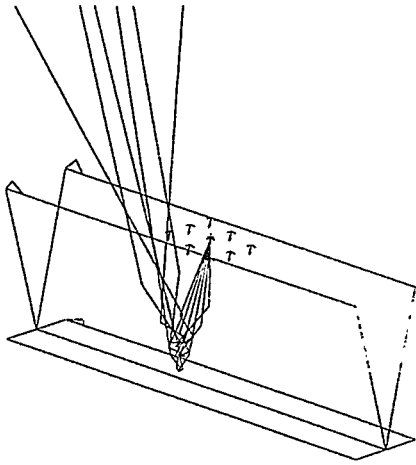
Beam 1 Intensity Plot

Figure 2. Traced rays from one point source entering the joint and reflecting back out.
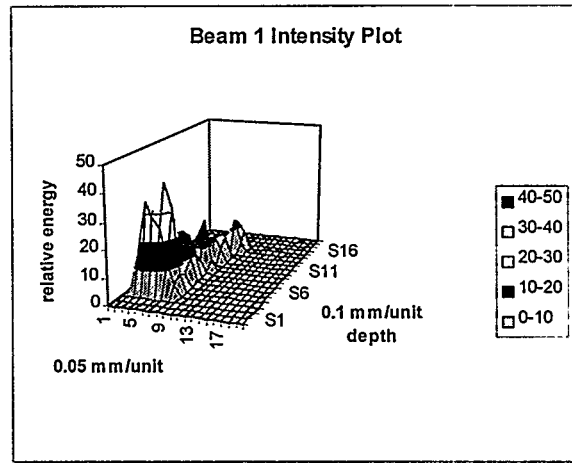
Figure 3. A plot of the location of energy absorbed within the weld joint for beam #1.

## Experimental Study

A Lumonics 1 kW Nd:YAG laser operating in pulsed and continuous wave modes was used to weld aluminum alloy 5052. This laser uses three 400 W average power lasers, and fiber optic delivery to focusing optics which deliver the beams to a single focal point as shown in the rendering of three beams in Figure 4. The pulsed lasers may be fired simultaneously at 50 Hz to achieve higher peak power. We refer to this as a 33% low duty cycle (LDC) wave form. The laser may also be fired sequentially to achieve a near continuous wave energy delivery or 100% high duty cycle (HDC) wave form. Bead on plate (BOP) melt runs, butt joints, butt joints with 1100 Al shims, and 28 degree included angle, 2 mm deep, narrow gap V groove joints were welded, sectioned and metallographically analyzed. Table 1 shows the laser welding parameters used.



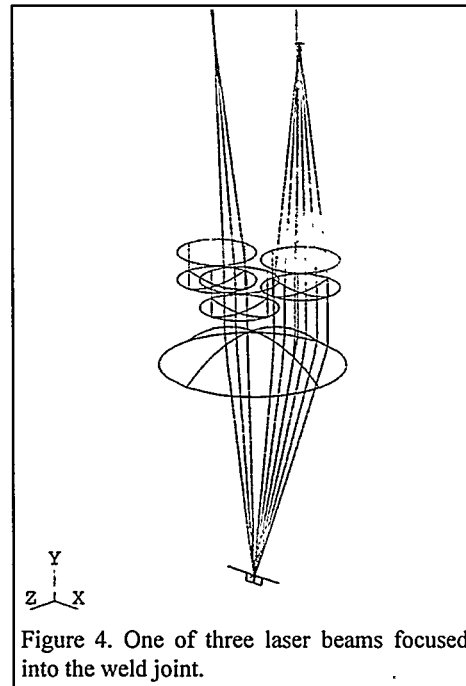Figure 4. One of three laser beams focused into the weld joint.
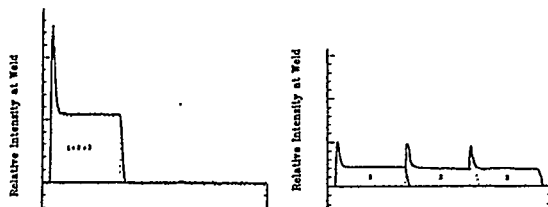


Figure 5. Low and High Duty Cycle wave forms.

Figure 5 shows the pulse shapes of 33% and 100% duty cycle welding. The 3 mm thick 5052 Al plates were cleaned in an alkaline etch, hot water and alcohol rinse prior to welding. The plates were aligned and clamped to a numerically controlled motion axis and traversed beneath the laser.

| Nd:YAG laser welding parameters for each of three lasers fired sequentially or simultaneously | |
|---|---|
| pulse length | 7 ms |
| energy per pulse | 5.7 J |
| repetition rate | 50 Hz |
| average power delivered | 885 watts |
| spot size | 1 mm |
| travel speed | 3.15 mm/s |
| pulse overlap | 94% |

Table 1. Laser Parameters

## Simulation Results

Simulation results indicated a distribution of energy along the walls of the V groove joint walls extending from the top of the joint to the joint root. A energy peak was located in the bottom third of the joint. Assuming the 10% coupling efficiency of the laser, the bead on plate and butt welds would couple 10% of the delivered energy. The model predicted a 54% coupling of the beam energy into the V groove joint for all three lasers.

## Experimental Results

Bead on plate and butt welded joints displayed similar melt depths of 0.4 mm and depth to width aspect ratios of 1 to 3. V groove welds displayed improved weld melt depths of 1.25 mm and aspect ratios of 1 to 2. The weld cross sectional area of the V-groove welds increased by a factor of 4.8 over the BOP corresponding to a similar increase in melt volume in the HDC case with similar increases in the LDC case. The LDC welds displayed cracking and the formation of large porosity, attributed to the higher cooling rates and higher energy density [9]. Spatter and plume instability was observed in the BOP and butt LDC welds thus creating the large voids and surface porosity. Large pores were significantly reduced in the V groove welds which displayed a bright stable plume during welding. The pulsed LDC weld in the V groove displayed lack of fusion at the root.

High duty cycle welds displayed coupling problems along the length of the welds with some sections of the plate left unmelted. Plume instability was observed in these regions of poor

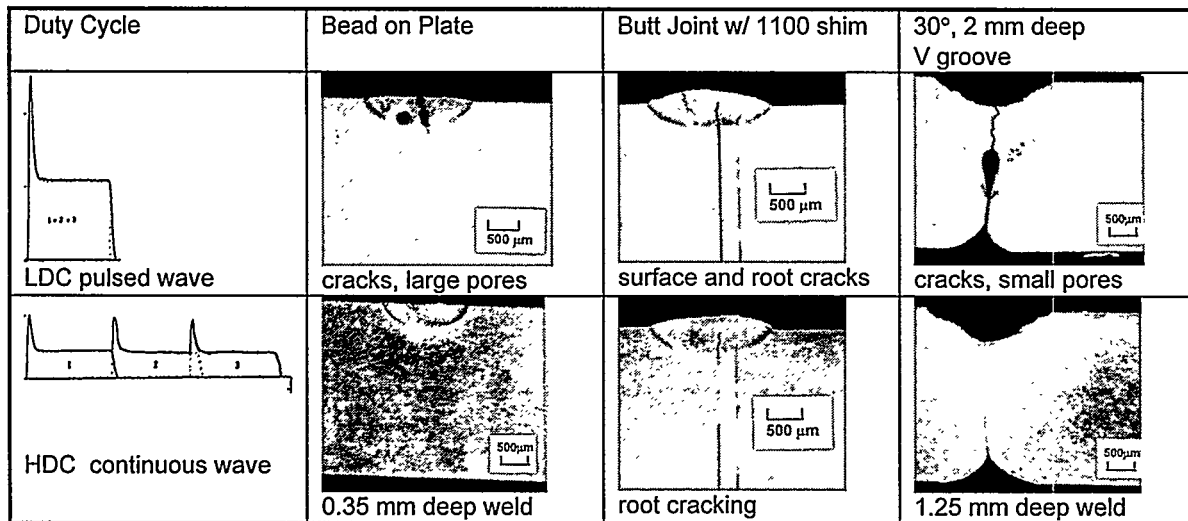| Duty Cycle | Bead on Plate | Butt Joint w/ 1100 shim | 30°, 2 mm deep V groove |
|---|---|---|---|
| LDC pulsed wave | cracks, large pores | surface and root cracks | cracks, small pores |
| HDC continuous wave | 0.35 mm deep weld | root cracking | 1.25 mm deep weld |

Figure 6. Experimental Results for Nd:YAG laser welding of 5052 aluminum

coupling. Centerline cracks were not evident in the BOP HDC welds but were again seen in the butt welds and shim welded butt welds. Aluminum alloy 1100 shims were placed in some of the butt welded samples extending 1 mm above the plate surface. This reinforcement provided a convex top bead reinforcement which allowed cross sectioning. These sectioned and polished shim welds distinctly show lack of fusion along the faying surfaces at the weld root due to failure of beam melting or fluid flow to break up the oxides along the weld root. The high duty cycle welds in the V joint were smooth and continuous without evidence of cracking or pore formation or poor fusion at the weld root. Bright stable plumes were observed above the V joints in both the LDC and HDC V joint welds. Figure 6 above summarizes these results.

Discussion

A comparison between the 54 % predicted energy coupling ( a factor of 5.4 increase) and measured increase of a factor of 4.8 in weld volume compared favorably for the conditions of this study. Quantitative understanding of the effects of parameter changes such as joint depth, gap angle, spot size, focal point location and other parameter changes are possible through use of the model. The model does not predict the degree of melting but it does predict the location of energy deposition which qualitatively corresponds with the location of the melting within the weld joint. The relatively shallow ( 2 mm ) weld joint, combined with the relatively large spot size of this laser ( 1 mm ), and the complication resulting from 3 separate laser beams, proved difficult to model. It was marginal with respect to the demonstration of the narrow gap effect of enhanced melting and weld aspect ratio improvement as compared to past experiments when much narrower beam and joints were able to be used.

Application of the energy concentrating joint design did allow the improvement in penetration and reduction in weld defects needed to allow sound continuous welds to be made with this laser which was not possible in the past. The reduction in weld defects were particularly interesting. Alloy 5052 aluminum contains 2.2%-2.8% magnesium, which has a similar melting point (651°C, 660°C) but a much lower boiling point (1110°C, 2450°C) than aluminum. This may contribute to a violent over heating of the weld pool and rapid transition in vapor pressures resulting in large amount of material expulsion and entrapped voids. The V groove geometry spreads out the energy impinging on the joint over a much larger area than the single focal spot on a flat surface, resulting in decreased energy density. At the same time it couples more energy deeper into the weld joint. The rapid cooling of the pulsed, LDC welds, contributed to cracking that was not alleviated to any degree by the narrow gap geometry. This intergranular cracking is a function of the resultant microstructure[9]. The V groove geometry does allow concentrated laser energy to heat the opposing joint surfaces to remove the surface oxides during melting as opposed to a straight butt joint with faying surfaces which are not directly exposed to the laser beam. This may prove to be a method to clean the joint or oxides prior to welding.

The effects of angle dependent absorption was not included within the model as most of the reflections within the joints of interest in our studies occur at angles within 45 degrees of normal to the surface as seen in Figure 1. We believe the energy concentration effect is dominated by the increasing frequency of reflections occurring at the bottom of the weld joint, also shown in Figure 1. The effect of polarization was not included in this model and is not considered to be a significant effect due to the highly multi-mode, homogenized beam of the fiber delivered Nd:YAG laser beam, and the small difference of S and P wave coupling at angles near within 45 degrees of normal to the joint wall. The effect of coupling as a function of wavelength and

material is affected by temperature, surface oxides, surface roughness and other numerous conditions. We leave these effects to be investigated in future experiments.

This modeling and design of energy concentrating weld joints can enhance the laser welding process and provide solutions to many of the problems facing the technology today. Power limitations may be overcome by a significant increase of usable laser energy being coupled to the part. Requirements for precise focal position control may be relaxed when using a weld joint with a wide opening which acts as a wave guide to capture, concentrate and direct the beam into the joint to be welded. Precision weld joints may not be required as the bevel on a sheared joint edge or a laser cut blank edge may be used to an advantage to trap and concentrate the laser beam energy. This method relies on the designing of weld joint which act as a "keyhole like" feature which transports energy deep within the part and enhances coupling without the spatter, vaporization and voids associated with keyhole mode welding. With this method, high depth to width aspect ratio welds can be achieved while relying on stable conduction melting.

## Conclusions

The first order effects of laser beam geometry, weld joint geometry and specular reflections provide qualitative understanding of the location of melting within a narrow joint gap. Quantitative understanding of the effects of changes to the geometry of the laser or weld joint can be obtained. Energy concentration and enhanced melting was observed in aluminum alloy 5052. A reduction in cracking, spatter and porosity formation was observed when directing the laser energy into a narrow V groove.

## Acknowledgments

## References

[1] Mendenhall, C. E., "On the Emissive power of Wedge Shaped Cavities and their use in Temperature Measurements", The Astrophysical Journal, 33(2):91-97.

[2] K. Minamida, et al., Wedge Shape Welding with Multiple Reflecting Effect of High Power $CO_2$ Laser Beam, *Proc. Int'l. Congress on Applications of Lasers and Electro-Optics*, (1986), 97-104.

[3] Sepold. G., Rothe.R, Teske.K. "Laser Beam Pressure Welding - A New Technique", Proc. Conf. Laser Advanced Material Processing LAMP '87, Osaka, May 1987, High Temperature Society,, Japan, 1987, pp. 151-156.

[4] Huntington, C.A., Eager, T.W. "Laser Welding of Aluminum and Aluminum Alloys", Welding Journal, 62(4), 1983, pp.105s-107s.

[5] Murphy, J.L., Mustaleski, T. M. Jr., Watson, L. C., Multi-Pass Autogenous Electron Beam Welding", Welding Journal, 67(9), 1988, 187s-195s.

[6] Fuerschbach, P.W., MacCallum, D.O., Variation of Laser energy Transfer Efficiency with Weld Pool Depth", Proceedings ICALEO '95,, LIA, Vol 80, 1995, pp. 497-503.

[7] Milewski, J., Sklar, E., "Modeling and Validation of Multiple Internal Reflections for Enhanced Laser Welding", Modeling and Simulation in Materials Science and Engineering, Institute of Physics, March 1996, pp. Pp. 305-322.

[8] Milewski, J., Sklar, E. "Modeling and Validation of Multiple Internal Reflections Using Ultra-Narrow Gap Laser Welding" , Proceedings of ICALEO '95, LIA, San Diego, CA, 1995, pp. 875-884.

[9] Milewski, J., Lewis, G., Wittig, J., "Pulsed and Continuos Laser Welding of Aluminum Alloy 2024", Welding Journal Research Supplement, July, 1993, AWS, pp. 341s-346s.

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