CONF-951146-2

LA-UR- 95-3424

Title: MODELING AND VALIDATION OF MULTIPLE JOINT REFLECTION'S FOR ULTRA-NARROW GAP LASER WELDING



Author(s): J. O. Milewski, E. Sklar, G. Keel

Submitted to: ICALEO '95, Laser Inst. of America,
San Diego, CA
November, 1995



Los Alamos
NATIONAL LABORATORY

# Modeling and Validation of Multiple Joint Reflections for Ultra-Narrow Gap Laser Welding

J. Milewski G. Keel and E. Sklar *

Los Alamos National Laboratory, Los Alamos, New Mexico, USA
* Opticad Corporation, Santa Fe, New Mexico, USA

## Abstract

The effects of multiple internal reflections within a laser weld joint as a function of joint geometry and processing conditions have been characterized. A computer model utilizing optical ray tracing is used to predict the reflective propagation of laser beam energy focused into the narrow gap of a metal joint for the purpose of predicting the location of melting and coalescence which form the weld. The model allows quantitative analysis of the effects of changes to joint geometry, laser design, materials and processing variables. This analysis method is proposed as a way to enhance process efficiency and design laser welds which display deep penetration, high depth to width aspect ratios, reduced occurrence of defects and enhanced melting. Of particular interest to laser welding is the enhancement of energy coupling to highly reflective materials. The weld joint is designed to act as an optical element which propagates and concentrates the laser energy deep within the joint to be welded. Experimentation has shown that it is possible to produce welds using multiple passes to achieve deep penetration and high depth to width aspect ratios without the use of filler material. The enhanced laser melting and welding of aluminum has been demonstrated. Optimization through modeling and experimental validation has resulted in the development of a laser welding process variant we refer to as Ultra-Narrow Gap Laser Welding.

## Introduction

Deep penetration of laser beams into metals for materials processing applications rely on high average power or high peak power and beam focusing conditions to create energy densities needed for drilling, cutting and welding. These processes rely on transport of energy and coupling mechanisms within the hole, kerf, or "keyhole" respectively, deep within the material to achieve high depth to width aspect ratio melt regions.

High aspect ratio welds achieved by high energy density welding typically rely on keyhole melting and do not usually require joint groove preparation or back fill . Disadvantages of the higher aspect ratio weld, are increased chances for cold shut voids, root porosity, and missed joints. The goal of conventional deep penetration laser welding is to maintain the keyhole necessary for energy delivery, penetration ,coalescence and solidification ,while conserving the mass of the melted material. Keyhole mode melting relies on many competing thermal and physical processes which are difficult to control, particularly in the case of partial penetration welds of high aspect ratios. Given the inherent inefficiency of the laser welding process, achieving and maintaining a keyhole of sufficient size and stability requires large, expensive, and complex lasers.

Applications where the reflective nature of the weld joint to the impinging laser has been used to deliver energy into a narrow weld joint have been documented. [1][2]. Multi-pass narrow gap welds for electron beam and laser processing has been demonstrated ,both autogenously and with filler material [3][4][5] for thick section or high aspect ratio laser welds and rely on high energy lasers and wire or powder fed filler material. Murphy, et. al.[3] used weld joint shrinkage and side wall melting to provide joint gap fill for multi-pass autogenous EB welding.

## Ultra-Narrow Gap Laser Beam Welding

In comparison to conventional conduction mode melting where impinging laser energy has but one opportunity to be conducted into the material before being reflected away, a narrow gap may provide multiple opportunities for energy coupling thus increasing process efficiency and produce larger welds of a more efficient weld geometry as is shown in Figure 1. Ultra-Narrow Gap Laser Beam Welding (UNG-LBW) allows the use of a computer model, calibration of the model through experimentation and iterative application of the model to optimize system parameter selection to achieve a desired processing goal. This optimization and process understanding allows the use of weld joints with top surface gap openings of a millimeter or less thus reducing or eliminating the requirement for joint back fill. The technique relies on the design of a weld joint as an optical element, parameter selection based on the laser optical characteristics, and the desired weld geometry. The weld joint preparation is partially or fully consumed during the welding process. Portions of the weld joint not consumed during a single weld pass may either be removed by machining, filled in a conventional manner, or used to concentrate the beam of subsequent weld passes. Back filling of the narrow gap may be minimized by the effects of transverse weld joint shrinkage and side wall melting, thus simplifying the process.

## The ray tracing model

A computer program to perform optical ray tracing was used to model the laser beam and joint geometry. We begin with a simplified ray tracing model, considering the most dominant effects of well understood parameters. The *3D problem* is represented by the propagation of a radially distributed focused beam of laser energy into a metal joint gap where through multiple reflections it propagates along the side walls into the weld joint. Each reflection allows the coupling of energy into the metal. A region of the side wall may absorb sufficient energy to reach the melting threshold. Under the proper conditions, flow and coalescence may occur along adjacent side wall regions to form a weld. Our *2D model* considers the propagation of rays along a single plane *transverse* to the weld joint and containing the axis of the laser beam. For simplicity and ease of computation we consider this single plane over which the greatest effect of energy concentration is seen. To the first approximation the joint is an optical system or light "guide" that directs light from the focused laser spot deep into the joint. The ray tracing code performs non-sequential ( unconstrained ) ray tracing, in which rays may hit the surfaces in a any order. The joint side walls are represented as surfaces that reflect a portion of the light (60% for stainless steel, 90% for aluminum ) thus modeling an absorption coefficient which is fixed as a function of incident angle. This partially reflective surface is followed immediately by a 100% absorbing detector plane Fig [2] . This detector plane collects the energy to gather statistics of energy deposited as a function of joint depth. It is analogous to the energy which is absorbed by the walls in the actual weld joint prior to melting. For illustrative purposes, the detector plane on the left wall of the joints shown in Figure 2 , was removed to show the direction of the incident rays. It can be seen the direction of the rays change as a function of depth and angle until turning around and propagating back out of the joint. The balance of the energy is reflected at the incident angle of the ray. For these initial studies we consider only specular reflections and neglect second order effects such as melting, heat flow, angle and temperature dependent reflectivity, and surface scattering.

The focused laser spot is modeled as the sum of a number (ie:5) point sources of light. To represent a multi-mode ("top hat") spatial energy distribution, they are evenly weighted and distributed over the diameter of the laser spot. This representation is analogous to a blocked laser beam passing through pin holes at these points. These pin hole sources each posses the optical characteristics of the full focused beam. The point source distribution is centered above the weld joint in the plane of the material top surface. Figure [2] shows rays emanating from one such point source at the surface above an angled wall gap. This method of illustration provides a qualitative view of spot size, location and ray angle in scale with the weld joint geometry. The ray trace illustrations will also be inset into plots of energy vs depth to help illustrate the quantitative data and may be given in tabular form. Rays are traced from each point source into an angle corresponding to the F-number of the optics. We trace rays in a plane orthogonal to the joint , and report energy concentration in one dimension. For this study we distribute 5000 rays over the number of point sources considered (i.e.: 5) . Rays are terminated when their energy is less than 1% of their initial value ( i.e.: 9 bounces for steel, 43 bounces for aluminum for a given system). The angle of reflection is shown to increase with each bounce until the ray direction turns around and in some case "walks" all the way back out. The energy distribution along the detector plane is represented by a plot of relative energy deposited as a function of depth within the weld joint. Statistics such as relative peak height, peak location, peak width, relative energy at the weld root, depth of first reflection and integrated energy deposited can be gathered for quantitative comparison between test cases. The energy peaks represent the locations where laser energy propagating into these weld joints is concentrated. These statistics can be used to test candidate joint designs to optimize the location where energy is deposited prior to melting.

## Simulation and weld experimental studies

Computer simulation allowed for studying the effect of changes to a number of system variables. Data for absorption and wavelength as a function of material, focal spot size, intensity distribution, coupling coefficient, F# and position of the beam focal point were included in the model. These parameters were changed to determine their effects on the system. Simulations were run on a 486 PC , data was plotted and compared with transverse profiles of the weld cross sections for qualitative comparison and identification of the location of the melting threshold corresponding to the location in the relative energy plot. Simulations were performed for comparison with stainless steel weld experiments where joint angles of 8 and 16 degrees included were modeled and quantitative comparisons were made with respect to the distribution of laser energy within the weld joints Fig.[3]. Simulations were performed for direct comparison with aluminum . Simulations were performed for changes in focal position and beam offset to illustrated the utility of the model.

Weld studies were performed to explore the Ultra-Narrow Gap Laser Weld joint designs and compare with the ray tracing model results. A fiber optically delivered Nd:YAG industrial laser welder was used to focus a 2 kW continuous wave beam into weld joint gaps in 304 SS and 1100 aluminum. V- Groove weld joint angle and weld parameters are shown in Fig. [5]. Multiple weld passes in stainless steel were made along the entire length of the 4" samples. Data regarding the optical parameters, joint geometry and material type were used as input to the computer model to simulate these conditions.

A second series of samples were welded using the 2 kW Nd:YAG laser welder to direct the laser beam into a narrow gap of 1100 Al Fig. [6]. The thick section 1100 Al joint design utilized a joint angle produced by a common shearing and clamping operation. This did not require machining to prepare the joint gap. Machined rings of 1100 aluminum 9 cm in diameter, 4 cm thick, were machined with 7 degree included angles in a V-Joint configuration. They were welded using the parameters in Fig [6]. A bead on plate weld was performed on the same material using the same parameters for comparison with the narrow gap weld.

## Simulation and weld experimentation results

Ultra-Narrow Gap V-Groove welds demonstrated that energy sufficient to melt the material could be transported and focused into a weld joint at significant depths. The joint design for stainless steel used in these trials fixed the joint gap opening at 1 mm. The narrower joint displayed an deeper narrower weld while the wider angle joint weld displayed more of a "nail head" cross section. Initial weld passes produced transverse shrinkage and closing of the weld joint which in effect narrowed the gaps another 1 to 2 degrees. Optical inspection of the welds showed no evidence of voids, porosity or cracking. Fusion was complete at the root of the weld joint. Transverse shrinkage and side wall melting allowed a two pass weld with a depth of 3 mm and a depth to width aspect ratio of 5:1 to be produced as shown in Figure 4.

A comparison between a simulation of an aluminum weld joint and a weld made under the same conditions show good qualitative agreement Fig. [5]. The energy peak in the plot was in the same location as the weld. As defined by our absorption coefficient, a beam incident on a flat surface would only see an absorption of 10%. The model showed an absorption of the incident rays of 81% under these conditions prior to melting. These welds showed a smooth consistent weld top bead, no porosity and consistent penetration. Welds made in ring specimens using a 7 degree included angle displayed no evidence of porosity, had smooth surfaces and displayed no cracking. The depth to width aspect ratio of this weld was 2:1, and the weld penetration was 2 mm. The same parameters were used to produce a bead on plate melt run in Fig.[6]. The transverse cross section area of the melted region on the flat BOP weld was observed to be significantly less than the cross section of the weld made using the beam concentrating joint by a factor of five. This indicated an increase in melting efficiency due to the beam trapping joint design.

Changes in focal position were modeled for the V-groove weld joint geometry specified in Figures [7]. It was show that a focal position at the surface would direct the beam down into the joint a certain distance before reflecting off a side wall. Moving the focal point lower into the joint resulted in high peak energy deposition at the root of the weld and a narrower energy distribution band and a higher peak energy lower into the weld joint shown in Figure [7]. Moving the beam axis offset from the center of the joint was used to model the conditions of misalignment of the beam with the joint Fig [8]. This result would indicate that preferential melting of one side wall in addition to joint root melting is possible.

## Discussion

The Ultra-Narrow Gap Method provides an alternative to keyhole mode welding to achieve high aspect ratio laser weld penetration while minimizing the occurrence of "keyhole mode" weld defects. We propose that the decreased energy density of the impinging beam may avoid many of the problems associated with keyhole mode melting such as vaporization , alloy loss, high thermal and pressure gradients.

V-groove joints propagate the beam by reflections which increase in incident angle, and increase in frequency as a function of distance into the weld joint. The implications of this are an increase in coupled energy as a function of depth. The joint angle and depth of the weld joint may be changed to achieve variation in energy deposition and the resultant weld. Practical considerations such as available lens optics, laser power, spot size and the desire to reduce the volume of the weld joint to be filled will closely dictate the selection of these parameters. As a result, the degree to which these parameters may be varied will have limitations based on available processing equipment.

Simulation runs using the ray tracing model allowed quantitative comparison of the effect of various weld parameter changes. The model was in good agreement with experiments to identify the most dominant effects of parameters, i.e.; strong angle dependency, weaker focal position dependency. Simulation showed that damaging back reflections to equipment could be reduced by almost an order of magnitude with the proper choice of joint angle.

The model has shown itself useful as a prescription for design of Ultra-Narrow Gap Weld joints and the selection of important welding parameters. It has been shown that energy distribution as a function of depth can be can be affected by changes to laser and joint parameters. The effect of energy peak location, width and height as a function of joint geometry and material reflectivity show there is no single solution i.e.: no rule of thumb for joint designs. Any changes that increases the angle of the beam with respect to the weld joint tends to walk the beam out of the joint faster and is less likely to deposit energy deep into the weld joint. Conversely, the utilization of high divergence beams could be used to melt side walls while accommodating gaps in the weld root region. This model incorporates the weld joint design into the design of the optical system as a way to enhance the laser welding process. This method enhances the ability to melt material by extending the usefulness of conduction mode welding by melting a larger volume of material along the joint to be welded. The model predicts the melting of highly reflectivity materials such as aluminum is enhanced by this process. This prediction has been validated by demonstration of the enhanced melting of 1100 aluminum.

## Acknowledgments

The authors would like to thank Joe Fonseca, Paul Burgardt and Gary Lewis of Los Alamos National Laboratory for their help in weld sample preparation, 3D rendering and discussions of laser welding technology. This work was performed under the U.S. Department of Energy contract. W-7405-ENG-36.

## References

[1] 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.

[2] Y.Arata, *Plasma, Electron & Laser Beam Technology*, American Society For Metals, (1986)

[3] J. L. Murphy, T. M. Mustaleski, L. C. Watson, Multipass, Autogenous Electron Beam Welding, Welding Journal research Supplement, September (1988), !87-s-195-s.

[4] R. H. Phillips, E. A. Metzbower, Laser Beam Welding of HY80 and HY100 Steels Using Hot Welding Wire Addition, Welding Journal Research Supplement, June (1992), 201s-208s.

[5] E. M. Breinan, D. B. Snow, "Powder-Feed LAYERGLAZE $^{sm}$ / Narrow-Gap Laser Welding of Titanium-6Al-4V", SPIE, 255-264.

## Meet the Authors

John Milewski is a technical staff member and the Welding and Joining Section team leader in the Metallurgy group at Los Alamos National Laboratory. His technical areas of interest include laser and electron beam welding, process sensing, control, process modeling and directed light fabrication. email: milewski@lanl.gov

George Keel has been with Los Alamos National Laboratory for 17 years. His primary areas of expertise include CAD/CAM, multi-axis numerically controlled motion systems, high powered laser systems and operation of the Los Alamos Material Science Laboratory's laser processing lab. His interests include laser welding of aluminum for the development of tailored blank technology. email: keel@lanl.gov

Edward Sklar is the principal optical scientist at Opticad Corporation. Formerly with Los Alamos, his technical areas of interest include the design and engineering of optical instruments, laser welding, real-time computer software, optical diagnostics, non-imaging optics and machine vision. email: 102061.3437@compuserve.com

# Enhanced Laser Melting

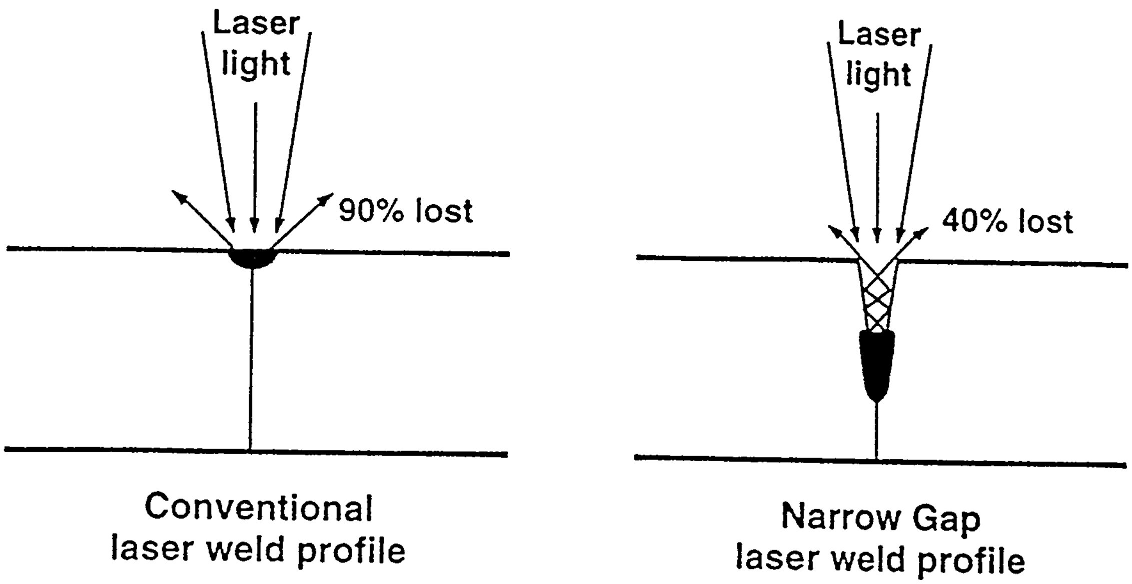



Figure 1. Enhanced Laser Melting

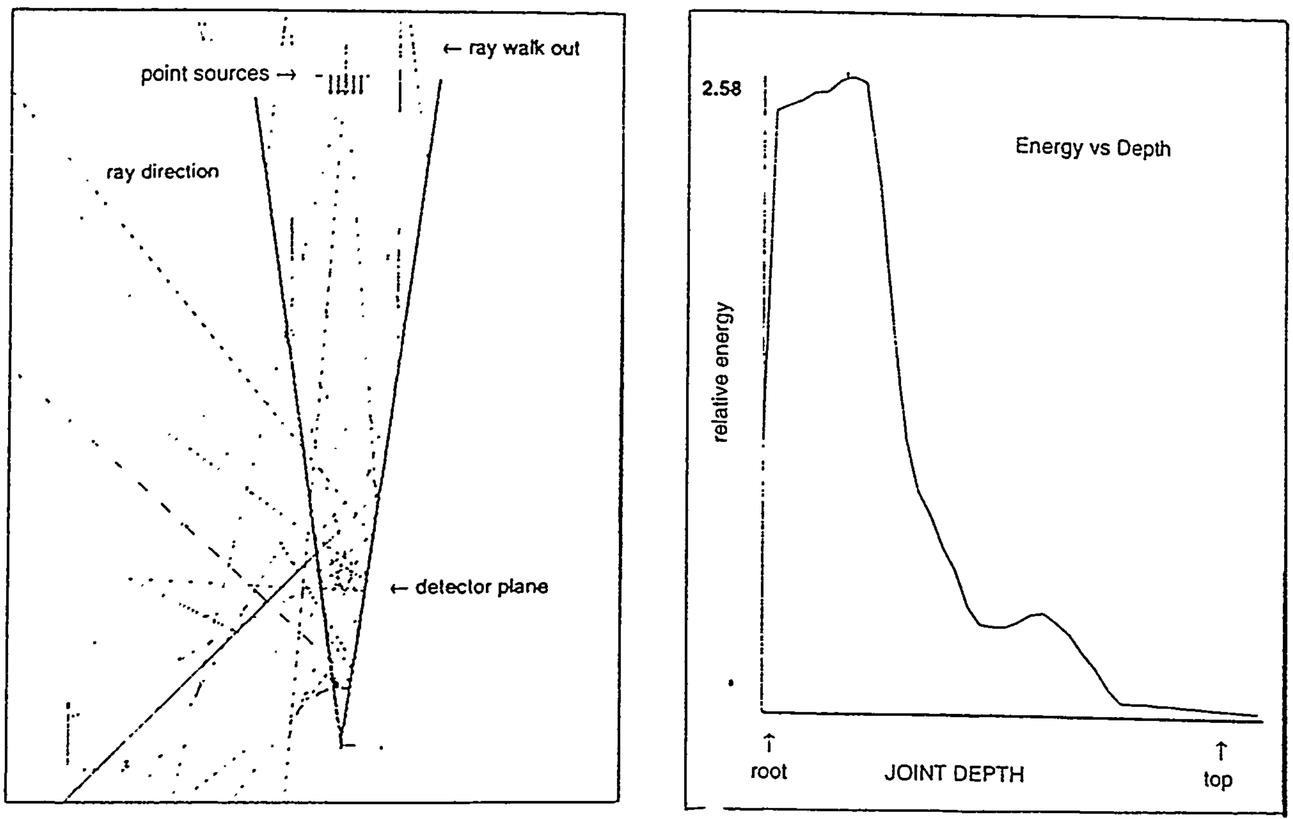
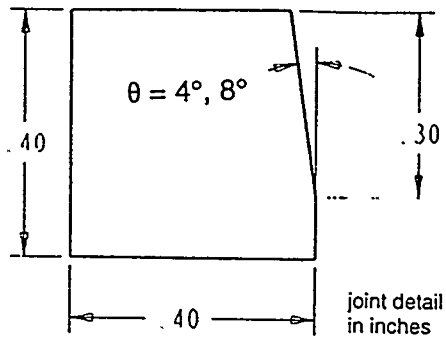
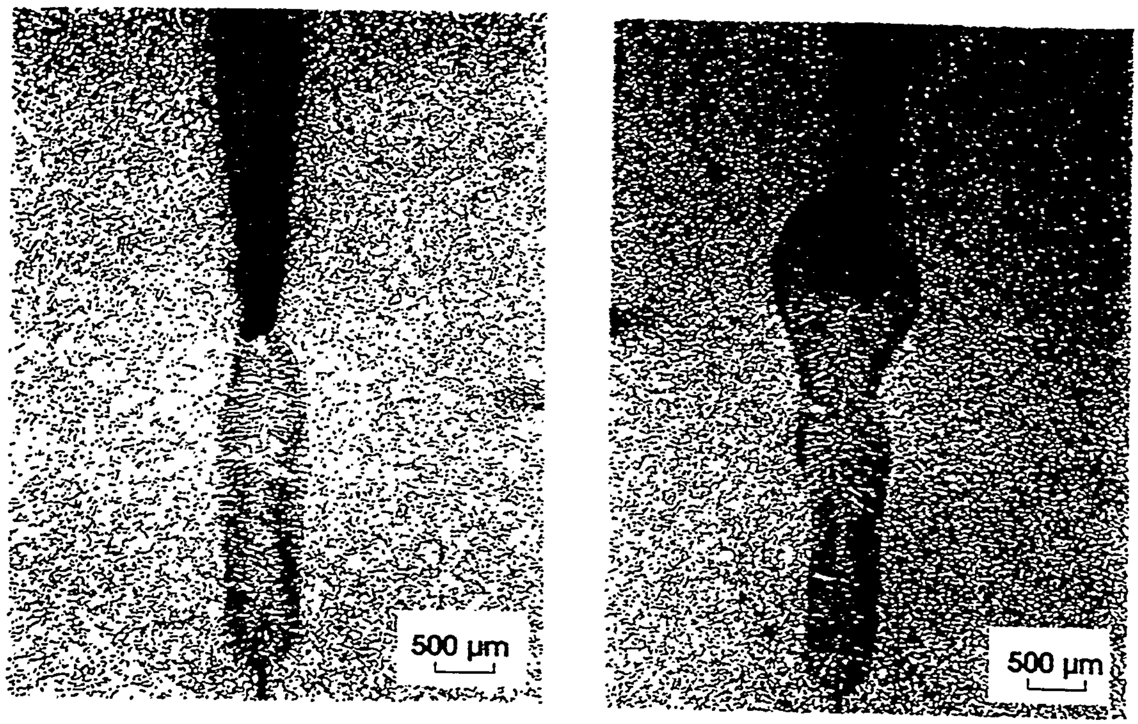



Figure 2. Ray Tracing Model and Energy Plot

| Characteristic (d = depth of joint) | +/- 4° joint | +/- 8° joint |
|---|---|---|
| peak height (relative) | 3.35 | 2.58 |
| peak location | .9d | .9d |
| Peak width (half max intensity) | .28d | .28d |
| relative energy at root | .4 | 1.2 |
| depth of first reflection | .13d | .3d |

Figure 3. Comparison Between Simulation Test Cases for Two Joint Angles



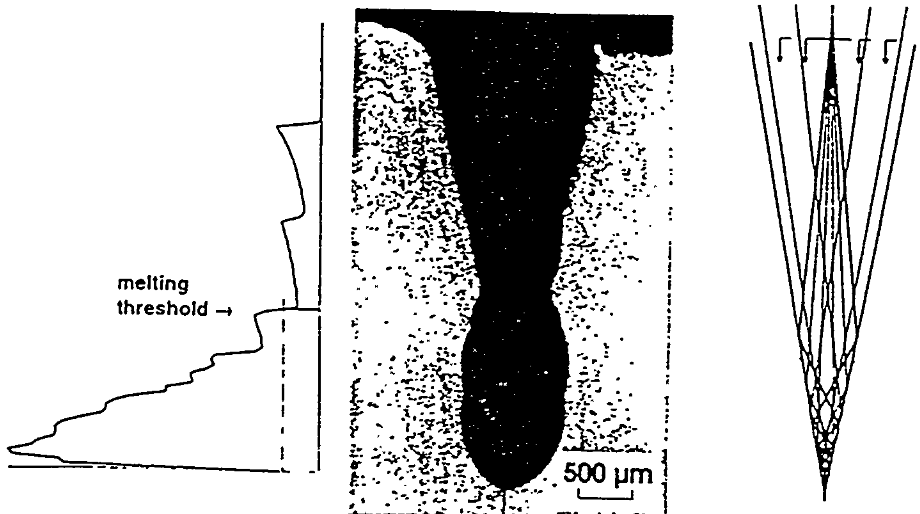

a) 1st pass in 8° included angle weld joint

b) 2nd pass in 8° included angle weld joint

**Continuous Wave Nd:YAG Laser Parameters for 304 stainless steel**

| | |
|---|---|
| laser / wave length | 2kW Nd:YAG 1.06 µm |
| travel speed | 110 cm/min |
| laser head tilt angle | 10° |
| shield gas | argon |
| joint type | ultra-narrow V-joint |
| joint width at surface | 1.0 mm |
| joint included angle | 12° sample 1, 8° sample 2 |

Figure 4. Multi-pass Autogenous Ultra-Narrow Gap Laser Weld in 304 Stainless Steel



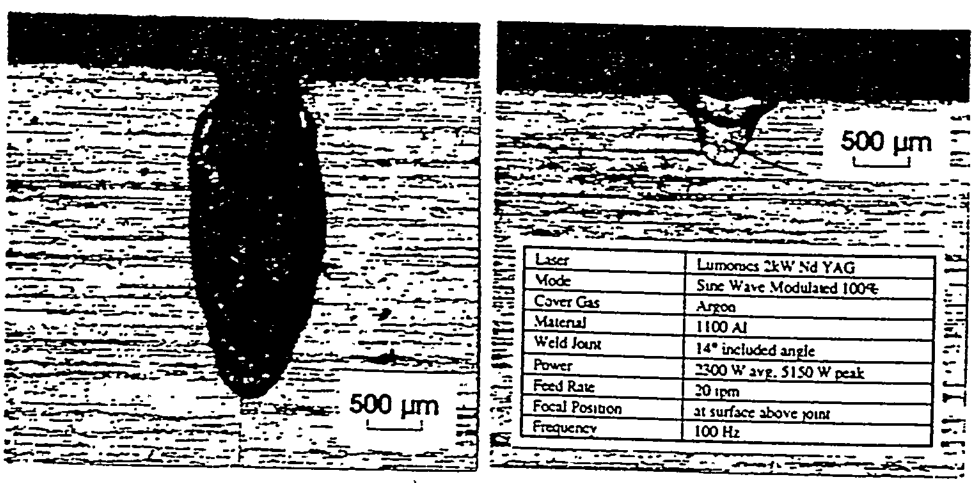

Material · 1100 Al
Laser   Lumonics Multi-Wave 2000
Laser Type : 2kW, CW, Nd:YAG
Laser Power : 2kW

Focus Point: Surface Above Joint
Focus Location · Center of Joint
Spot Size : 0.75 mm
Joint Depth : 3 mm
Joint Angle : 20° included
F# : F5

Reflectance : R=0.75
Welding Speed : 50 ipm

Surface Coupling : 25 %
Joint Coupling (Model) : 81 %

Figure 5. Comparison Between a Simulation and a Laser Weld in Aluminum




| | |
|---|---|
| Laser | Lumonics 2kW Nd YAG |
| Mode | Sine Wave Modulated 100% |
| Cover Gas | Argon |
| Material | 1100 Al |
| Weld Joint | 14° included angle |
| Power | 2300 W avg. 5150 W peak |
| Feed Rate | 20 ipm |
| Focal Position | at surface above joint |
| Frequency | 100 Hz |

Figure 6. Comparison Between a Narrow Gap Laser Weld and a Bead on Plate Weld

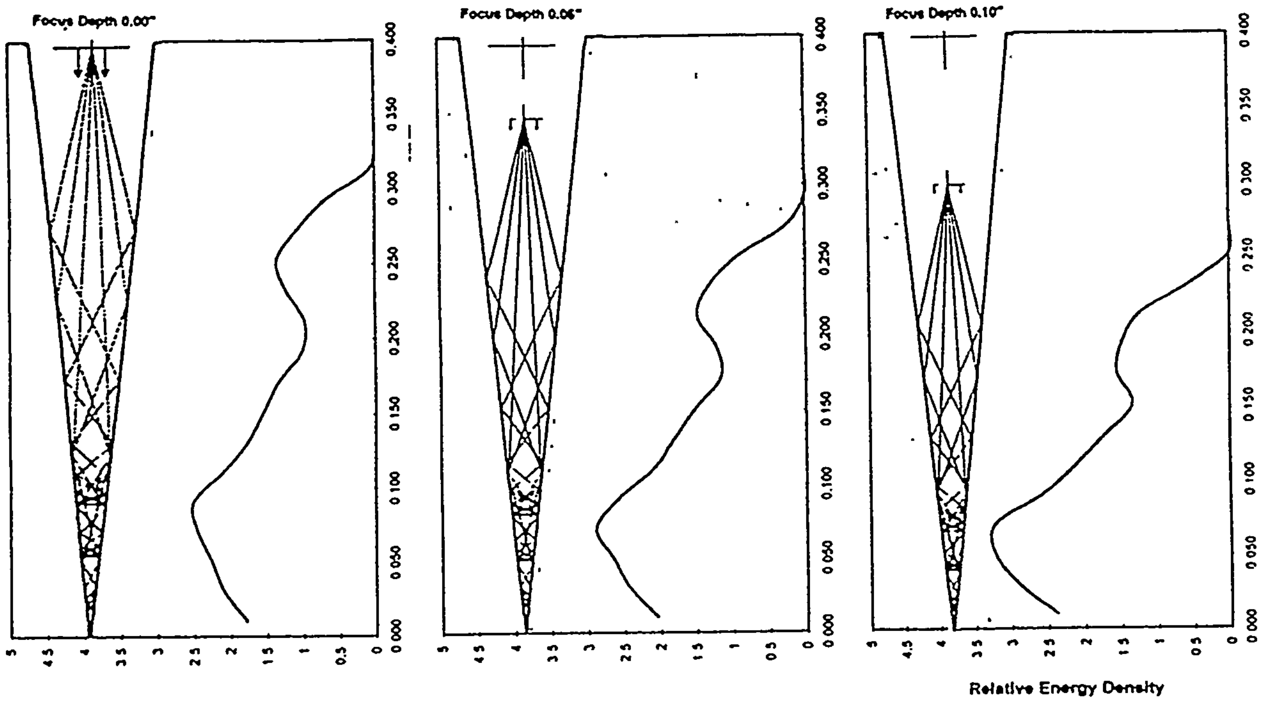



Figure 7. Focus Depth Simulation Study

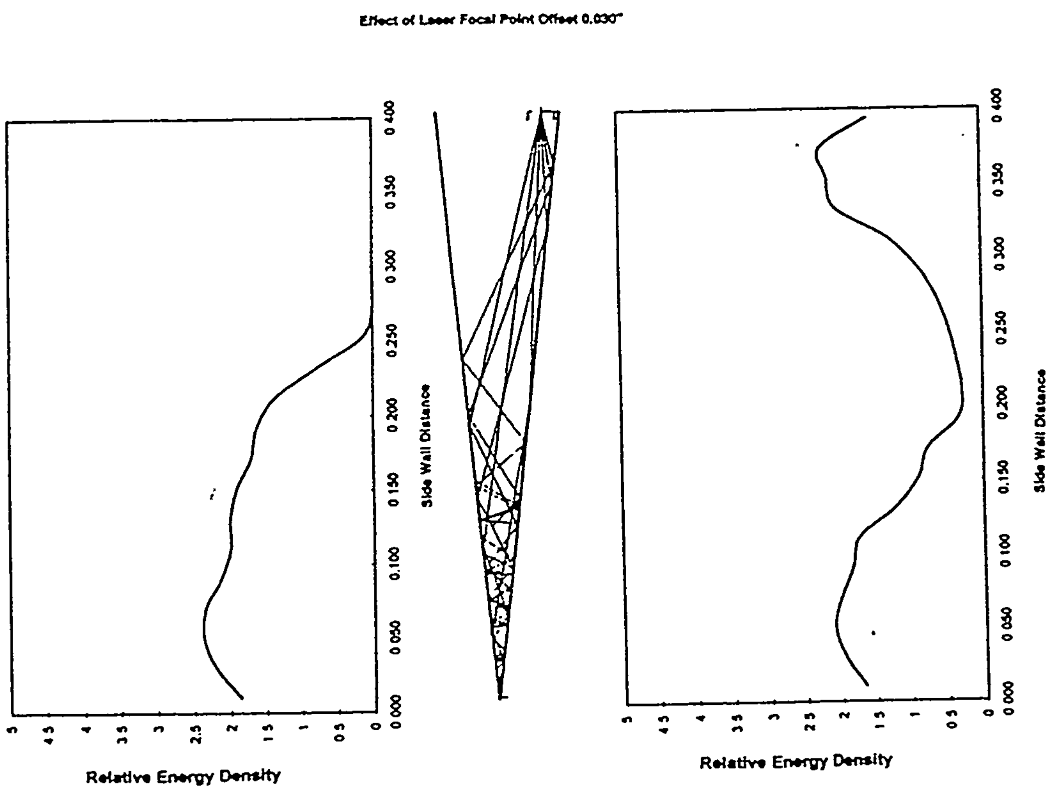



Figure 8. Focus Offset Simulation Study