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Modeling of Laser Energy Concentration in Narrow Gap Joints

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Abstract

A three dimensional, computer based, optical ray tracing model is used to simulate the combined effect of key geometric parameters for laser welding. This allows us to characterize a range of joint designs for their ability to concentrate or dissipate laser energy. The effects of angle dependent absorption and diffuse reflections on beam transport are evaluated through simulation to determine the contributions of these effects on the system. The effects of energy loss through weld joint gaps are modeled for common weld joint preparations. Practical applications of extending the optical design of the system to include the weld joint are proposed.

Introduction

The principals of non-imaging optics may be applied to the design and study of narrow gaps and weld joints for laser processing applications. Past work using a 2D geometric model has shown [1,2] that application of computer designed optical ray tracing models can predict the location of melting within narrow gap joints. Understanding the physical laws of optics governing the system and describing the geometry of the joint gap, one can predict and optimize energy trapping and melting. This is particularly useful for producing enhanced penetration laser welds without the problems of conduction or keyhole mode welding. This has been effectively demonstrated in enhanced laser welding of aluminum [3,4], a material that is highly reflective to laser light and therefore difficult to weld. Development and comparison of a three dimensional model with experiment [5] has shown good correlation between predicted melting and energy absorption and laser spot melt patterns within a narrow V groove. In this paper we describe the application and extension of the three dimensional model of the physical system to consider effects of various joint geometry and the second order effects of angle dependent absorption and light scattering.

Modeling the Optical System

The laser system is generally modeled using sequential ray tracing considering the first -order properties of imaging optics, and radiometry of classical optical systems. To the first order, each point on the source corresponds to another point on the target image with deviations described by aberration theory. Design techniques are well known for these well-defined optical trains characterized by sequential propagation of light through the system.

The weld joint however must be considered as a non-imaging optical system where light rays follow many ray paths that do not follow a prescribed or sequential order. At various surfaces light energy can be transmitted, reflected, absorbed or scattered. Polarization and coherent effects may also effect the system making the system analysis far more complex. A Monte Carlo method treats the generation of rays as a stochastic process, randomly distributing a large number of rays within the system to converge upon a solution. The OptiCAD® software program employs this method of non-sequential ray tracing integrated into a geometric CAD design environment and was used for these joint-modeling studies.

The purpose of our model is to extend the modeling of the laser optical system to include the optical conditions within the weld joint or laser processing interaction region. We design around the existing geometric and optical constraints of the system such as focal length and F-number. We then consider the effect of variables either within or beyond our control such as joint geometry or uncontrolled joint gap.

Constructing the Ray Tracing Model

We begin first by modeling the energy source at the focal point of the laser. This is accomplished by representing the laser spot as an array of point sources spatially distributed according the beam spot diameter. Each emanating ray carries a unit of energy, propagating in a direction within a solid angle described by the laser beam F-number. Many thousands of rays are traced from each point source within the geometric constraints of the model. A square matrix is used to approximate the typical top hat beam intensity profile of a fiber optically delivered Nd:YAG laser beam in this simplified model, as shown in Figure 1. Although this spatial approximation is crude, immediately near to the point sources, the structure of the energy emitted from the array is self-obscuring and adequately represents the top hat beam distribution at locations further into the weld joint. Each ray is propagated within the model until it intersects a surface at which it splits. The model is constructed to partially

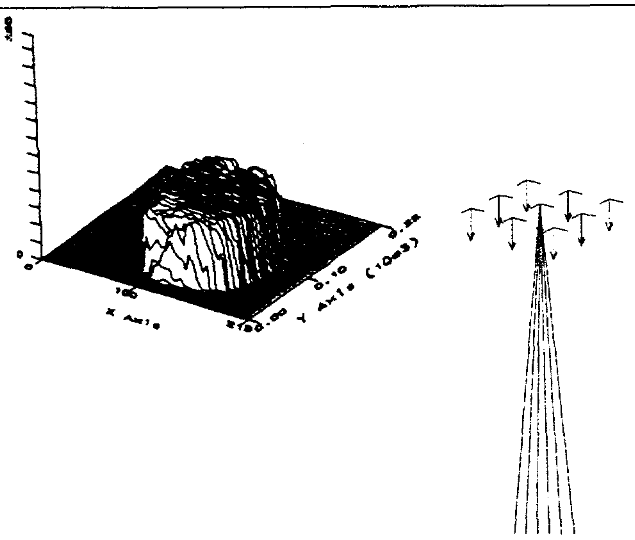

Figure 1. Representation of the top hat beam profile uses an array of point sources.

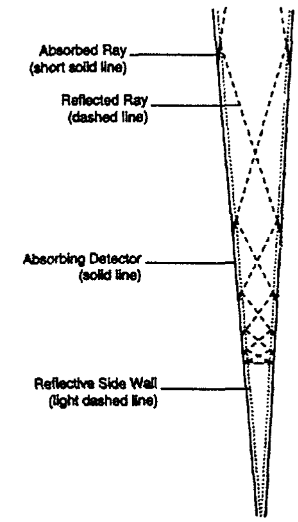

Figure 2. Ray propagation into a Vee groove showing absorption and reflection.

transmit the laser energy as a reflected ray. Another portion of the energy is carried through the surface to an absorptive detector array that records the location absorption. Figure 2 shows ray propagation, reflectance and absorption.

The three dimensional geometry of the system is then modeled to include the joint surfaces and surface properties such as reflection and absorption. Figure 3 shows a typical joint geometry with a point source tracing a few rays downward into the weld joint. Absorption is accomplished by an array of absorptive elements below the partially reflective surfaces. The location of the absorptive elements marks the location of energy deposition due to ray impingement. The absorption coefficient can be fixed or vary with the angle of incidence within the system. Ideal specular reflection may be assumed, or a scattering function may be applied to alter the path of

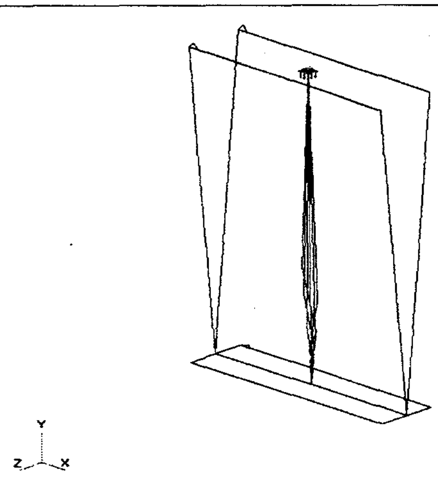

Figure 3. Tracing a few rays in the 3D model shows energy concentration in the bottom of the joint.

the reflected ray. After a ray has deposited 99% of its original energy it is eliminated from the model. After all rays have been terminated, the location of energy absorbed within the array may be plotted as in Figure 4 and evaluated according to a merit function.

Using The Ray Tracing Model

Various cases of the model can be evaluated according to some merit criteria such as energy location, distribution, peak fluence, or total energy absorbed. Concepts may then be evaluated as to the effect of changes within the free parameters of the system, such as joint gap shape. Figure 5 shows two curved surfaces with differing radii, propagating and concentrating energy beyond the line of sight of the impinging laser beam. This model case predicts the ability to laser weld around a corner. Figure 6 shows two curved opposed joint faces acting as divergent lens, spreading energy along the joint walls, thus providing a poor energy propagation and concentration condition. Evaluation of similar or widely varying concepts may be

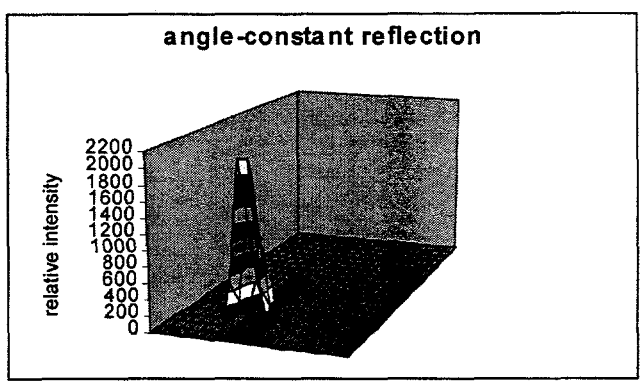

Figure 4. Plotting energy deposited by 9000 rays within the weld joint as a function of location for the left wall in Figure 3.

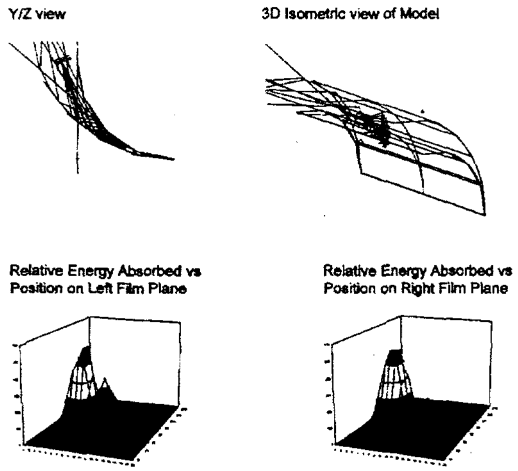

Figure 5. Energy concentration occurs beyond the line of sight using a curved joint gap.

made in simulation, which may reduce the need for expensive weld development or prototyping.

Optimizations may be rerun for a wide range of concepts and variables to optimize the desired merit criteria. Effects that degrade the system such as tilting, offset, surface roughness or scattering may be evaluated to determine the sensitivity of the system to these perturbations. Tolerance of the system to variations that degrade the system performance may be evaluated by varying the parameters or parameter interactions to check for problems in the system design. The ability to identify and avoid rapidly changing response functions and sensitive regions within the parameter space could prove useful in development of a robust process.

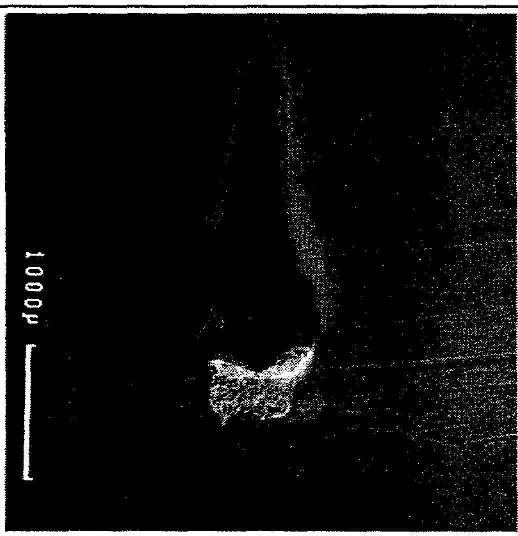

Figure 7. A joint side wall melt pattern of a single laser pulse is useful for model verification.

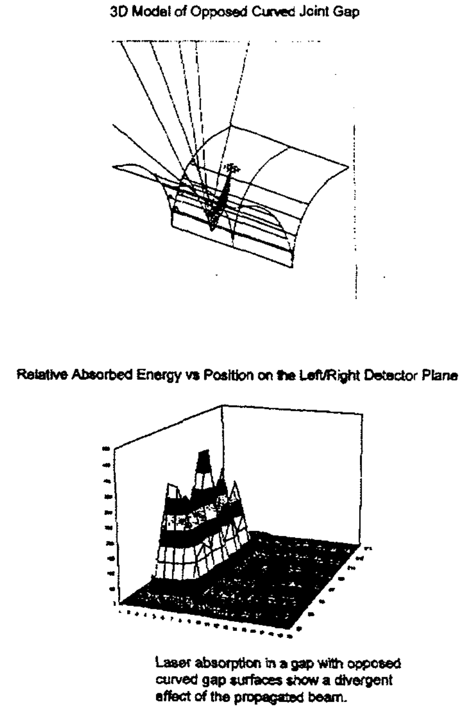

Figure 6. Opposing curves within a joint gap act as divergent reflectors.

Verifying the Ray Tracing Model

Weld development using prototypical weld joint designs can prove useful in calibrating the model with respect to the predicted location and intensity of energy deposition and actual melt regions determined by experiment. Although, many optical effects such as polarization and temperature dependent absorption are not considered, preliminary experiments have shown a good correlation between actual welds and the first principals effects considered in this model [1-5]. Figure 7 shows a melted region along a joint side wall. The predicted shape of the melted region as determined by simulation is shown in plot of energy vs. location as derived from simulation as shown in Figure 4. It corresponds well to that of the actual side wall melt region.

Enhancements To The Narrow Gap Model

The secondary effects of scattering and angle dependent absorption were incorporated into the model to evaluate the effects these functions had on the manner in which energy propagated within a narrow gap Vee joint.

OptiCAD® models scattering (diffuse surfaces) based on a probabilistic change in the direction of the specular (unscattered) ray. The Bi-directional Scattering Distribution Function (BSDF) is therefore treated as a probability density function, in direction cosine space. The ray–trace procedure is as follows:

1. The direction of the ray(s) leaving a surface (by either reflection or refraction or both) is calculated.

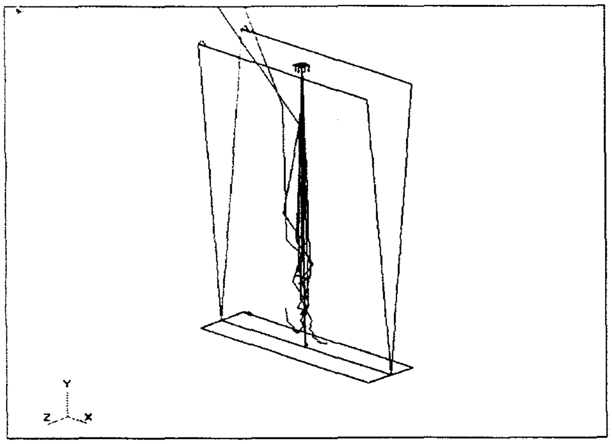

Figure 8. A Gaussian scattering function is applied to the reflected rays within the model.

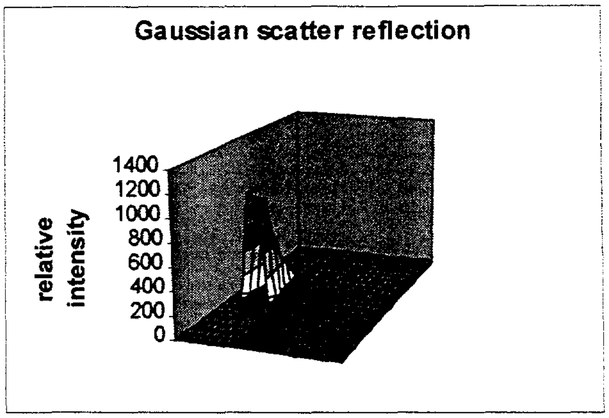

Figure 9. Scattering of reflected rays reduces peak energy concentration with little effect on location.

2. Based on a user selected fraction of the energy scattered (actually the probability that a single ray is scattered) the ray is either scattered or unchanged.
3. If the ray is to be scattered, a new direction is determined based on a weighted random number, using a probability density function centered about the specular ray in direction cosine space.

In addition to choosing a fraction scattered, a scattering function and its parameters are chosen. The reflected rays will be operated on by the same scattering function having the same parameters. OptiCAD® has four types of scattering functions: a rotationally symmetric Gaussian distribution, a Lambertian surface, an x-y exponential distribution, and a power law distribution. In these trails we evaluated the effect of Gaussian and Lambertian scattering functions.

The Rotationally Symmetric Gaussian Scattering function has the form

$$f_{l,m}(l,m) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{r^2}{2\sigma^2}}$$

where

$$l = l_{scattered} - l_{specular}$$

and

$$m = m_{scattered} - m_{specular}$$

and

$$r = \sqrt{l^2 + m^2}$$

are all direction cosines with respect to the x and y axes, and σ is the standard deviation of the rotationally symmetric Gaussian scattering distribution.

The model and weld data presented in Figure 3 and four for the angle-constant reflection case was used as the baseline case for comparing the effect of the various scattering function simulations on the predicted shape of the energy deposition location. Various values for the percent scattered and percent deviation of the Gaussian function were evaluated. An ideal Lambertian scattering surface was also modeled. Figure 8 shows a deviation in the path of a few rays traced into a Veee joint, simulating the application of a Gaussian scattering function in which 100 percent of the rays traced had a probability of being scattered. A sigma value of 0.1 was used in this simulation. The location of energy absorption within the model for this case case is shown in Figure 9. Compared to the unscattered case plotted in Figure 4., lower peak energy was observed in the weld joint root. The results of increased scatter failed to significantly change the shape of the deposited energy intensity. This function, in effect, diffused the energy deposited and lowered the peak energy prediction. Iso-intensity contours remained about the same shape, corresponding to the shape of the melt region in Figure 5.

Taken to an extreme, a sigma value of 2 would, in effect, create a Lambertian surface, scattering and diffusing away all but the energy deposited from the direct ray impingement. This diffused away the effect of reflected ray impingement, absorption and concentration. Running the case of a Lambertian surface diffusion did indeed confirm this bounding case.

The effect of angle dependent surface reflection was investigated using a Fresnel metal reflection function and a long wavelength, IR energy, angle dependent function. These were modeled using the complex index of refraction for aluminum for Nd:YAG laser energy and a function for long wavelength angle dependent reflection given in [5]. Figures 10 shows the energy trace assuming a Fresnel metal surface. It can be seen the energy peak is reduced in intensity and the peak energy location is only slightly altered from that of the baseline case of Figure 4. Figure 11 shows the application of angle dependent reflection most often applied to lower wavelength laser light such as would be the case for CO_2 laser welding. Little reduction of peak intensity was observed while a noticeable shift in the energy peak toward the joint root was observed.

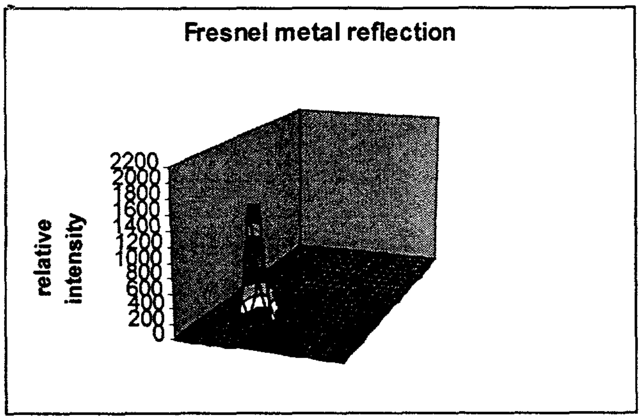

Figure 10. Fresnel metal reflection considered within the model reduces peak energy as shown in simulation.

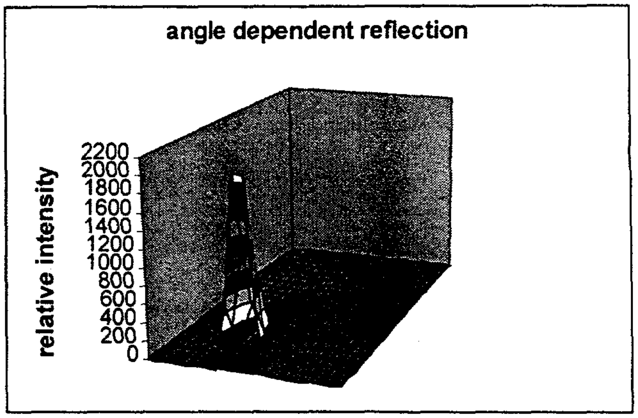

Figure 11. Angle dependent reflections concentrate more of the laser energy within the root of the joint.

Discussion

The results obtained from considering scattering and angle dependent absorption of ray energy provided a qualitative appreciation of these effects on the location of melting and energy absorption. Past experiments showed a good correlation between predicted and actual melting without considering these secondary effects. Inclusion of these effects within the model did little to improve the fit between the enhanced model and previous experimental data.

While the predicted location of energy absorption does not always correlate to the location of melting, it would be the logical input to common thermal analysis heat flow codes. Future work will link the output of this energy absorption model to heat flow and melting models using other software.

Calorimetric experiments would be useful to verify energy absorption predictions and calibrate them using actual welds. The precise functions for angle dependent absorption and scattering were not known and would have to be characterized for each material and surface type by experimentation. The diffuse function for typical RMS surface roughness values has been reported in the open literature and will be included in future work.

The XY exponential scattering function may be useful in modeling surface with non-uniform scattering characteristics such as surfaces grooved or disturbed by machining. The changes in scattering characteristics of a surface upon heating may not be easily characterized, but are considered a higher order effect contributing only a secondary effect to the solution of this problem.

Practical applications of the model could include optimization of joint designs utilizing narrow gaps for tailored blank welding of dissimilar thickness materials and laser enhanced tube and pipe welding. Other applications of non-imaging laser energy concentration may include in-position laser brazing and soldering devices.

Conclusions

The first order effects of laser beam geometry, weld joint geometry and specular reflection provide qualitative understanding of the location of energy absorption and to a lesser degree melting within a narrow joint gap. Quantitative understanding of the effect of changes to geometry of the laser or weld joint can be obtained. The predicted location of melting with experiment compared well with laser spot welds in a narrow stainless steel Vee joint gap. Functions representing angle dependent absorption and scattering may be applied to the model, but without detailed understanding of these effects, derived through experimentation, the results may only be used to identify gross effects. The simplified model based on the effects of well understood first order optical principals can serve as the radiation transfer input to thermal analysis problem simulation.

Acknowledgments

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