Weld Procedure Development with OSLW — Optimization Software for Laser Welding

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Abstract

Weld procedure development can require extensive experimentation, in-depth process knowledge, and is further complicated by the fact that there are often multiple sets of parameters that will meet the weld requirements. Choosing among these multiple weld procedures can be hastened with computer models that find parameters to meet selected weld dimensional requirements while simultaneously optimizing important figures of merit. Software is described that performs this task for CO_2 laser beam welding. The models are based on dimensionless parameter correlations that are derived from solutions to the moving heat source equations. The use of both handbook and empirically verified thermophysical property values allows OSLW to be extended to many different materials. Graphics displays show the resulting solution on contour plots that can be used to further probe the model. The important figures of merit for laser beam welding are energy transfer efficiency and melting efficiency. The application enables the user to input desired weld shape dimensions, select the material to be welded, and to constrain the search problem to meet the application requirements. Successful testing of the software at a laser welding fabricator has validated this tool for weld procedure development.

Introduction

Finding the best automated welding parameters to achieve a specific weld size on a new material is usually an expensive and time consuming task. To determine a weld procedure in a logical manner, one must consider many competing factors including productivity, thermal input, defect formation, and process robustness. The tradeoffs between these factors can be substantial as well as hard to quantify. For example, we might expect that process robustness is inversely proportional to productivity, but in fact, the result depends on the defect we are concerned with. Humping and undercut are defects that occur primarily at high feedrates, however thermal damage and base metal distortion are deficiencies that are reduced at high feedrates. The development problem is complicated by the fact that there are often multiple sets of parameters that will meet the weld size requirements. Identifying the preferred set of parameters for an application can require extensive experimentation and keen process insight.

Choosing among numerous weld procedures can be hastened with computer models that find parameters to meet selected weld dimensional requirements while simultaneously optimizing important figures of merit. Two fundamental figures of merit for fusion welding processes are the energy transfer efficiency and the melting efficiency. Energy transfer efficiency indicates what fraction of the energy incident on the workpiece is actually absorbed by the metal. Melting efficiency quantifies the fraction of net heat input to the workpiece that is used to produce melting rather than unnecessary heating of the metal that can lead to thermal damage and distortion. Other figures of merit which we may wish to consider are the physical extent of the heat affected zone or the fusion zone size tolerance to a changing base metal temperature. Desktop computer models to quantify these and other figures of merit for the numerous welding processes in use today present a formidable task that has only recently been undertaken. (Ref. 1,2,3)

For laser beam welding, a dimensionless parameter model (Ref. 4) has been shown to be effective in relating melting to power, speed, and the material thermophysical properties. By combining this thermodynamic based relationship with additional correlations for penetration depth, weld shape, spot size, and energy transfer efficiency, a computer model of the continuous wave CO_2 laser welding process has been developed called OSLW (Optimization Software for Laser Welding). The application is written in MATLAB*, which provides integrated numerical computation, graphics, and a graphical user interface. A description of the construction of OSLW, features of the graphical user interface, and example problems will be presented.

The Model

Usually, analytical weld models require the weld procedure parameters to be input in the problem statement, the model then calculates the weld dimensions and other material responses such as temperature. OSLW solves the more universal engineering

* The MathWorks, Inc. Natick, MA 01760-1500

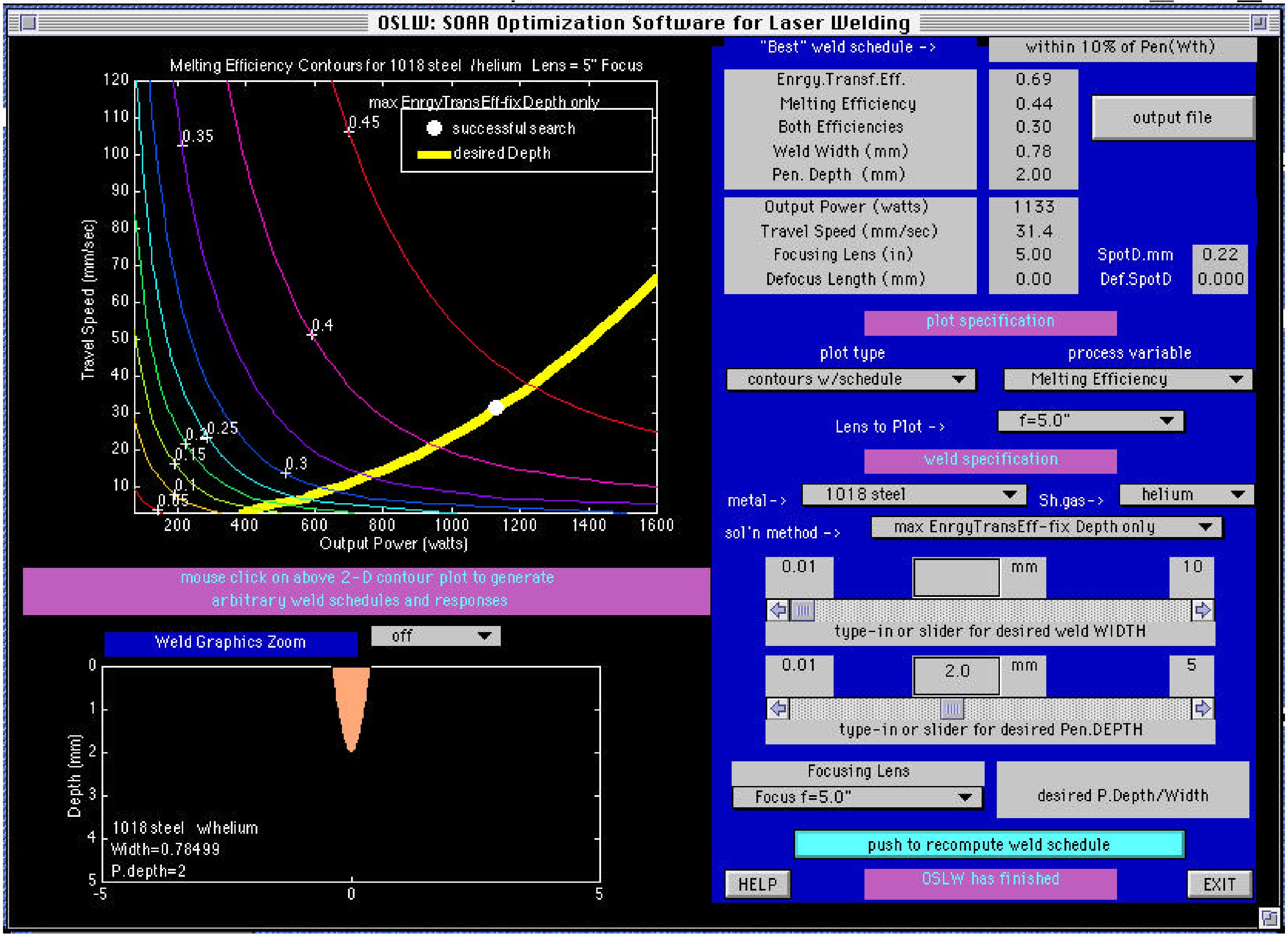


Fig.1 — The graphical user interface for OSLW.

problem where the user needs to find the weld procedure parameters to obtain already specified weld dimensions on a particular material. In this inverse problem, the responses become the weld penetration depth, P, the weld width, W, and the figures of merit, energy transfer efficiency, η_t, and melting efficiency, η_m. Depending on the user specified requirements for these responses, a distinct set of possible weld procedures will be analyzed in the optimization. In other words, the degree of complexity in the problem statement will constrain the optimization to a more or less confined region of possible solutions.

The response model is given by the following set of equations:

$$P = \frac{c_1\, a\, q_0}{u^{c_2}\, d^{c_3}} \qquad [1]$$

$$h_t = c_4 - c_5 e^{\left|\frac{\Pi}{2\,\mathrm{atan}(c_6 d / P)}\right|} \qquad [2]$$

$$h_t = c_7 - c_8 e^{\left[\frac{-Ry}{c_7}\right]} + c_9 e^{\left[\frac{-Ry}{c_{11}}\right]} \qquad [3]$$

$$Ry = \frac{h_t\, q_o\, u}{a^2\, dh} \qquad [4]$$

$$A = \frac{Ry\ h_m a^2}{u^2} \qquad [5]$$

$$W = \frac{3A}{2P} \qquad [6]$$

Where α is the thermal diffusivity, q_o is the laser output power, υ is the travel speed, *d* is the laser spot diameter, *Ry* is a dimensionless parameter, *dh* is the enthalpy of melting, and *A* is the weld cross-sectional area. Numerical constants, c_i, are those found via least squares fitting of the above equations to experimental data presented in Ref. 4. The six equations are given in simplified form and are, of course, interrelated.

The utility and robustness of the model is primarily due to the heat conduction based weld size correlation. Weld cross-sectional area of the fusion zone is calculated by substituting [5] into [3]. Equation [3] is a dimensionless parameter correlation (Ref. 4) derived from the moving heat source solution to the conduction heat flow equation, as such, it is thermodynamically based and extensible to other materials and conditions outside the empirical set. The correlation between laser output power and net power absorbed by the workpiece is modeled by [2], and is based on Fresnel absorption (Ref. 5) by way of multiple internal reflections in the keyhole. The depth of penetration equation [1] is essentially an empirical correlation and simply relates laser keyhole depth to beam intensity and travel speed. Penetration depth is correlated with cross-sectional area [6] by a simple but quite realistic parabolic shape approximation.

Optimization Problem

Given the parameterized model equations shown above, a genetic algorithm optimization method is used in consort with either a gradient-based optimization scheme or a non-linear algebraic solver to find the weld procedure parameters. The exact solution method depends on the problem formulation specified by the user.

The basis of our optimization effort is to climb to the highest figure of merit (i.e. efficiency) which will simultaneously yield a solution to satisfy the width and depth constraints. In the genetic algorithm (GA), the width and depth constraints were attached as a quadratic penalty function onto the performance metric to form a composite metric. The GA treats all values of qo, υ, d as discrete, makes up various combinations of them (members of the population), and evaluates the composite metric according to the response model. It then chooses the highest value after a designated number of population or "generation" changes.

The optimization space can be discontinuous for problems where the laser spot diameter is a discrete variable. Such is the case when a user specifies an exact focal length lens. Since gradient schemes necessitate continuous parameters it was necessary to reformulate the discrete optimization problem as a continuous one. The OSLW model distinguishes the following two types of problems:

1. *Both width and depth are specified*: For each value of d, solve for the q_o, u combination that algebraically solves the constraint equations $W\ desired - W(qo,u,d)=0$ and $P\ desired - P(qo,u,d)=0$. Since d is known, this reduces to solving two nonlinear algebraic equations in two unknowns. Then, sort the solutions that produce acceptably small residuals in the constraint equations to find the desired maximum according to the efficiency criterion chosen. This was accomplished using a Newton-type solution algorithm.

2. *Penetration depth only specified*: For each value of d, solve for the q_o, u combination that maximizes the efficiency criterion chosen subject to: $P\ desired - P(qo,u,d)=0$. This was accomplished using a MATLAB routine to do nonlinear programming. Then sort the solutions that produce acceptably small residuals in the single constraint to find the desired maximum according to whichever "efficiency" criterion was chosen.

Graphical User Interface

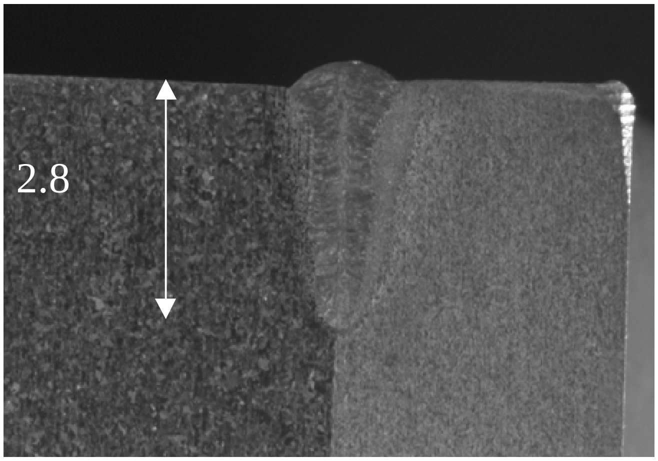
Welding technologists can readily apply the model and perform "What if" like analyses through the use of the graphical user interface (GUI). The GUI panel shown in Fig. 1, displays both the user input and model output information. In the weld specification section, the user can select the metal to be welded, the desired weld penetration depth, and the width if there is a preference. The user also specifies if there is a preferred lens focal length and whether argon or helium shielding gas will be used. The choice of solution method allows the user to optimize for specific weld pool dimensions, low heat input, or high beam absorption in any of seven combinations. Execution time is usually less than 15 seconds. The weld graphics window displays the pool shape and allows the user to adjust the weld pool dimensions interactively to meet the requirements of the weld joint.

The plot specification window enables the user to select the process response variable to be displayed on the speed vs. power contour or surface plot. One can also select the focusing lens to be plotted in this window. The result of optimization is shown as a bright point on the contour plot along the bold line that represents the desired weld penetration depth. The contour plot window is especially useful in allowing one to see the effects of changes in power and speed on the weld dimensions and the efficiencies. As the user clicks the cursor in the contour field, the weld pool shape is immediately updated, and the numerical values of the responses for that condition are displayed in a box below the graph. By moving the cursor around the contour plot, the user can readily visualize the dramatic effects of changes in the laser weld process variables.

In the "Best" weld procedure window, OSLW lists the results of the optimization run. The weld procedure solution details the laser power, the travel speed, and the laser spot diameter needed to meet the selected requirements. Also listed here are the values of the energy transfer efficiency and the melting efficiency. In some instances there may not be an exact solution given the constraints of the problem statement. OSLW will then output a procedure that is as close as possible to the penetration and depth requirements but will flag the procedure if it is not within 10%. In these instances it is advisable to relax the problem statement constraints somewhat in order to expand the region of possible solutions.

Example Applications

Early beta testing of OSLW has been ongoing at the Naval Air Warfare Center (NAWC) in China Lake, California. The welding fabrication shop there does prototype weld procedure development and small lot production welding on a wide variety of aerospace hardware. Deep penetration and low heat input requirements often necessitate the use of laser welding. NAWC uses a Rofin Sinar fast axial flow CO_2 laser for many of these applications. NAWC has had good success using OSLW for



weld procedure development even though the software was written using models developed with a lower power Photon Sources slow flow CO_2 laser.

Fig. 2 — Cross-section of CO_2 laser welded assembly, weld procedure parameters developed with OSLW.

OSLW proved to be especially useful for laser welding of Sidewinder missile training warheads at NAWC. The assembly drawings specified that manual gas tungsten arc welding be used to weld the 500 assemblies. Laser welding was favored to reduce the fabrication time and to minimize distortion. To meet these goals and to increase weld quality, the constraint problem specified minimal heat input with 2.8 mm penetration depth. OSLW suggested 1440 watts at 28.4 mm/s with a f = 5 in. lens. The resulting optimization predicted a very high melting efficiency of 0.45 with an energy transfer efficiency of 0.78. Laser weld procedure optimization with OSLW yielded an ideal weld procedure on the first assembly without any costly trial and error development trials. The resulting weld is given in Fig. 2. It was estimated that 30 minutes would be required to manual weld each assembly. Laser welding of the assembly took less than 10 minutes. Moreover, inspection of the finished assemblies showed less than 0.002 in. positional error.

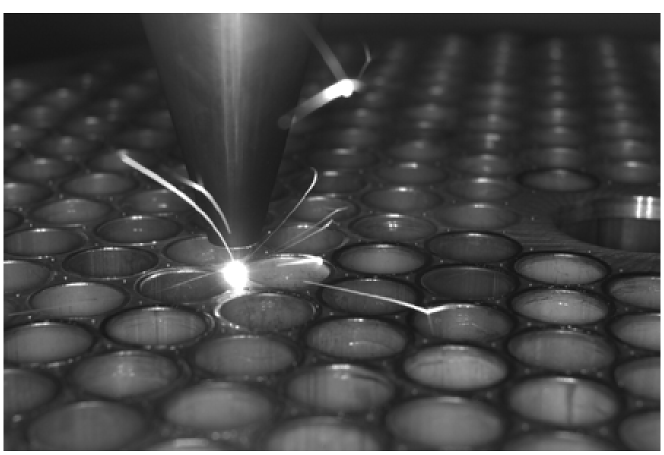


Fig. 3 — CO2 laser welding of 1 in diameter tubes into pressure vessel tubesheet.

In another application at NAWC, OSLW was used for weld procedure development on a rocket motor nozzle test device. The pressure vessel (see Fig. 3) required the assembly of 372 tubes, 1.0 in. diameter by 0.065 in wall thickness into a 0.25 in tubesheet. The small 0.050 in. spacing between the tubes required a deep and narrow weld with minimal distortion. Substantial distortion could result on the one of a kind unit if the laser weld procedure parameters were not chosen correctly. OSLW recommended 1300 watts at 29 mm/s to meet the penetration depth of 2.4 mm required. The resulting melting efficiency of 0.44 was sufficient to keep distortion to a minimum. Proper selection of weld procedure parameters was critical in welding the assembly without prior weld development efforts.

Summary

The above examples illustrate the utility of easy to use analytical models for weld procedure development. Continued development by other researchers will hopefully yield similar models for many other welding processes. As the models evolve, better optimization strategies may result in even more robust weld procedure parameters. It is expected that users of this type software will increase as the advantages of model based weld procedure selection are realized. Someday, weld procedure development for automated processes utilizing software such as OSLW will be commonplace.

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