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SOAR: Smartweld Optimization and Analysis Routines

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SOAR: Smartweld Optimization and Analysis Routines

An Extensible Suite of Codes for Weld Analysis and Optimal Weld Schedules

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Abstract

A suite of MATLAB-based code modules has been developed to provide optimal weld schedules, regulating weld process parameters for CO_2 and pulse Nd:YAG laser welding methods, and arc welding in support of the Smartweld manufacturing initiative. The optimization methodology consists of mixed genetic and gradient-based algorithms to query semi-empirical, nonlinear algebraic models. The optimization output provides heat-input-efficient welds for user-specified weld dimensions. User querying of all weld models is available to examine sub-optimal schedules. In addition, a heat conduction equation solver for 2-D heat flow is available to provide the user with an additional check of weld thermal effects. The inclusion of thermodynamic properties allows the extension of the empirical models to include materials other than those tested. All solution methods are provided with graphical user interfaces and display pertinent results in two and three-dimensional form. The code architecture provides an extensible framework to add an arbitrary number of modules.

Acknowledgment

The authors wish to thank Kim Mahin, Dept. 1807, for her continued support of this work.

Summary

Four MATLAB-based software applications have been developed to do weld analysis and provide optimal weld schedules for several common welding processes at Sandia National Laboratories in support of the Smartweld manufacturing initiative. The thrust of this effort has been to provide model-based tools for the welding engineer.

The weld models for the three methods have been derived from known thermodynamic relations and extended via numerical fitting methods to encompass experimental data. These *input-response* models were constructed such that input weld schedules (consisting of input energy, part travel speed, and laser lens size) were related in a nonlinear algebraic fashion to responses consisting of efficiency metrics and weld cross-sectional dimensions. Optimization "wrappers" were constructed to iteratively query (or "invert") the model in search of weld schedules that maximized (or minimized) these metrics, while simultaneously producing welds of a specified size. The optimization methodology consisted of mixed genetic and gradient-based algorithms. Genetic algorithms were used to survey the possible solution "space" and provide a good initial guess from which a gradient-based optimization or nonlinear, algebraic solution scheme could proceed toward a "tight" convergence on a final weld schedule.

User querying of all weld models is available to examine sub-optimal schedules. This provides the analyst with the flexibility to choose an alternative, if it is felt that recommended conditions are not practical in terms of energy or travel speed to obtain optimal weld efficiency. The inclusion of thermodynamic properties allows the extension of the empirical models to include materials other than those originally tested. All solution applications are provided with graphical user interfaces to show or input:

- Best results and an accuracy measure
- Plot Specifications (plot type, plot variable, corresponding lens)
- Material of interest
- Optimization problem (efficiency or heat transfer metric) and user-input cross sectional depth-width specifications
- Code operational status
- Text help information

Graphics displays show all response variables in two (2-D) contour and three-dimensional (3-D) surface form. The laser applications also display weld depth-width regimes which correspond to feasible weld schedules.

In contrast to the "weld schedulers", a steady-state, heat-conduction equation solver for 2-D heat flow is available to provide the user with an additional check of weld thermal effects. Results from this application show steady-state temperature contours in 2-D graphical form and tabulate the individual contour dimensional information.

The overall code architecture provides an extensible framework to add an arbitrary number of these applications modules.

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Nomenclature

A	Weld cross-sectional area, mm^2
Ch	Christensen parameter, dimensionless
K_o	zeroth-order Bessel Function
P	weld penetration depth, mm
Q	input energy, joules
Ry	Rykalin parameter, dimensionless
T	temperature, ^oC
T_o	base metal temperature, ^oC
W	weld pool top width, mm
c_i	least squares fit constant
d	laser spot diameter, cm
f	lens focal length, cm
k_s	thermal conductivity, Joules/(m-sec-^oC)
q_o	laser output power, watts
q_p	peak power for YAG lasing, watts
r	distance from weld source to temperature contour
t	plate thickness, mm
x,y	coordinate directions for 2-D heat flow
α	thermal diffusivity, mm^2/sec
δh	enthalpy of melting, Joules/mm^3
ν	YAG pulse frequency, Hz
τ	YAG pulse duration, msec
η_t	Energy Transfer Efficiency, dimensionless
η_m	Melting Efficiency, dimensionless
υ	part travel speed, mm/sec

Superscripts

'	scaled value, dimensionless

Subscripts

desired	user-specified
max	maximum value
min	minimum value

Abbreviations

GUI	graphical user interface
WS	weld schedule (q_o,υ,d), (q_o, υ), or (q_p, Q, f)
2-D, 3-D	two, three dimensional

Units

cm	centimeters

Hz	Hertz (cycles per sec)
in	inches
mm	millimeters
msec	mm/second
sec	seconds

SOAR: Smartweld Optimization and Analysis Routines

An Extensible Suite of Codes for Weld Analysis and Optimal Weld Schedules

Introduction

This report summarizes the development of a set of MATLAB-based computer codes to aid the weld engineer. This set has been developed in conjunction with the Smartweld manufacturing initiative. The contents cover solution methods to generate optimal weld schedules for:

- CO_2 laser welding
- Plasma or gas-tungsten arc welding
- Pulse Nd:YAG laser welding

For these applications, weld schedules represent the constant-value settings on the device for output power (q_o) or energy delivered (Q), part travel speed (υ), and in the laser-device cases the focusing lens size (f). In addition a fourth application has been written to provide graphical solutions to a two-dimensional (2-D) steady-state, heat conduction equation. Results of the constant-value weld solutions provided by the "scheduling" applications can be entered into this application (dubbed ISO) to provide the engineer with a geometric check of weld thermal effects.

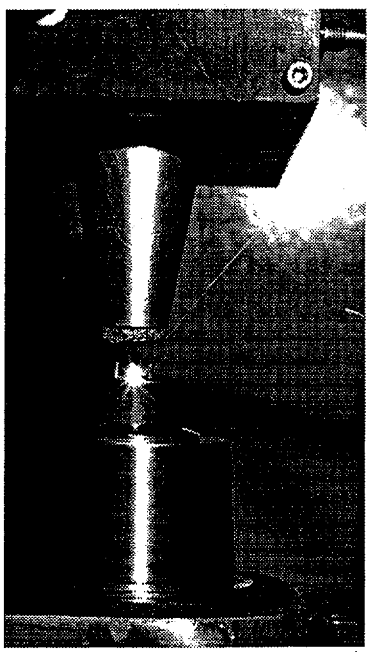

Figure 1. CO_2 Laser weld in progress

Since an important goal of the Smartweld program is model-based design, it was felt that more software tools were necessary to make the specialized knowledge more accessible to the weld community. An application for CO_2 laser welding [1] was an initial foray into this area. Based on models furnished by given in [2], additional weld schedule applications were able to be brought on-line. All have implemented the following basic approach:

1. Formulate a semi-empirical, input-response model of the weld process. (A conceptual model is shown in Fig.2) These may consist of pure polynomial fits of experimental data, or may be parameterized extensions of relations developed in the literature to better fit experimental data. Model expansions to other than the experimentally-tested materials is accomplished via the embedding of thermodynamic properties within the model. The use of numerical scaling may be relied upon to achieve better data fits.

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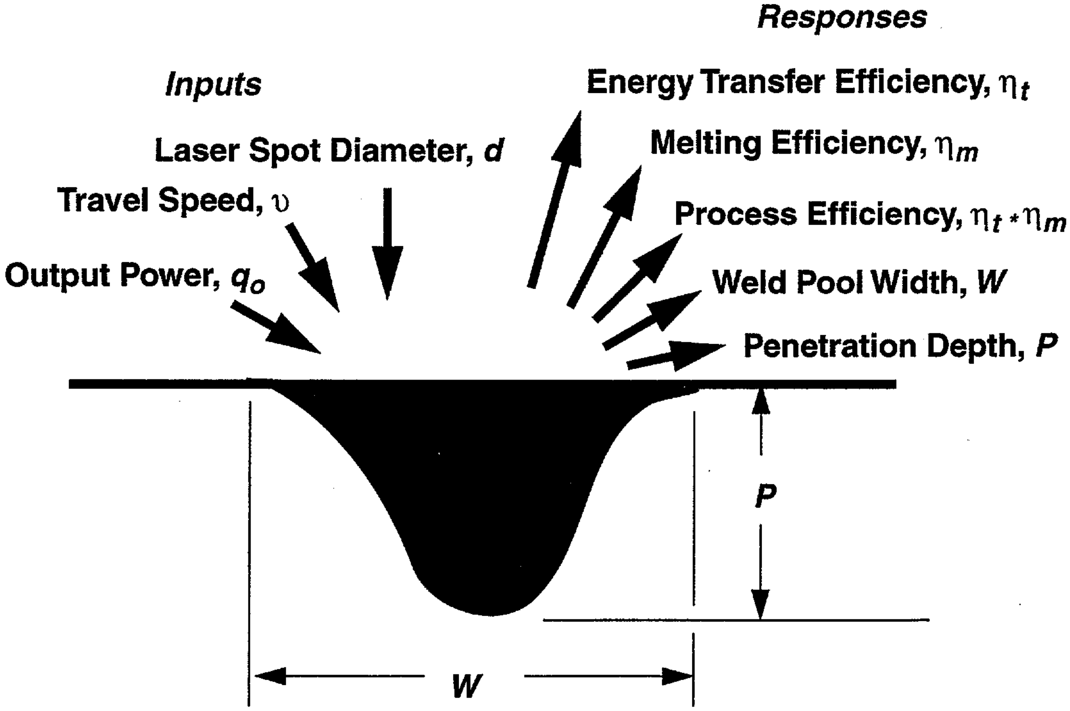

Figure 2. The Input-Response Model for CO_2 Laser Welding

2. Use a combination of genetic and gradient-based optimization algorithms to *invert* the model by solving for the inputs to provide an "optimal" response. A surface of possible responses for a "grid" of inputs is shown in Fig.3. Typically, the optimal solution is one that *maximizes* an efficiency metric (i.e., Melting Efficiency, which can also be interpreted as *minimizing* heat input), while simultaneously yielding a weld of given depth/width dimensions.

   The use of a mix of optimization algorithms stems from the fact that genetic-based methods can survey a wide range of solution possibilities efficiently, and are thus better disposed towards finding the most promising region in the solution space from which a gradient-based scheme can converge quickly to the final optimal solution.

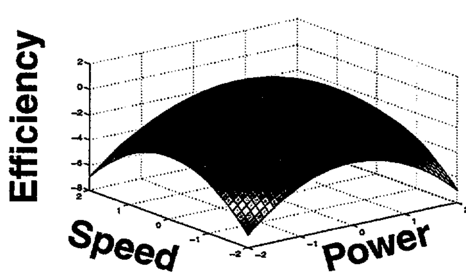

Figure 3. A Weld Response Surface

   The use of numerical scaling aids the searching algorithms when various quantities are disparate in magnitude.

3. Provide 2-D and three-dimensional (3-D) presentations of this output (Fig.4) in a manner that allows the weld engineer to assess how this type of solution, which may

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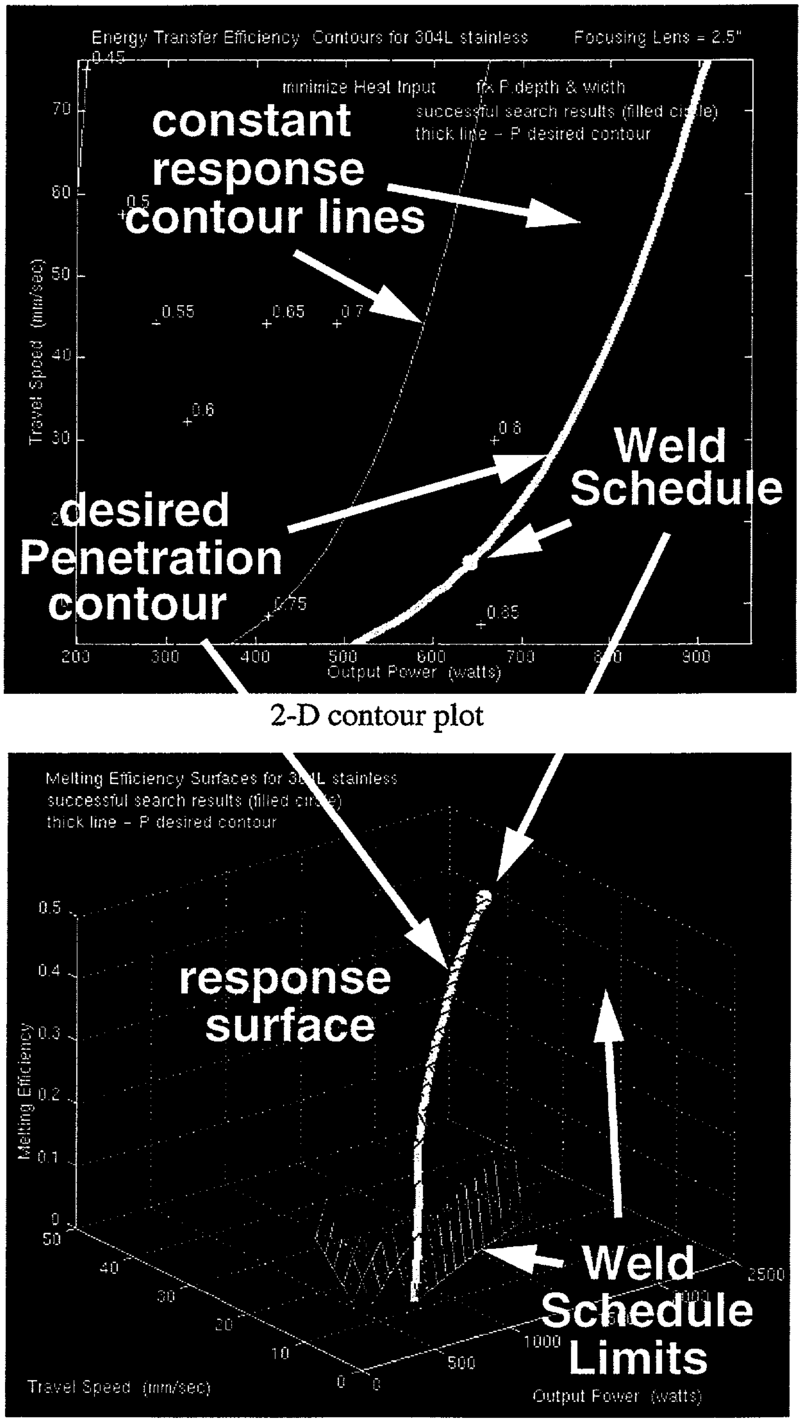
not be intuitive, fits in with qualitative metrics such as weld appearance, past experience, and equipment capability.



2-D contour plot

3-D surface plot

Figure 4. Analysis graphics available in weld scheduler applications

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All applications were written in MATLAB [3] which provides integrated “number-crunching”, graphics, and graphical-user-interface (GUI) routines. The applications were separately launched from the SOUP “executive” control panel in Fig.5. The architecture of this panel allows the addition of an arbitrary number of analysis modules to cover future needs. The applications will be covered in the ensuing sections.

To access this panel:

1.Enter MATLAB

2.Type: **`soar`** (lower case) at the command prompt

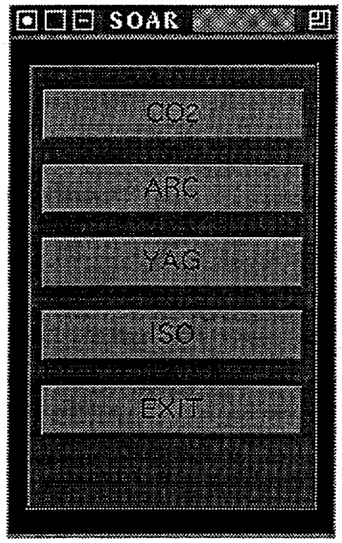


Figure 5. The SOUP Executive Control Panel

The *CO2* Application

This application was the first developed and is explained in detail in [1]. It will be summarized briefly here. For this study, the desired response characteristics are concerned with heat input efficiency on a given metal, while attaining a user-specified weld geometry. Weld schedules consist of constant values over a given weld for:

1. laser output power (q_o) in watts,
2. part travel speed (υ) in millimeters(mm)/second(sec), and
3. laser focusing lens focal length characterized by spot diameter (d) in centimeters (cm).

In the context of laser welding, q_o and υ can be considered to vary continuously over a given range. However, spot diameter, d, corresponds to only a select few *discrete* lens focal lengths. It was decided to model 4 output *responses* or *process variables* as functions of the weld schedule (WS) parameters, q_o, υ, and d. These quantities were:

1. energy transfer efficiency (η_t, dimensionless), defined as the ratio of net heat input to the part to the incident energy produced by the power source.
2. melting efficiency (η_m, dimensionless), defined as the ratio of the amount of heat required to just melt the fusion zone to the net heat input deposited in the part. Slow travel speeds usually encountered in manual welding operations result in low melting efficiency.
3. top width of the weld (W, mm). Area of the weld is used for the thermodynamic calculation and a parabolic, weld shape approximation was used to map area to width.
4. weld penetration depth, (P, mm).

For CO_2 laser welding, the weld schedule (WS) implies the triple, q_o, υ, d. The method proposed for generating optimal weld schedules required a parameterized, algebraic model to relate the WS to the responses, η_t, η_m, W and P. Experimental input-response data for 126 different welds for the 304 stainless steel, 1018 steel, and tin were fit with a nonlinear least- squares algorithm. The parameters in the algebraic model were computed to minimize the sum of the squares of the errors (i.e., the least-squares fit) between experimental responses (η_{ti}, P_i for the ith weld) and those from the model. Given η_t and P, then η_m and W were generated from known relations. Extensions to molybdenum, nickel, and titanium were done via the use of material thermal diffusivity, α, and enthalpy of melting, δh, values embedded in the model. The final response model was given by the following:

$$P = \frac{c_1 \alpha q_o}{\upsilon^{c_2} d^{c_3}} \qquad P' = \frac{1}{P_{max}}\left(\frac{6.5026\alpha' q_o'}{\upsilon'^{\,0.2127} d'^{\,0.3351}}\right)$$

$$\eta_t = c_4 - c_5 e^{\left[\frac{\pi}{2\,\mathrm{atan}(c_6 d/P)}\right]} \qquad \eta_t' = \frac{1}{\eta_{tmax}}\left(0.9016 - 0.6328 e^{\left[\frac{\pi}{2\,\mathrm{atan}(0.2582 d'/P')}\right]}\right)$$

$$Ry = \frac{q_o \eta_t \upsilon}{\alpha^2 \delta h} \qquad Ch = \frac{\upsilon^2 Area}{\alpha^2}$$

$$\eta_m = \frac{Ch}{Ry} = 0.48 - 0.29 e^{\left[\frac{-Ry}{6.82}\right]} - 0.17 e^{\left[\frac{-Ry}{58.8}\right]} \qquad Area = \frac{Ry\,\eta_m\,\alpha^2}{\upsilon^2}$$

$$\text{---->} \quad W = \frac{3Area}{2P} \quad \text{(parabolic shape approximation)}$$

Unprimed variables represent the actual physical values. Primed variables are the physical quantities scaled by their maximum values given in the following table. Numerical constants, c_i, are those found via least-squares data fitting. Ry and Ch represent the Rykalin and Christensen parameters [4].

Variable	Min	Max
η_t	0.318	0.952
η_m	0.0731	0.5107
W (mm)	0.01	10
P (mm)	0.340	4.23
q_o (watts)	198	960
υ (mm/sec)	5.08	76.2
d (cm)*	0.0118	0.0294

*d values are .0118, .0164, .0225, .0294 cm

Given the parameterized model which provides the best "least-squares" fit to the experimental data, a genetic algorithm optimization method was used in consort with either a gradient-based optimization scheme or a nonlinear algebraic solver to find the WS to solve the following problems,

Performance Metric Goal	Weld Specifications	Solution Method
1.Maximize η_t	$W_{desired}$, $P_{desired}$	genetic w/nonlinear algebraic solver
2.Maximize η_t	$P_{desired}$ only	genetic w/nonlinear optimization
3.Maximize η_m	$W_{desired}$, $P_{desired}$	genetic w/nonlinear algebraic solver
4.Maximize η_m	$P_{desired}$ only	genetic w/nonlinear optimization
5.Maximize η_t*η_m	$W_{desired}$, $P_{desired}$	genetic w/nonlinear algebraic solver
6.Maximize η_t*η_m	$P_{desired}$ only	genetic w/nonlinear optimization

or stated somewhat differently

Maximize: $\eta_t(q_o,\upsilon,d)$, or $\eta_m(q_o,\upsilon,d)$, or $\eta_t*\eta_m(q_o,\upsilon,d)$
Subject to: $W_{desired} - W(q_o,\upsilon,d)=0$ and/or $P_{desired} - P(q_o,\upsilon,d)=0$

where the quantities followed by (q_o,υ,d) imply model responses resulting from the "constant" WS parameters. The optimization space is *discontinuous* due to the discrete variable, *d*, and would appear as separate surfaces in a vertical stack (one of which is shown in Fig.3). The largest lens (f = 7.5", d = .0294 cm) produces the lowest efficiencies and would be at the bottom of the stack. If *d* had been continuous, this "space" would have appeared "solid". The gist of our optimization effort is to "jump" to the highest surface (which corresponds to the lowest value of *d*), which will simultaneously yield a bounded WS solution to satisfy the ($P_{desired}$ and $W_{desired}$, $P_{desired}$) constraints.

In the genetic algorithm, the $W_{desired}$, $P_{desired}$ constraints were attached as a quadratic penalty function onto the performance metric to form a composite metric. The algorithm treats all values of q_o,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. In [1] the entire problem was solved with the genetic algorithm, but it was felt that the solution was too time-consuming for an adequate convergence of the search. However, it *was* found acceptable for narrowing the response space for initializing gradient scheme.

Since gradient schemes necessitate continuous parameters (i.e., variables), it was necessary to reformulate the discrete optimization problem as a continuous one. The solution was to pose the following two types of problems:

1. $W_{desired}$, $P_{desired}$ specified: For *each* value of *d*, solve for the q_o, υ combination that **algebraically solves** the constraint equations

$$W_{desired} - W(q_o,\upsilon,d)=0 \qquad P_{desired} - P(q_o,\upsilon,d)=0$$

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 whichever "efficiency" criterion (mentioned previously) was chosen. This was accomplished using a Newton-type solution algorithm. The analyst should note --> not all $W_{desired}$, $P_{desired}$ combinations are possible as shown in Fig.6. An intersection of the contours for a given d is needed to produce a solution.

2. $P_{desired}$ only specified: For *each* value of d, solve for the q_o, υ combination that

Maximizes: the efficiency criterion of interest (i.e. η_t, η_m, *or* $\eta_t{*}\eta_m$)

Subject to : $P_{desired} - P(q_o, \upsilon, d) = 0$

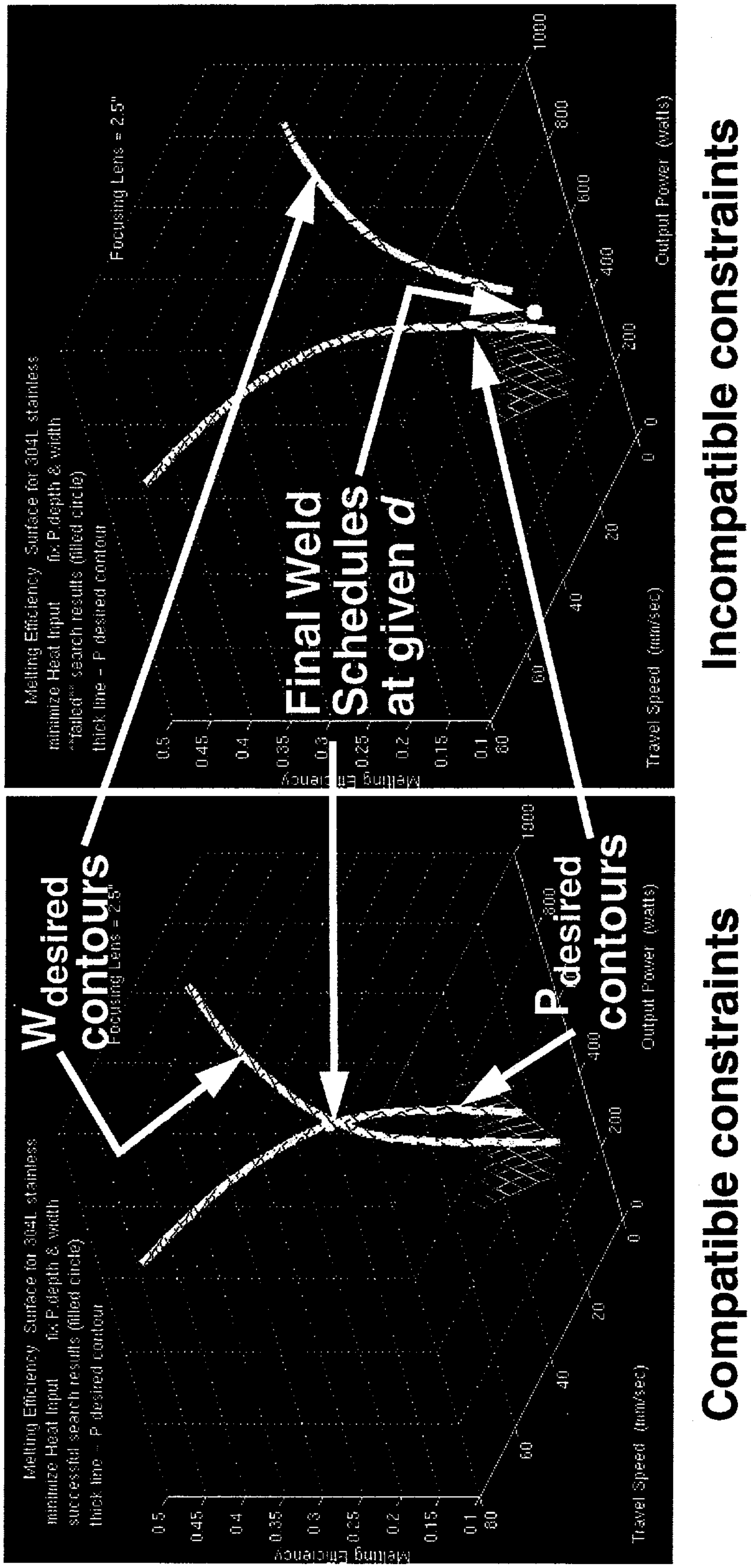
Then sort the solutions that produce acceptably small residuals in the single constraint to find the desired maximum according to whichever "efficiency" criterion was chosen. This was accomplished using a MATLAB routine to do nonlinear programming.

The capability developed for optimization and graphical model output can be most effectively used by integrating them via graphical user interface (GUI) tools (available in the MATLAB system). The GUI panel in Fig.7 allows the user to:

1. Select any of presently seven metals (304 stainless steel, 304L stainless steel, 1018 steel, tin, nickel, titanium, molybdenum) to analyze.
2. Plot any of five "responses" from the model (η_t, η_m, $\eta_t{*}\eta_m$, W, P). Surfaces are plotted as continuous functions of q_o, υ and as a discrete function of d. Contours appear as labeled iso-curves of the given response variable, continuous in q_o, υ, and for a single value of d.
3. Obtain the nearest optimal weld schedule for user-specified, $W_{desired}$ and/or $P_{desired}$.
4. Display the assumed weld shape as it is changed by the user or the completed solution
5. Get continuous weld model output via "mouse-down" button clicks on the 2-D contour plots.
6. Get text help describing the application.

The capability in items 4,5 are provided for the three weld scheduler applications. Item 5 provides the analyst with the flexibility to choose an alternative weld schedule. The optimization algorithms are configured to attain the extremum, be it minimum or maximum, regardless of the cost in terms of q_o, υ. If an efficiency response can be further improved or "optimized" by a few percent for a large increase in q_o or υ, then that is what the algorithm will recommend. It is up to the analyst to decide whether this recommendation is practical.

The capability in item 6 is provided for all applications covered in this report.



Compatible constraints

A weld schedule is found for a given lens (i.e. d), that will yield $W_{desired}$, $P_{desired}$

Incompatible constraints

A weld schedule could *not* be found for this lens (d) that would satisfy either $W_{desired}$ or $P_{desired}$. The algorithm stops at an intermediate value.

Figure 6. Feasible vs Unfeasible Weld Schedules

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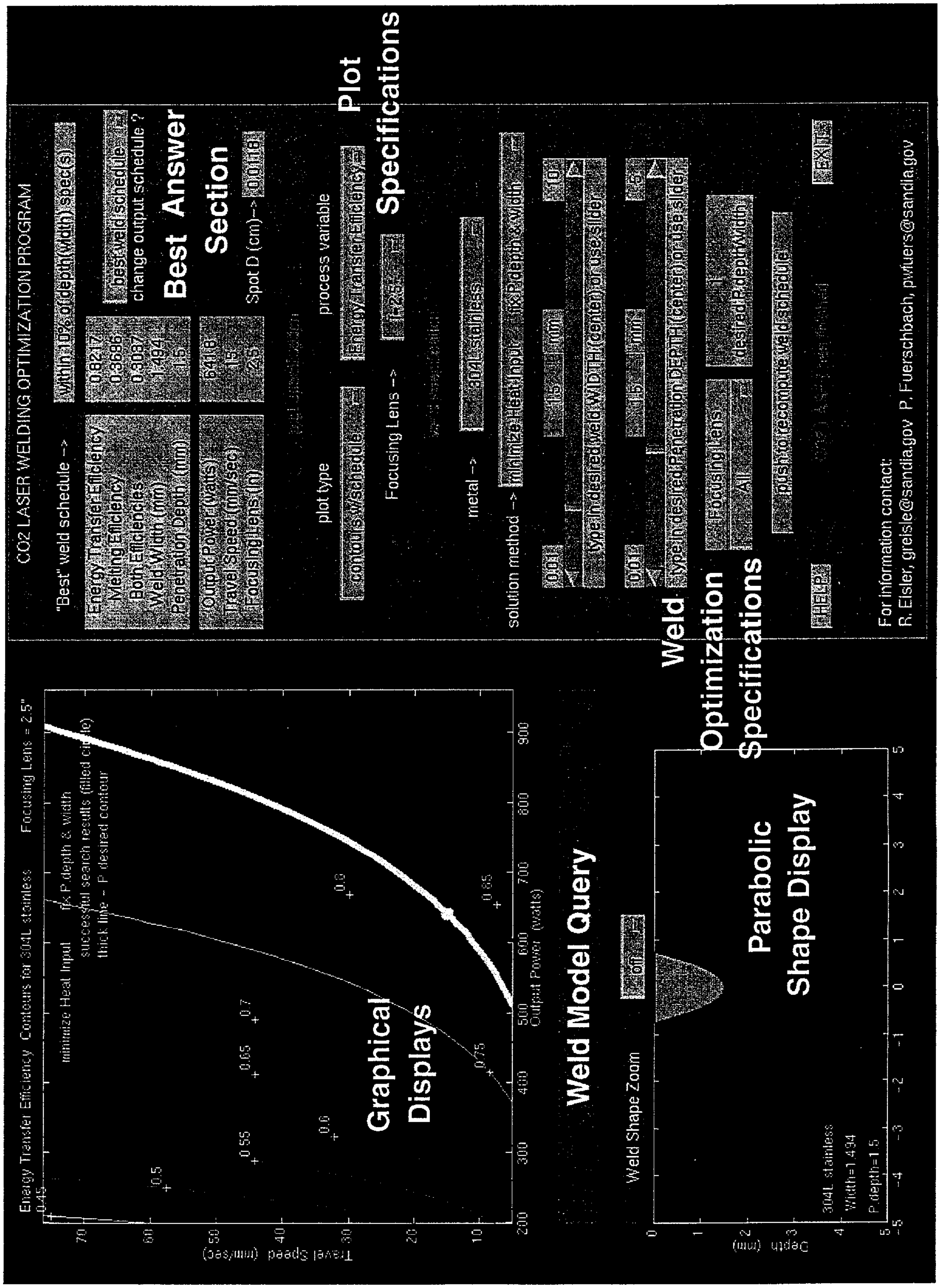

Figure 7. The CO2 Laser Application GUI

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The *ARC* Application

Response characteristics for plasma-arc or gas-tungsten arc welding are concerned with minimizing heat input on a given metal, while attaining a user-specified weld depth for an assumed semi-circular weld cross-section. The schedules are produced by applying parameter optimization to the mathematical model in [4]. Weld schedules consist of:

1. laser output (q_o) power in watts with a range of 100-2000, and
2. part travel speed (υ) in millimeters(mm)/second(sec) , with a range of 1-50.

For arc welding, q_o and υ can be considered to vary continuously over given ranges. It was not necessary to scale the model for this application.

Three output responses were modeled as functions of the WS parameters, q_o, υ. These quantities were:

1. melting efficiency (η_m, dimensionless),
2. top width of the weld (W, mm).
3. weld penetration depth, (P, mm). The weld cross-sections are assumed semi-circular and therefore $W=2P$.

The following is the nonlinear algebraic, plasma-arc model

$$Ry = 0.8\frac{q_o \upsilon}{\alpha^2 \delta h} \qquad \eta_m = \frac{Ch}{Ry} = 0.48 - 0.29e^{\left[\frac{-Ry}{6.82}\right]} - 0.17e^{\left[\frac{-Ry}{58.8}\right]}$$

$$Area = \frac{R_y \eta_m \alpha^2}{\upsilon^2} \qquad P = 2\sqrt{(2Area)/\pi} \text{ (semicircular area)}$$

Note that the Ry relation used here assumes a constant $\eta_t = 0.8$. The gradient-based, nonlinear optimization algorithm (in MATLAB), described previously, was used to find the WS to solve the single problem available for this application:

Maximize η_m for $P_{desired}$ only.

To compensate for initial guess sensitivity, this single problem was solved for five different sets of initial conditions which represent the boundaries of the ranges on q_o, υ as follows:

test initial condition #	q_o initial	υ initial
1	100	1
2	100	50
3	2000	1
4	2000	50
5	1000	25

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The solutions were sorted for those that produced acceptably small residuals in the single constraint and of these the one which maximized η_m was chosen.

Capabilities unique to this GUI-driven application (Fig.8) are the ability to:

1. Select any of seven metals (mentioned in the *CO2* application) to analyze.
2. Plot any of three responses (η_m, W, P) from the model as continuous functions of q_o, υ.
3. Obtain the optimal weld schedule for user-specified $P_{desired}$.

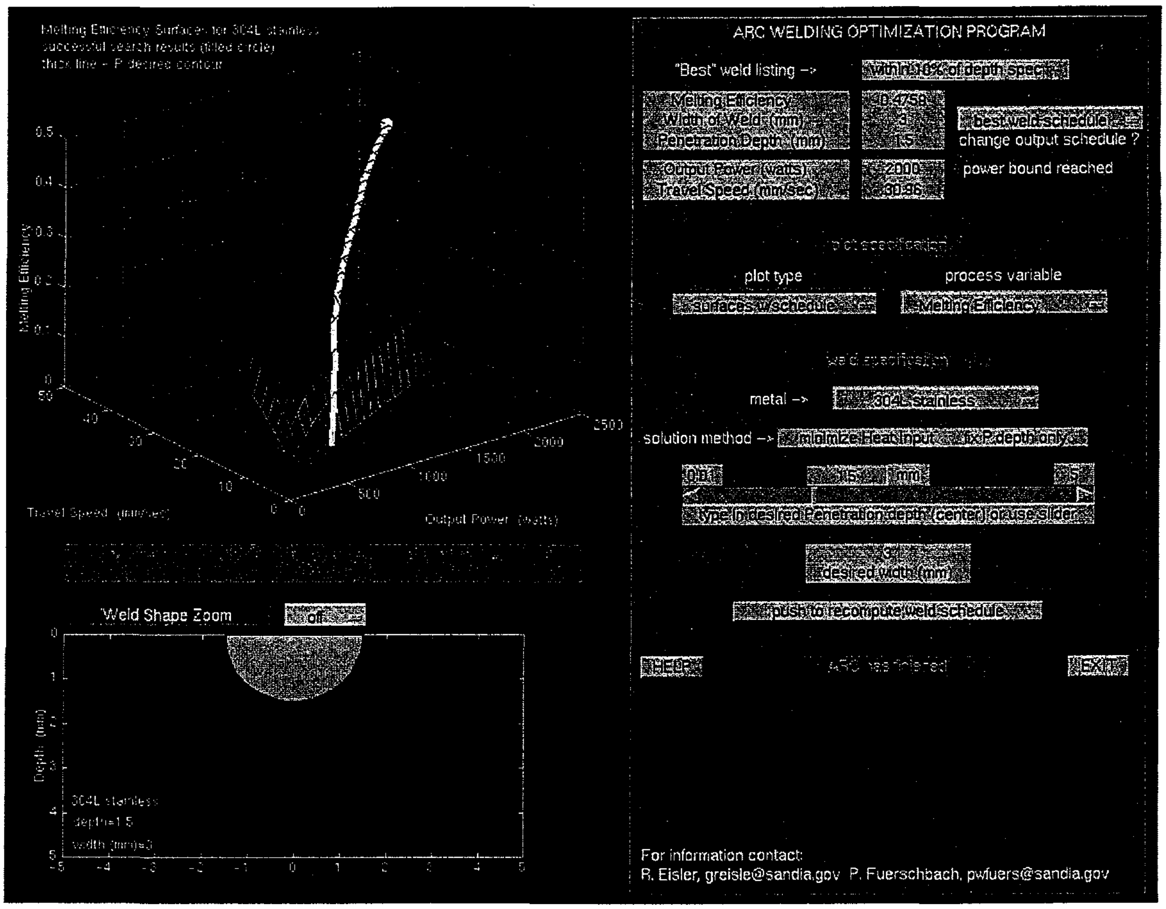

Figure 8. The ARC Application GUI

The *YAG* Application

Response characteristics for Nd: Pulsed YAG welding are concerned with minimizing weld-induced temperature on a specific component, while attaining user-specified weld dimensions for an assumed parabolic-shape weld cross-section. The schedules are produced by applying parameter optimization to a mathematical model obtained in [5] for 304 stainless steel. Weld schedules consist of constant values over a given weld for:

1. peak power in watts (q_p)

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2. energy in joules (Q), and
3. Lens focal length in mm (f)

In the context of arc welding, q_p and υ can be considered to vary continuously over given ranges. f is discrete as in the *CO2* application. It was necessary to scale the model for this application because of the magnitude disparity on q_p and Q. The following ranges on q_p, Q were available depending on the lens f used.

f (mm)	q_p Range (watts)	Q Range (joules)
120	$900< q_p<1500$	$0.5<Q<2.5$
160	$500< q_p<3200$	$1.0<Q<4.0$
200	$2000< q_p<3100$	$2.0<Q<4.5$

Three output characteristics were modeled as polynomial functions of the WS parameters, q_p, Q, f. These quantities were:

1. temperature (T, $^{\circ}$C)
2. width of the weld (W, mm). (Converted from area via a parabolic shape approximation)
3. weld penetration depth, (P, mm).

The polynomial functions, segmented by f, are

for f = 120 mm

$$T = 15.259003 + 34.00628Q + 0.0327997q_p - 1.280093Q^2 + 0.0042812q_pQ - 0.000012q_p^2$$

$$Area = -0.089332 - 0.026302Q + 0.0001929q_p + 0.0046435Q^2 + 5.72\times10^{-5}q_pQ + -8.8\times10^{-8}q_p^2$$

$$P = -0.520544 + 0.0366851Q + 0.0008552q_p + 0.005604Q^2 + 9.92\times10^{-5}q_pQ - 3.4\times10^{-7}q_p^2$$

for f = 160 mm

$$T = 56.926917 + 31.055164Q - 0.016345q_p - 4.489219Q^2 + 0.0064075q_pQ + 2\times10^{-7}q_p^2$$

$$Area = 0.0309287 + 0.0349242Q - 0.000021q_p - 0.008291Q^2 + 2.55\times10^{-5}q_pQ - 4.4\times10^{-9}q_p^2$$

$$P = -0.019819 + 0.1151805Q + 0.0000474q_p + -0.018832Q^2 + 0.0000193q_pQ - 1.4\times10^{-8}q_p^2$$

for f = 200 mm

$$T = 88.316654 + 12.453223Q + -0.020364q_p + -0.808704Q^2 + 0.0026979P_pQ + 2.5\times10^{-6}q_p^2$$

$$Area = 0.4083387 - 0.064881Q - 0.000216q_p + 0.0051722Q^2 + 2.27\times10^{-5}P_pQ + 3.4\times10^{-8}q_p^2$$

$$P = 0.9887108 - 0.204396Q - 0.000453q_p + 0.0165806Q^2 + 5.16\times10^{-5}P_pQ + 6.6\times10^{-8}q_p^2$$

Since W is generated for a parabolic cross-section model, $W = (3Area)/(2P)$. Travel speed (υ, mm/sec), pulse duration (τ, msec), pulse frequency (ν, Hz) are also computed, based on an average power of 200 watts. These relations are:

$$\upsilon = 50\frac{W}{Q} \qquad \tau = 1000\frac{Q}{q_p} \qquad \nu = \frac{200}{Q}$$

The gradient-based optimization and nonlinear algebraic solver schemes described previously for CO_2 were used to find the WS to solve the problems

1. **Minimize** T**, Subject to:** $P_{desired}$ only (nonlinear optimization at each value of f with sorting over lens f for minimum T).
2. **Minimize** T**, Subject to:** $W_{desired}$, $P_{desired}$. (nonlinear algebraic solution at each value of f with sorting over f for minimum T)

The solutions were sorted for those that produced acceptably small residuals in the constraints and of these the one which minimized temperature was chosen. Due to the fact that the ranges of q_p, Q were discontinuous (i.e., depending on the value of f), the genetic algorithm was used to provide an initial guess for the sub-WS (q_p, Q) each time a new value of f was considered.

Capabilities unique to this GUI-driven application (Fig.9) are the ability to:

1. Plot any of three responses (T, W, P) from the model. Surfaces and contours are plotted as continuous functions of q_p, Q and are discrete in f.
2. Obtain the nearest optimal weld schedule for user-specified $P_{desired}$ only, or the $W_{desired}$, $P_{desired}$ combination.

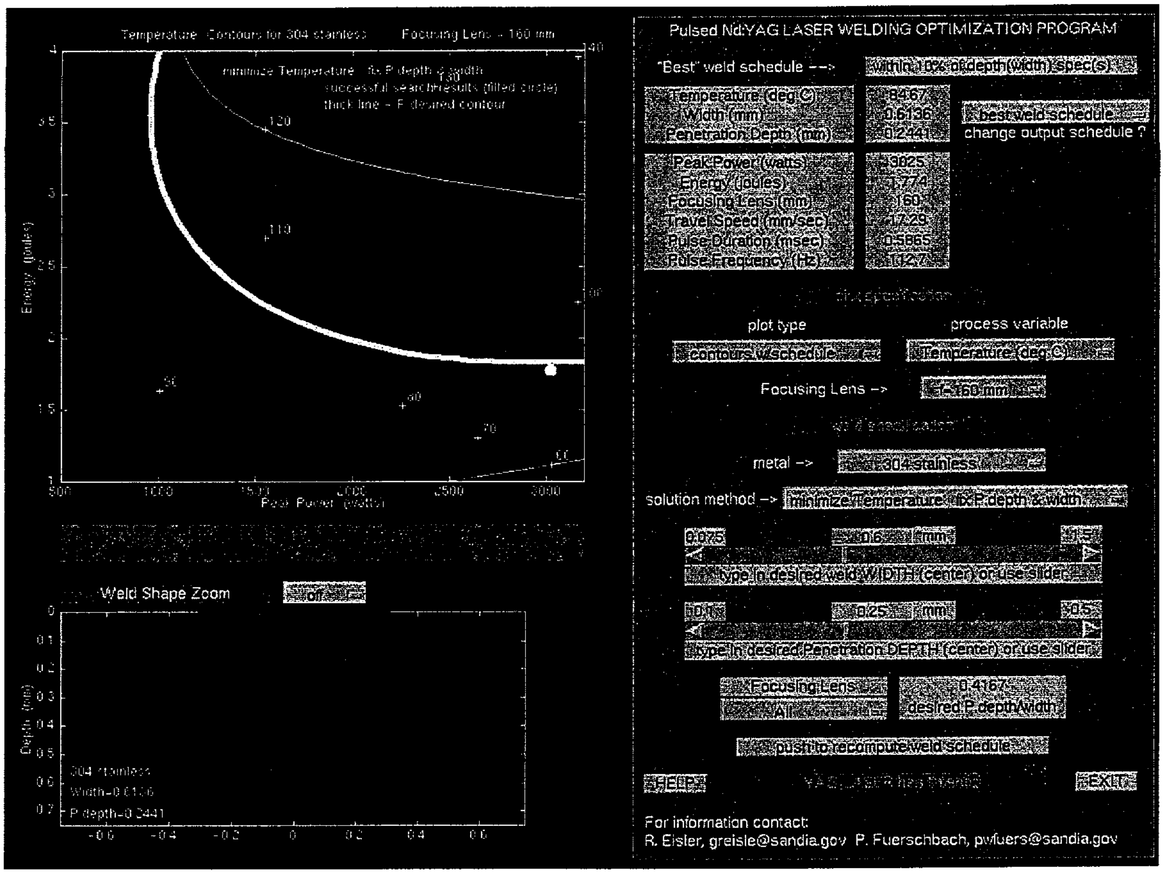

Figure 9. The YAG Laser Application GUI

The *ISO* Application

This application computes constant temperature contours due to saturation from a heat source according to the 2-D steady-state, heat-flow equation as derived by Rosenthal [6]. The 2-D model arises from modeling the welding of thin sheets where the temperature variation is considered negligible in the thickness direction. The steady-state description is derived from welding a plate whose dimensions are large with respect to the size of the contours. A schematic is shown in Fig.10.

Easy access to temperature isotherms for a given set of welding conditions provides the optimization user with an additional check of weld thermal effects. While melting efficiency indicates how effective a given weld schedule is in minimizing heat input to the part, the Rosenthal analysis graphically presents the resulting temperature distribution and indicates the *geometric* extent of the weld heat input.

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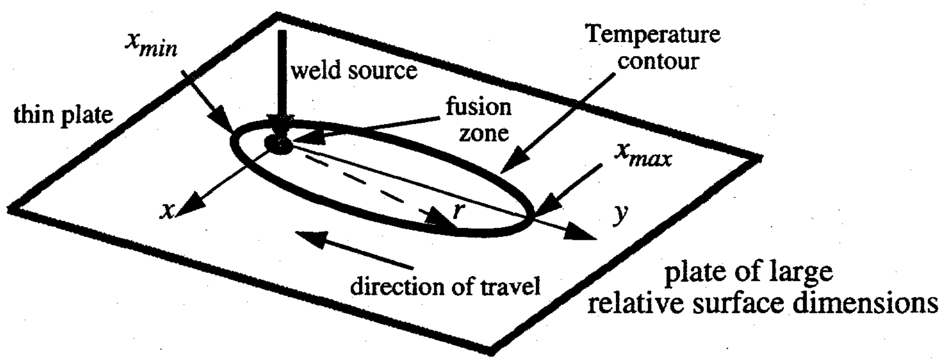

Figure 10. Schematic of the 2-D steady-state, heat-flow problem

The Rosenthal analytical solution is

$$\frac{2\pi(T - T_o)k_s t}{Q} = e^{\left(\frac{\upsilon x}{2\alpha_s}\right)} K_o\left(\frac{\upsilon r}{2\alpha_s}\right)$$

where the following are input by the user via the GUI-driven application,

T = contour temperature of interest (deg C)
T_o = base metal temperature
k_s = thermal conductivity of metal (Joules/(meter-sec-deg C))
t = thickness of metal plate (mm)
Q = energy (heat) input to the metal (Joules)
υ = welding speed (mm/sec)
α_s = thermal diffusivity of metal (meters^2/sec)

K_o is the modified Bessel function of the second kind and zero order (a MATLAB function) and e is the exponential operator. The variable, r, radial distance from origin ($(x^2 + y^2)^{1/2}$ in millimeters), is manipulated by the application.

Assumptions on the Rosenthal analysis are that:

1. The process is steady state. At saturation, the contours move with the weld source.
2. no melting and negligible heat of fusion
3. constant thermal properties
4. no heat loss from the metal surface
5. infinitely wide surface

The contour solution reduces to solving the above nonlinear algebraic equation as follows:

1. solve the equation: $c_1 - e^{c_2 x} K_o(c_2 x) = 0$ for $x = x_{min}, x_{max}$ using a nonlinear solver, where the constants $c_1 = (2\pi*(T-T_o)*k_s*t)/Q$ and $c_2 = \upsilon/(2*\alpha_s)$. $y(x_{min}) = y(x_{max}) = 0$.

2. solve for the intermediate x values on the top half of the contour by inputting a range of r values, $abs(x_{min})<r<x_{max}$, and solving $x=1/c_2*ln\ (c_1/K_o(c_2*r))$, and then the corresponding $y=(r^2-x^2)^{1/2}$. ln is the natural logarithm.

A complete contour is constructed by reflecting the top half and is approximately elliptical in shape.

Capabilities unique to this GUI-driven application (Fig.11) are the ability to:

1. Choose from presently seven materials to weld (iron, 304 stainless, 1010 steel, molybdenum, nickel, 2024 aluminum, copper, tin, titanium). This choice establishes k_s, α_s.
1. Plot up to five temperature contours (including the melt contour) on a single plot.
2. Resize the plotting region (and move the weld source) for comparisons.
3. Get dimensional output for maximum width, length, and area for all contours.

Conclusions

Computational methods have been developed to provide optimal weld schedules based on semi-empirical mathematical models. The mathematical relations in the models originated from past research and were modified to provide best least-squares fits to experimental data. Model extension to other metals was provided through the use of thermodynamic constants. Genetic algorithms were used to provide initial guesses to gradient-based solution schemes. Gradient schemes were used to provide tight convergence on specified weld dimensions as well as optimize various performance indices. Solution algorithms work well provided that the required width and penetration specifications co-exist. In addition, the Rosenthal 2-D heat flow equation was solved to produce a geometric view of weld effects. GUI-driven input-output interfaces were provided for all applications. Future applications can be added in a straightforward manner to the MATLAB architecture.

References

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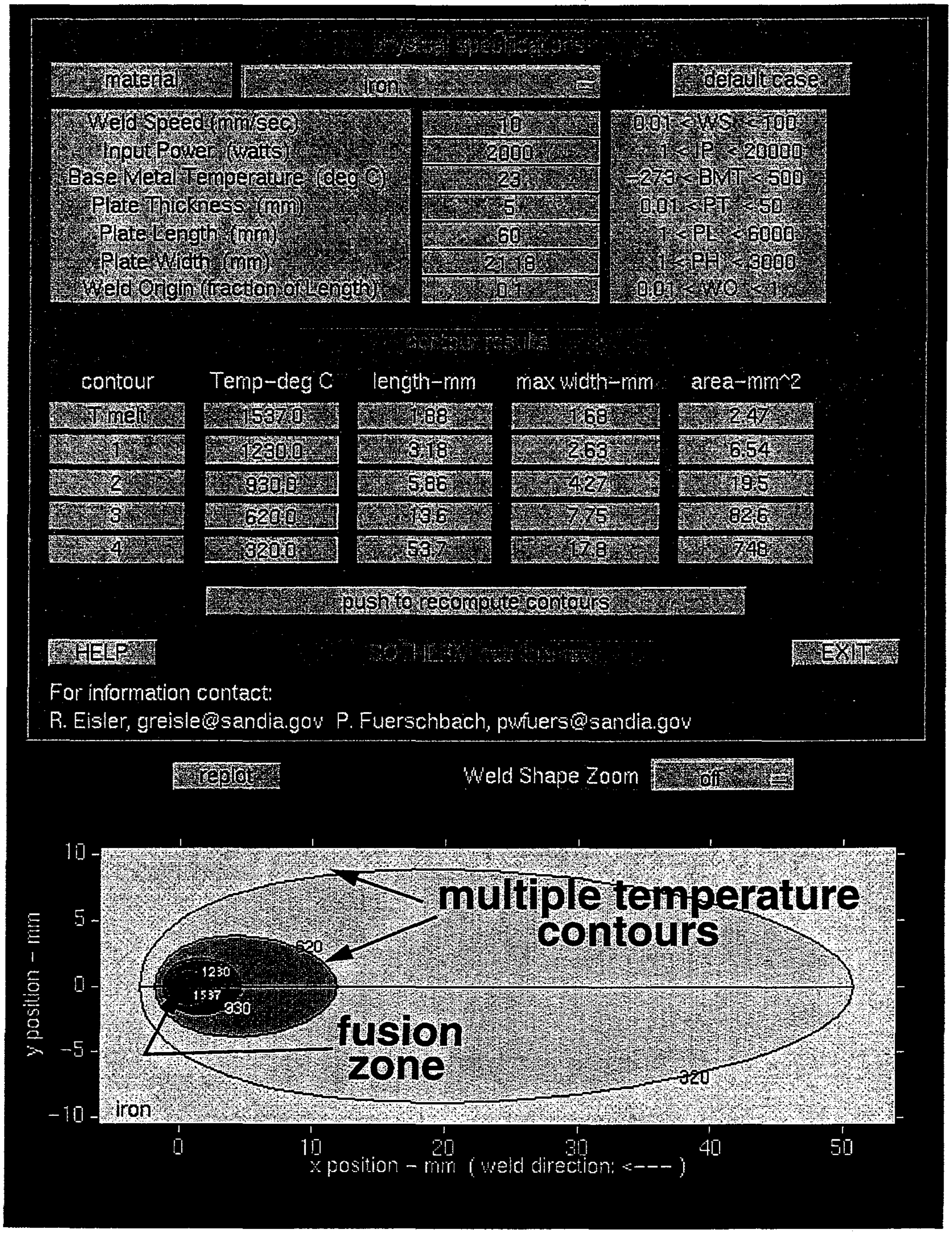

Figure 11. The ISO Application GUI

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Distribution:

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1	MS 0367	B.K. Damkroger, 1833
5	MS 0367	P.W. Fuerschbach, 1833
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