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SmartWeld: Open Source Applications for Weld Analysis and Optimization

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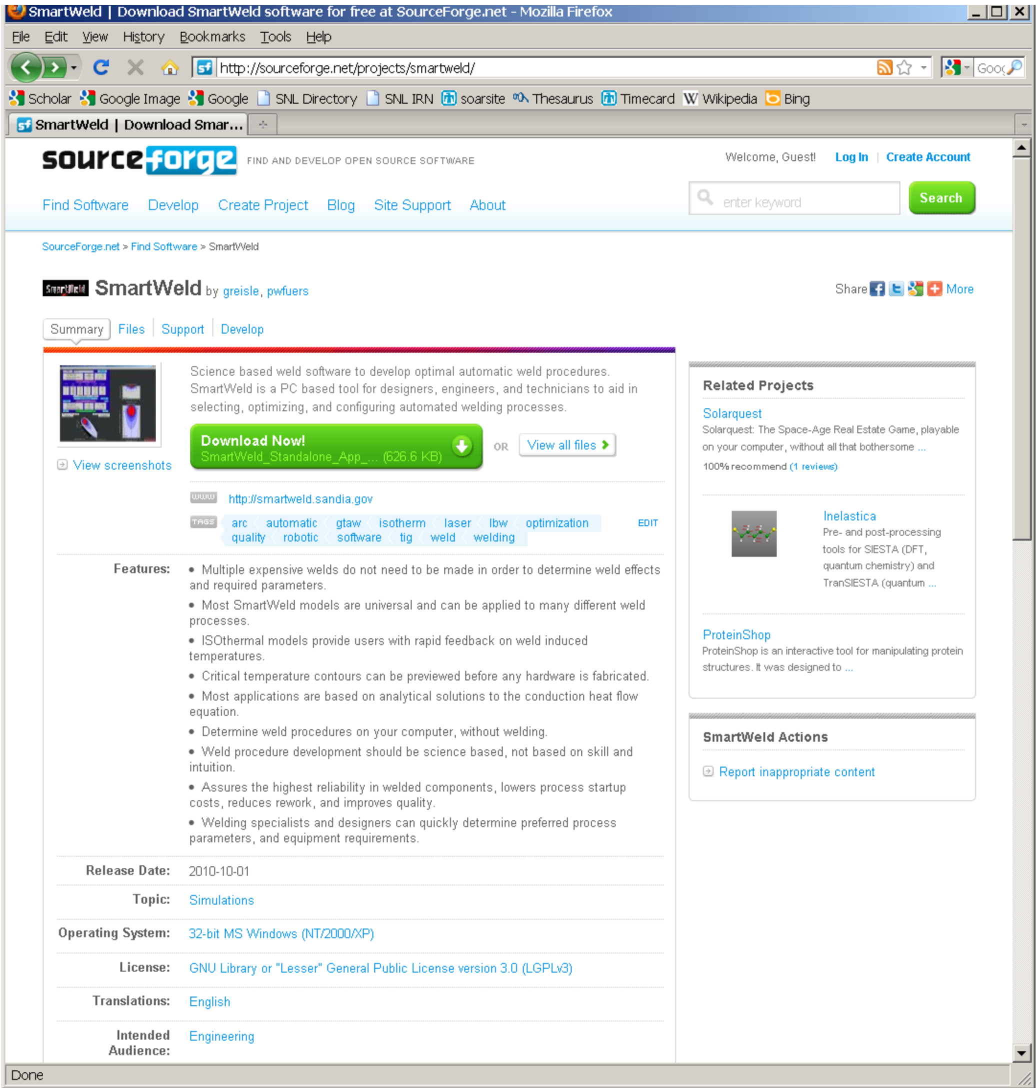
http://sourceforge.net/projects/smartweld/

or

http://smartweld.sandia.gov/

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy under contract DE-AC04-94AL85000.

SmartWeld is now an Open Source Project at SourceForge.net



- SourceForge is a free host website dedicated to making open source projects successful through community collaboration.
- 2.7 million developers create software in over 260,000 projects.
- "Open Source Tools for Materials Research and Education" TMS 2009 Annual Meeting - OpenThermo, FiPy, ATAT, ABINIT

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GNU Lesser General Public License

-Freedom to share and change software

- **Open Source software is distributed with source code, and with no restrictions on making and redistributing modified versions.**
- **There are no licensing fees involved, but anyone may charge a fee for the physical act of transferring a copy.**
- **Each time one redistributes the original or modified software the recipient automatically receives a license from the original licensor to copy or distribute.**
- **You must cause the whole of the work to be licensed at no charge to all third parties under the terms of the License.**

Partial List of SmartWeld Users

Manufacturers:

- ABB Inc.
- American Pacific Technology
- Baldt Inc.
- Borg Warner Automotive
- Bristol Babcock Inc.
- Carpenter Technology
- Coviant Inc.
- Caterpillar, Inc.
- Delphi Corporation
- DaySys Inc.
- Fischer Engineering Co.
- Honeywell International, Inc.
- Johnson Controls
- Joining Technologies LLC
- Lane Research
- Lockheed Martin Huntsville
- Multiplex Inc.
- Oplink Communications
- Scearce Laser Inc.
- Seagate Technology
- St. Jude Medical
- Sterling Weld Data Systems
- Texas Instruments
- The Timken Company
- Unitek Miyachi
- Yardney Technical Products

- **The SmartWeld project was first started in 1993.**
- **SmartWeld now contains over 15,000 lines of code.**

Universities:

- Kansas State Univ.
- Lehigh University
- Penn State University
- Princeton University
- Tufts University
- Cal. Poly San Luis Obispo
- Old Dominion University
- University of Hartford
- University of Nottingham
- LeTourneau University
- University of Alberta

Government & Research labs:

- Edison Welding Institute
- Los Alamos National Laboratory
- Pearl Harbor Naval Shipyard
- Naval Air Weapons Center
- Y12 National Security Complex

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SmartWeld features 14 selectable welding applications

Compute an optimal cont. wave laser weld procedure

Compute an optimal weld procedure for thin plate.

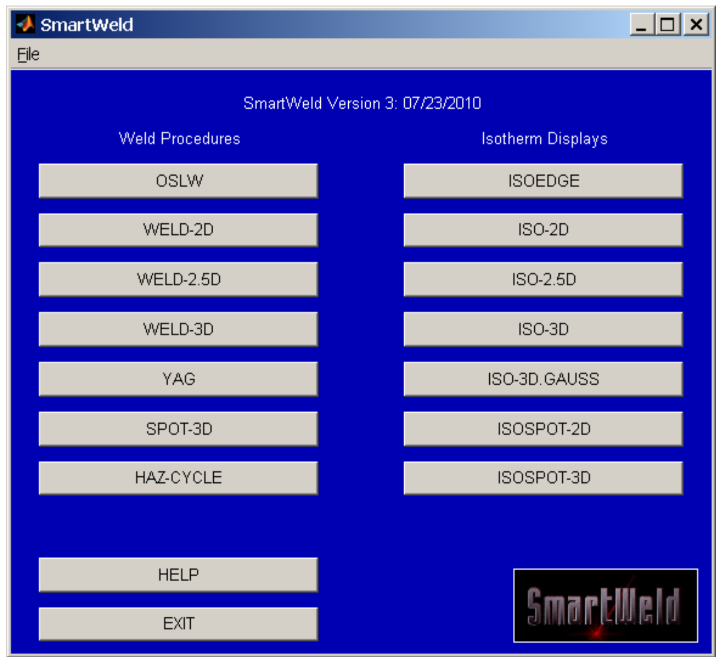
Compute an optimal procedure for moderately thick plate

Compute an optimal weld procedure for thick plate

Compute an optimal pulse Nd:YAG weld procedure

Compute an optimal thick plate spot weld procedure.

Compute temperature history in the weld heat affected zone.



Compute steady state temp. contours for an edge weld.

Compute steady state temp. contours on thin plate.

Compute steady state temp. contours on mod. thick plate

Compute steady state temp. contours on thick plate.

Compute temp. contours for distributed heat sources.

Compute spot weld temp. contours on thin plate.

Compute 3D spot weld temp. contours on semi-infinite body.

SmartWeld Executive Control Panel

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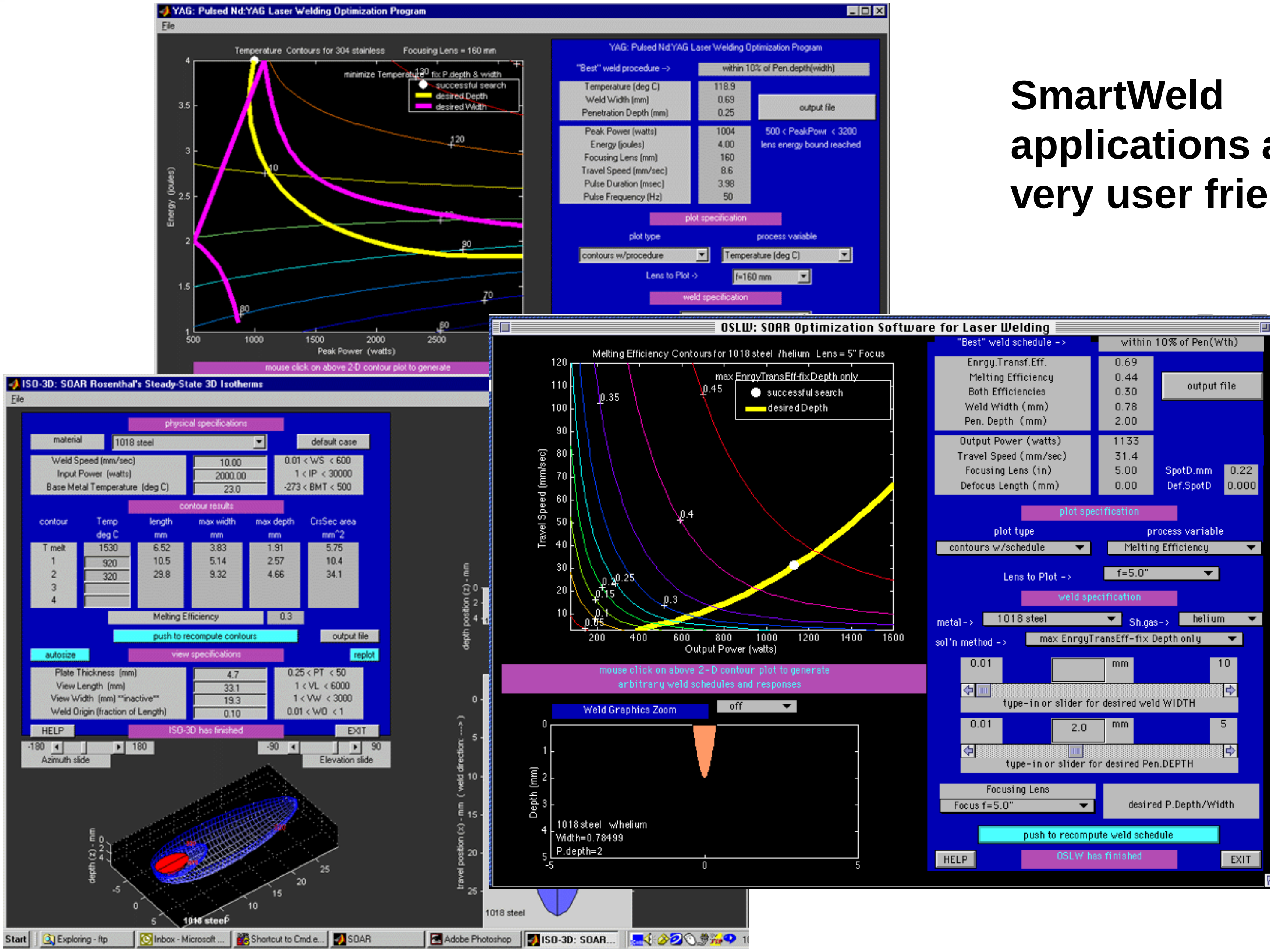
SmartWeld Common Look and Feel



SmartWeld applications are all very user friendly!

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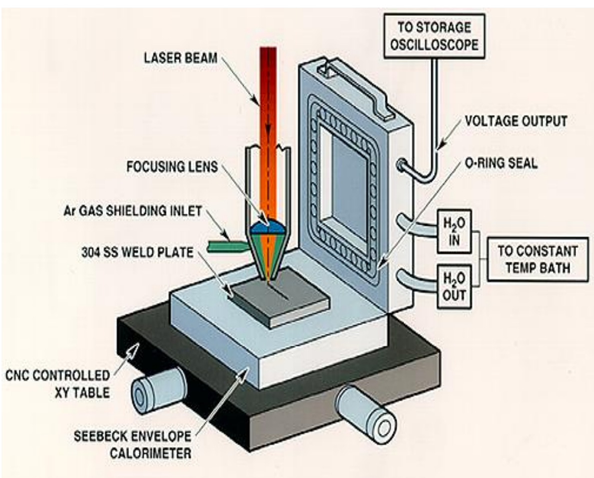
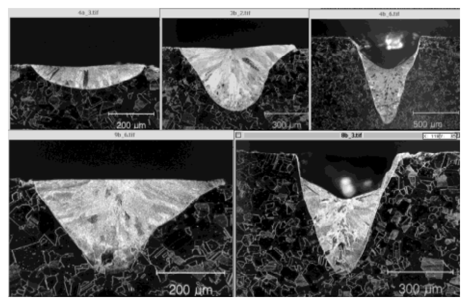
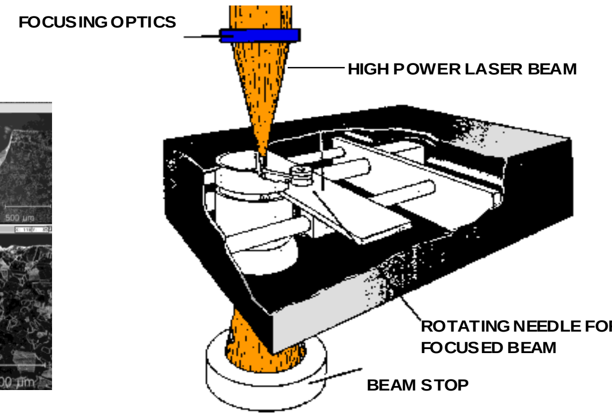
- *Sandia National Lab* **Weld Studies Used to Develop SmartWeld**



Energy Input: Calorimeter



Metallography



LaserScope

B83 Nuclear Weapon

SmartWeld

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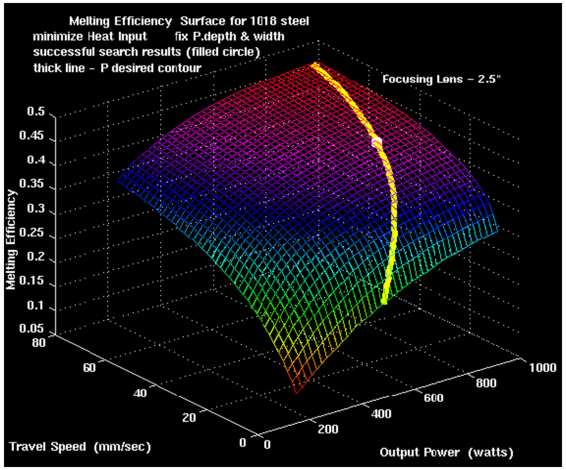
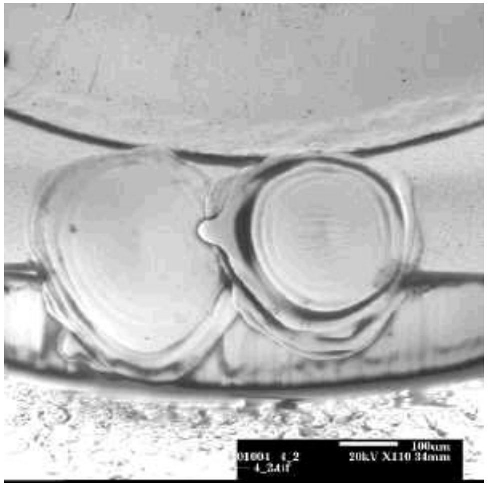
Two Primary Uses for SmartWeld

Predictive



- **Science based process models enable optimized automated weld procedures.**
- **Virtual manufacturing enables the user to ask "what if?" and quickly find the answer.**
- **With SmartWeld, multiple welds do not need to be made in order to determine weld effects and required parameters.**

Investigative



- **Welding problems can be solved by gathering information on efficiencies and other figures of merit.**
- **Most SmartWeld models are universal and can be applied to many different weld processes.**
- **Understand your welding process better.**

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Traditional Weld Procedure Development

- Code Qualified – simply assure that bridges, buildings, vessels, etc. are welded with some minimal degree of process control and inspection.
- Professional knob twisters who use sound and sight to "optimize" a complex and non-linear process to get the job done.
- Taguchi, Designed Experiments, Neural Nets and other experimental studies that are expensive, time intensive, and have no basis in welding theory.
- Historical non-optimized weld procedures that are continually modified until the process becomes: "Don't touch it"

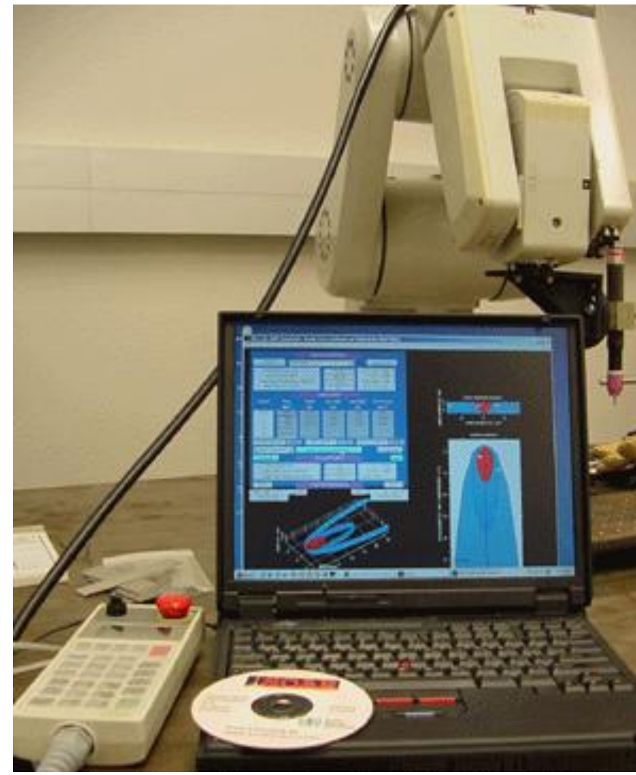
SmartWeld Features for **Predictive** and **Investigative** Uses

Automated Welding

- **Temperatures surrounding the weld. (maximum and history)**
- **Weld size (width, depth, cross-sectional area)**
- **Effect of material type.**
- **Process parameter values.**
- **Efficiencies**
- **Effect of metal thickness.**
- **Procedure sensitivities**
- **Optimization**
- **What if?**

Predictive Uses for SmartWeld - *"Virtual Manufacturing"*

- Weld parameters should be specific to the application requirements.
- Determine weld procedures on your computer, without welding.
- Weld procedure development should be science based, not based on skill and intuition.
- Welding specialists and designers can quickly determine preferred process parameters, and equipment requirements.
- Assures the highest reliability in welded components, lowers process startup costs, reduces rework, and improves quality.



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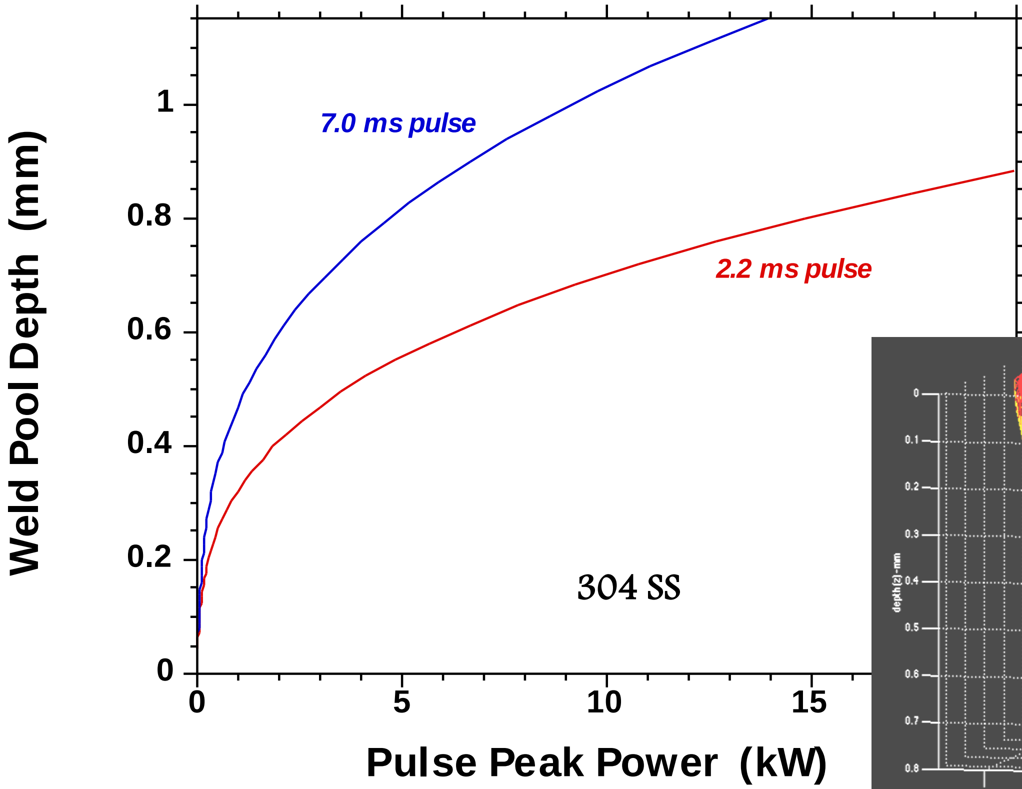
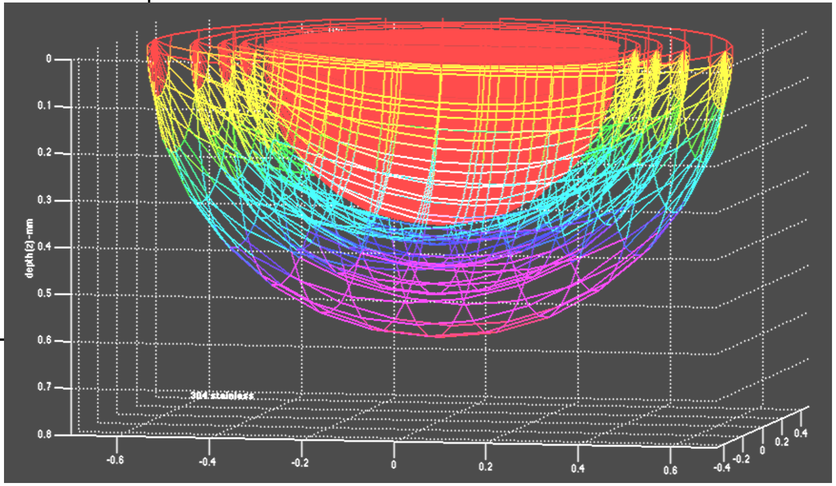
Predictive *Uses for SmartWeld*

More melting at lower power with long pulse durations.



Low peak power in spot welding reduces spatter and other defects.



ISOSPOT- 3D

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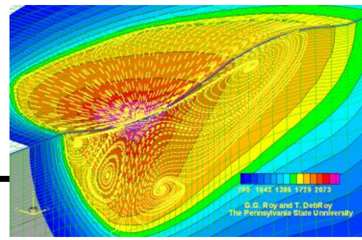
Some differences between SmartWeld and FEA computer models.



FEA Advantages

•Residual stress and distortion can be analyzed.

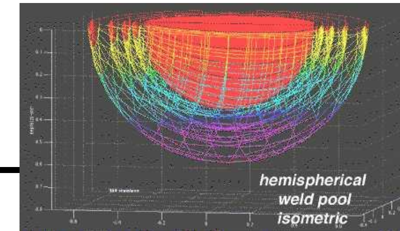
•Convective flow in weld pool can be simulated.

FEA Disadvantages

•Mesh generation and problem statement is time consuming and requires an expert analyst.

•Model complexity requires accurate knowledge of many material properties and boundary conditions.

•Limited materials list.



SmartWeld Advantages

•User friendly software is understandable to most process engineers.

•Fast desktop answers to common weld questions for many materials.

•Quick processing time enables multiple computations, alternate materials, joints, and conditions to be investigated.

SmartWeld Disadvantages

•Parts with complex geometries must be approximated with symmetrical shapes.

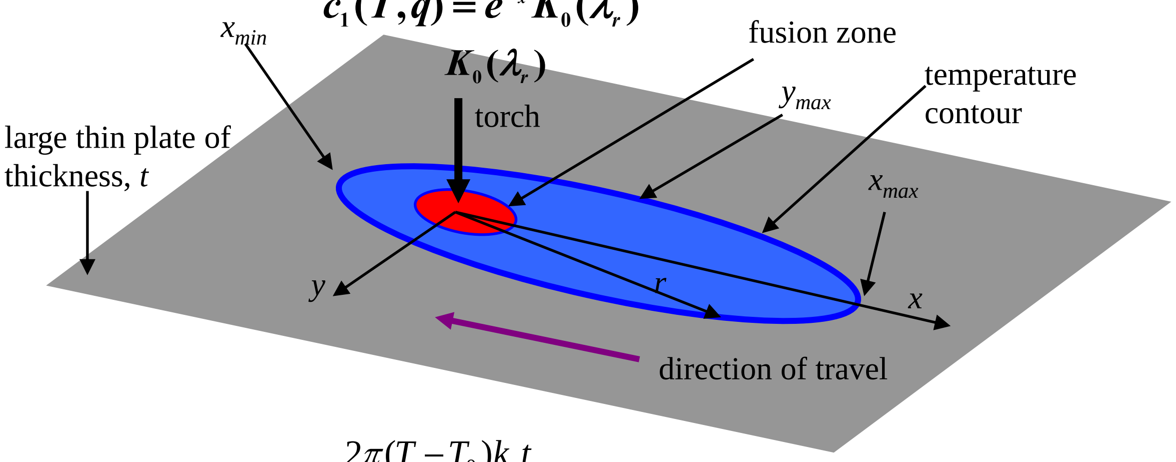
•Fluid flow is ignored with conduction only model.

•Stress and strain fields cannot be analyzed.

SmartWeld Applications Provide Solutions to Multiple Types of Heat Flow

- **Most SmartWeld applications are based on analytical solutions to the conduction heat flow equation.**
- **Conduction heat flow is really the 90% answer in most cases.**

$$c_1(T,q) = e^{\lambda_x} K_0(\lambda_r)$$

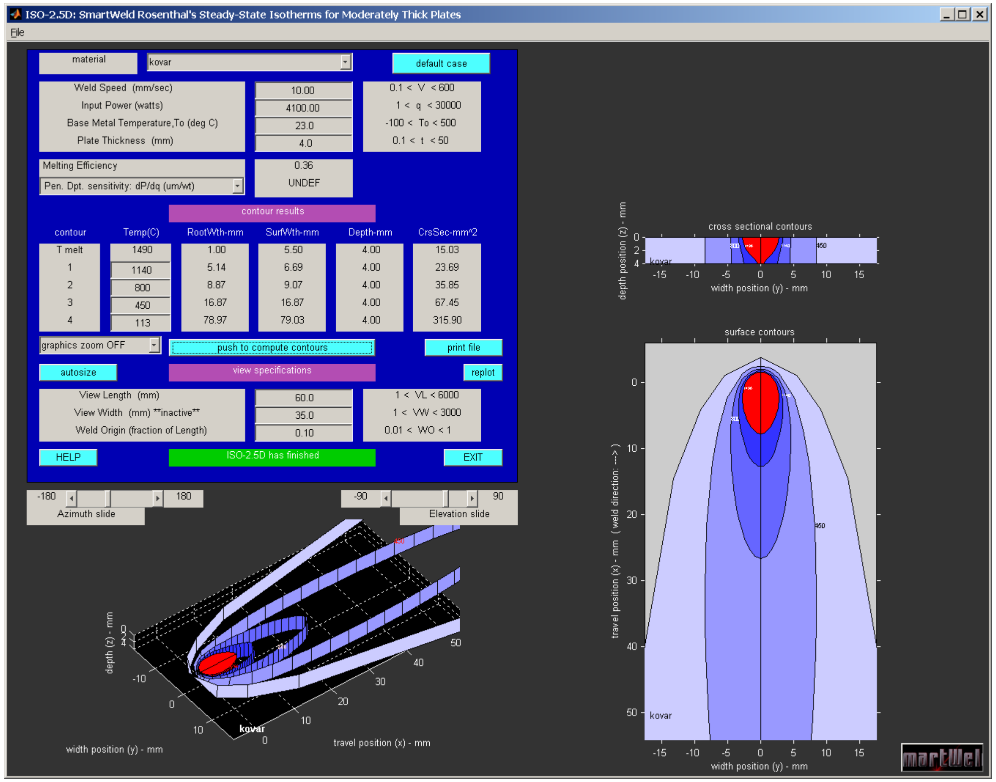


$$c_1(T,q) = \frac{2\pi(T - T_0)k_s t}{q}$$

Observe Weld Thermal Effects with 7 Isotherm Display Applications:

ISO -2D
ISO2.5D
ISO- 3D
ISOEDGE
ISOSPOT 2D,
ISOSPOT 3D,
ISO3D.GAUSS

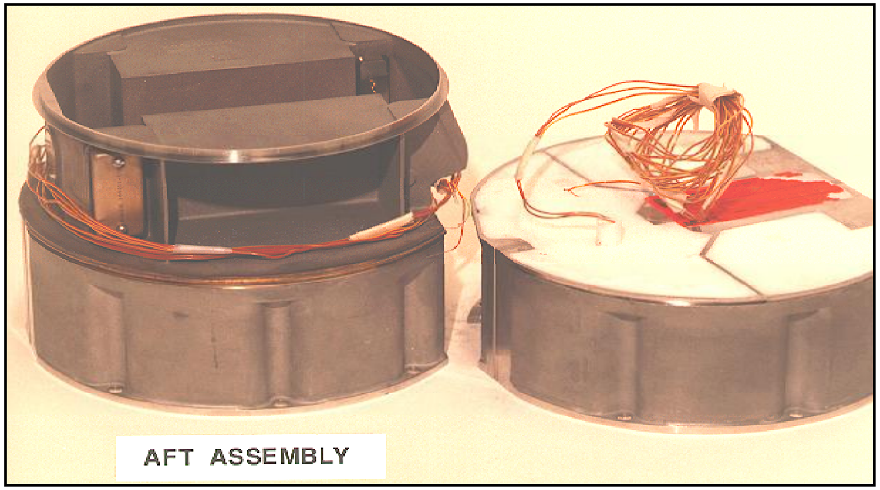
- **ISOthermal models provide users with rapid feedback on weld induced temperatures.**
- **Critical temperature contours can be previewed before any hardware is fabricated.**



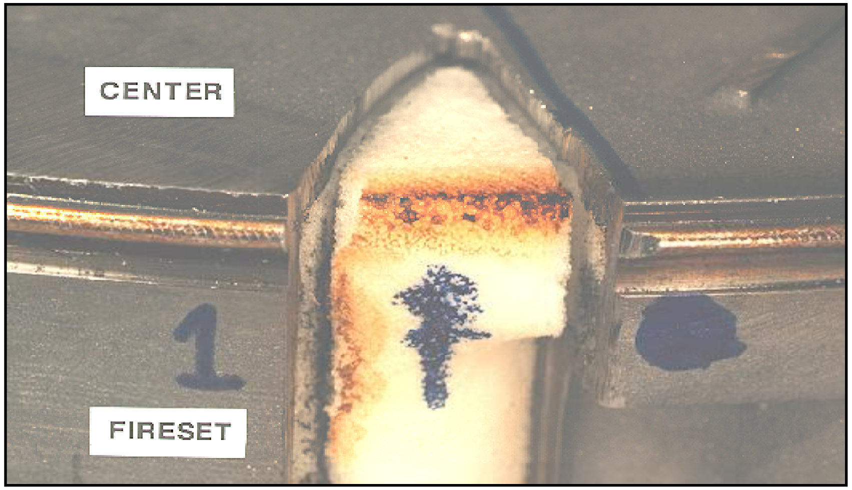
ISO-2.5D

Welding is Often the Final Step in High Value Added Manufacturing

- Fusion welding involves thermal excursions in excess of 1500°C for stainless steel components.



- Heat transfer and associated thermally-induced stresses can damage sensitive components.



Encapsulation foam can be charred from weld heat input.

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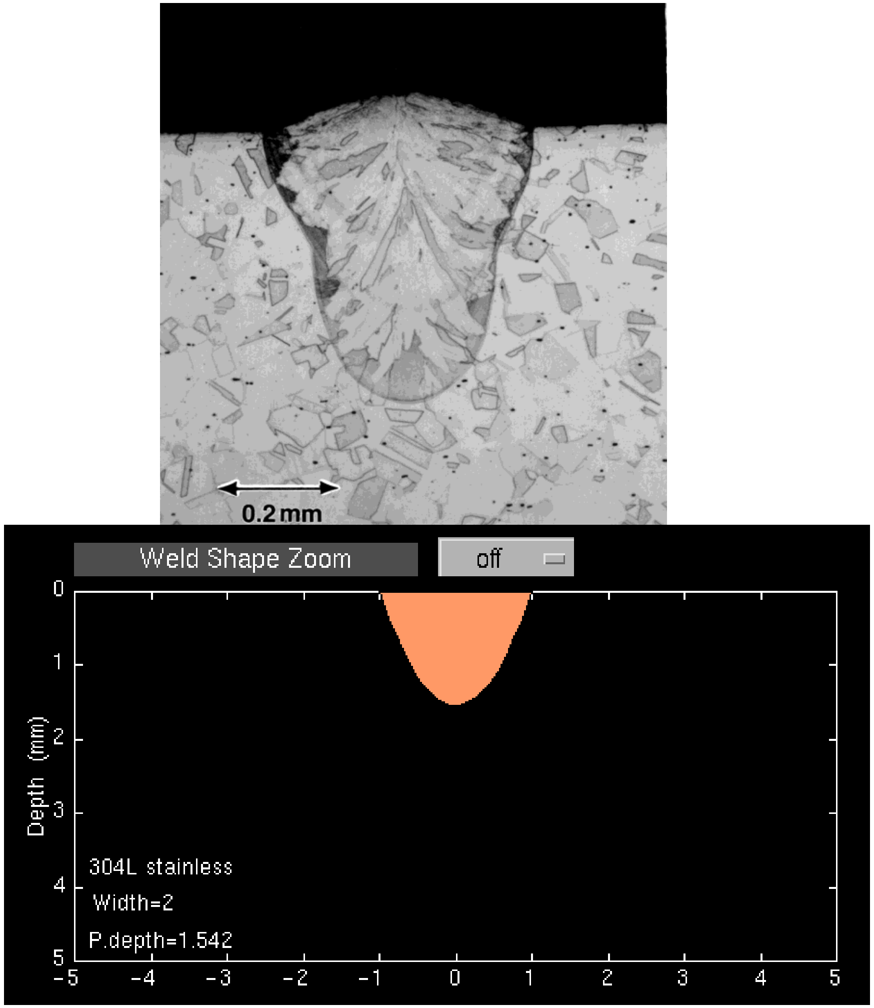
What SmartWeld Can and Can't Do.

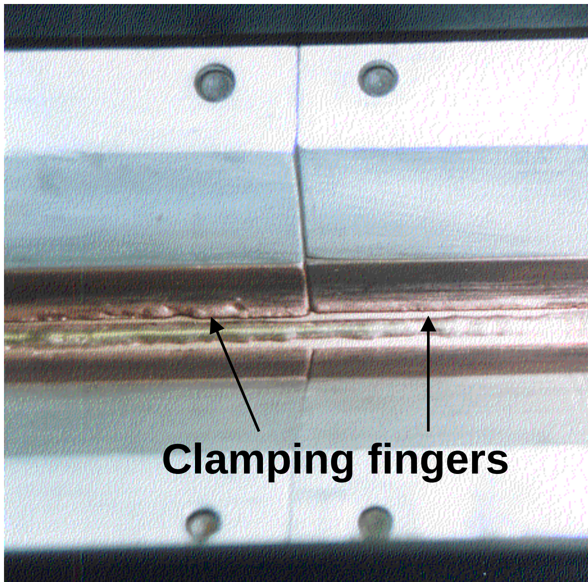


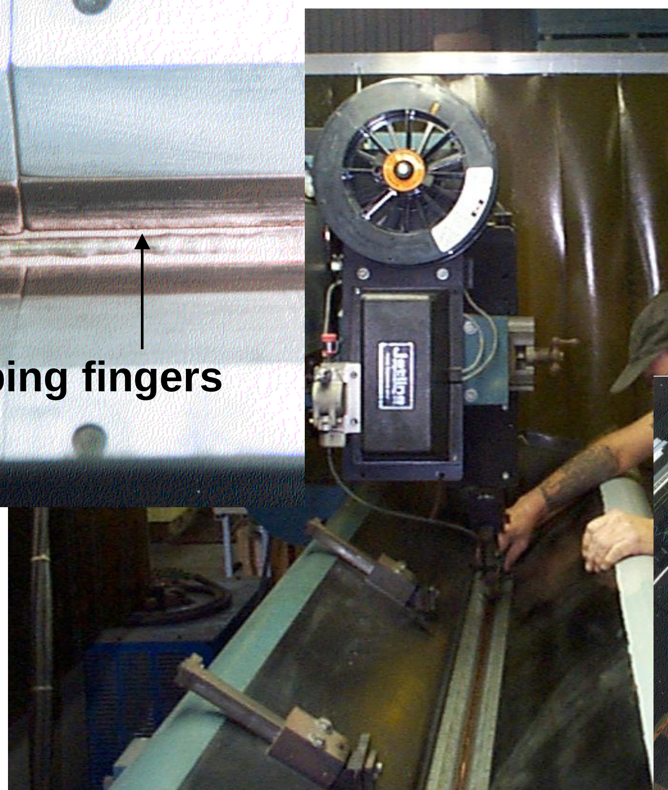
- SmartWeld is a <u>tool</u> for designers and engineers to aid in selecting, optimizing, and configuring automated welding processes.
- It won't tell you if the temperature is too high at a specific location – but it will tell you the temperature.
- It won't tell you what pulse duration is best,– but it will tell you what pulse durations give you the weld size you need.
- SmartWeld gives the user the information needed to understand and set-up a better process.

Example – Investigative

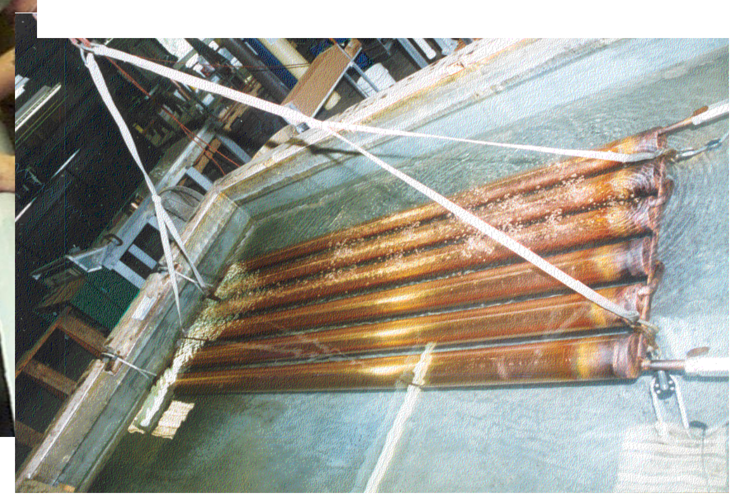
Small batch solar collector tubes leaking

- **Jetline automatic GTAW seam welder.**
- **ETP copper (type 110). Cold wire feed, AWS ERCu Cu-Si filler.**
- **Significant heat sinking through copper backing bar and clamping fingers. (Suspected input variability)**





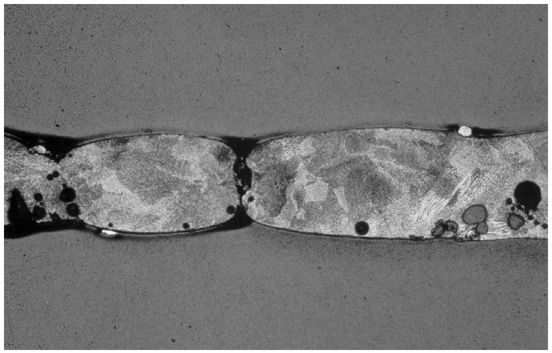
Automatic seam welder



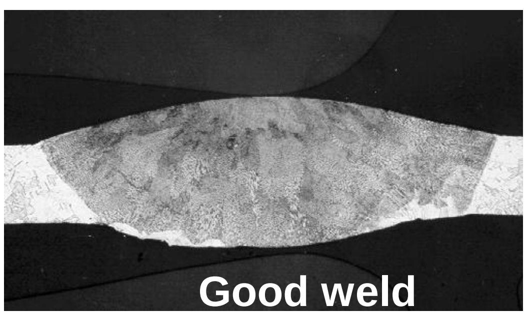
Submerged pressure test

Example – Investigative

GTA Tube Welding Consistency Problem Observed



Defective Cu Weld



Evidence -

- **Weld pool intermittently is disrupted for no obvious reason.**
- **Pool size becomes too large and unstable, weld defect is created.**
- **Onset and frequency of defect seems to be related to duty cycle of welding.**
- **Welding after the machine has cooled eliminates the problem.**

Suspect – **Temperature rise of the heat sink and workpiece is thought to be the source of the inconsistency.**

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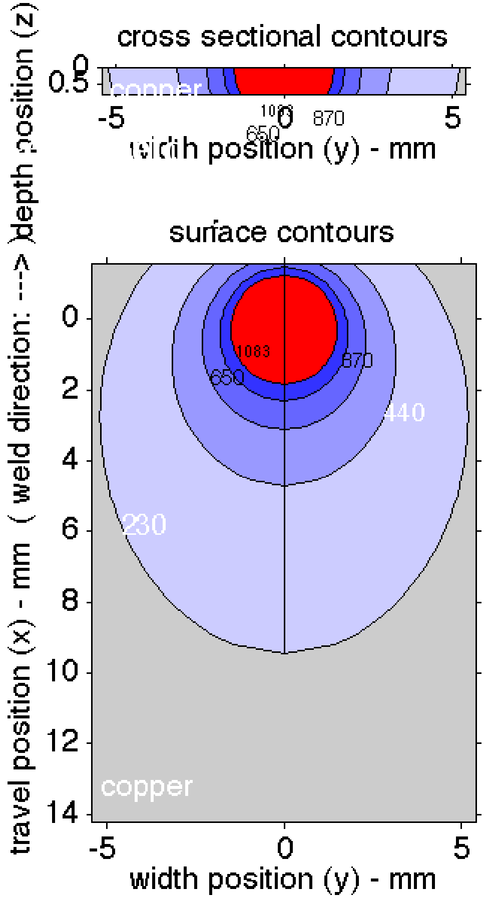
Example – Investigative

A more temperature insensitive procedure?

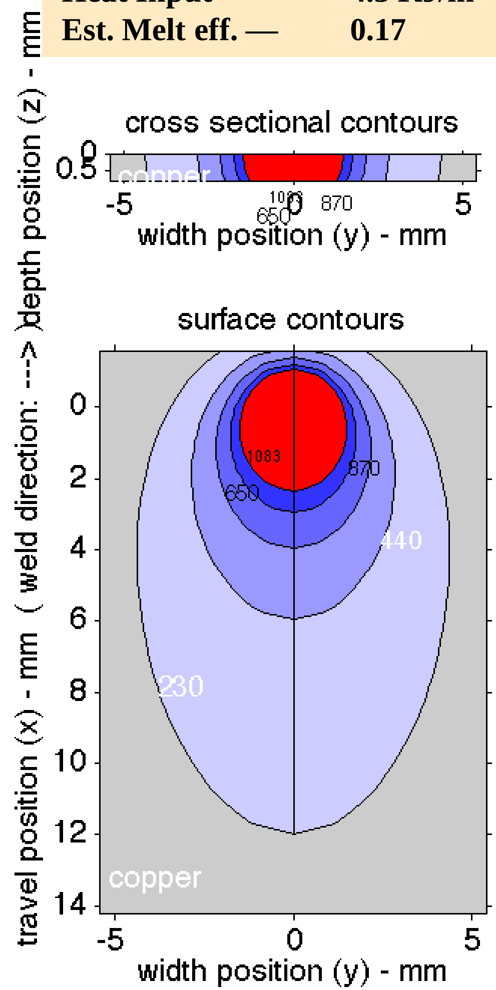
Old Weld Procedure

Arc Current —	**275 A**
Travel speed —	**24 in/min**
Heat Input —	**10.2 KJ/in**
Est. Melt eff. —	**0.09**



New Weld Procedure

Arc Current —	**400 A**
Travel speed —	**56 in/min**
Heat Input —	**4.3 KJ/in**
Est. Melt eff. —	**0.17**



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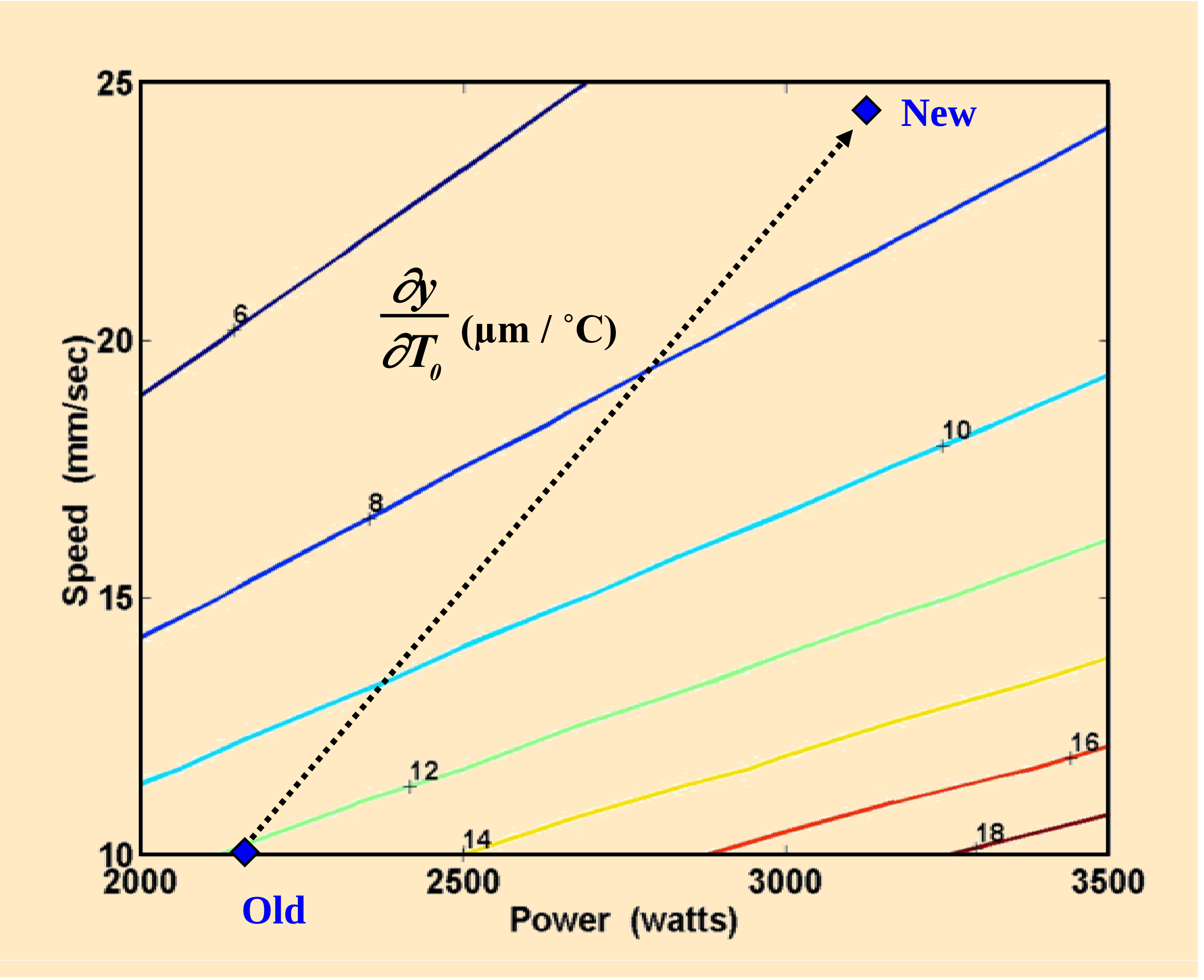
Example – Investigative

Workpiece temp. sensitivity is reduced

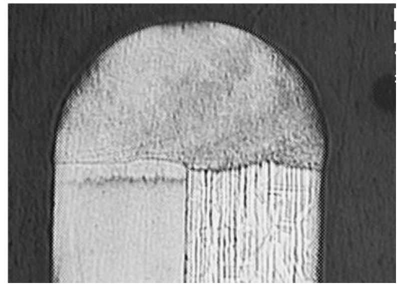
- Sensitivity to base metal temperature is reduced with new procedure.
- Variations in workpiece temperature result in a smaller change to the weld pool size.

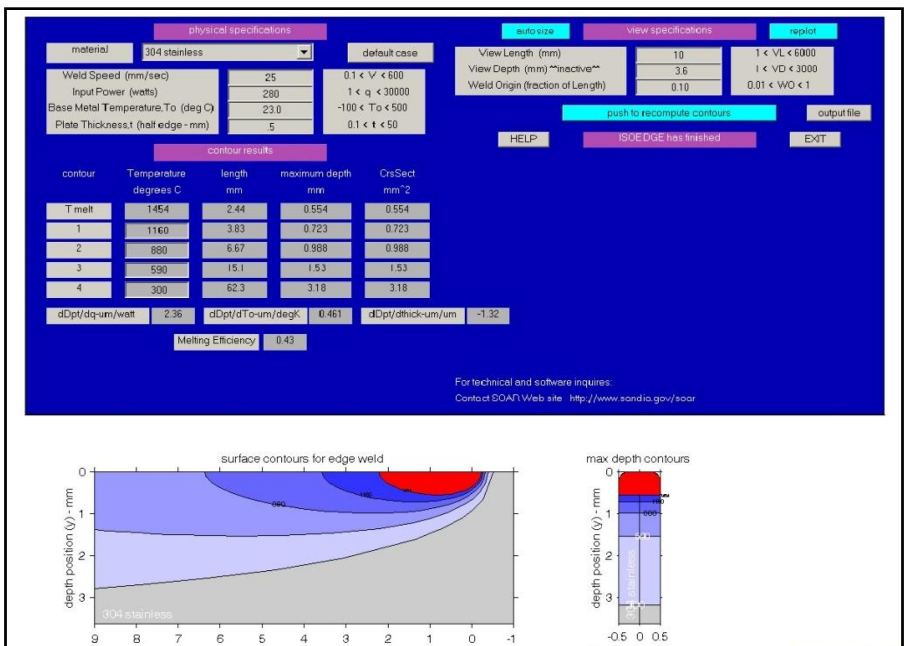


Example – Investigative

Why is a 350 W fast and big weld cooler than a 475 W slow and smaller weld?

304L stainless steel
350 watts
Flange = 0.020 in (0.5 mm)
60 ipm (25mm/s)
Est. weld area = 0.55 mm^2
Measured TC temperature = 185F





- **Using flange thickness, travel speed, and the weld cross-section.**
- **ISOEDGE analysis was queried to find a 304SS edge weld with the same weld area.**
- **The analysis indicates that 280 watts is required to make the weld.**
- **Which yields an energy transfer efficiency (absorption) of 80% (280/350) for the sharp focus weld.**

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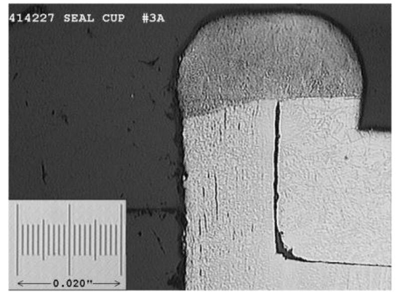
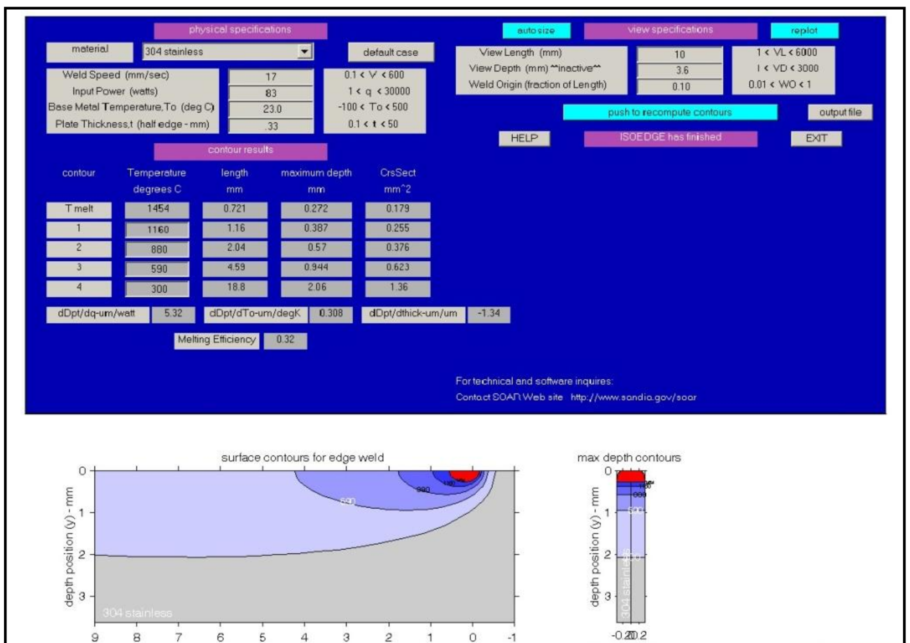
Anomalous Thermocouple Temps in Laser Welds

304L stainless steel
475 watts
Flange = 0.013 in (0.33 mm)
40 ipm (17mm/s)
Est. weld area = 0.18 mm²
Measured TC temperature = 104F





- **Using same application but with smaller flange thickness and weld cross-section.**
- **ISOEDGE analysis was queried to find a 304SS edge weld with the same weld area.**
- **The analysis indicates that only 83 watts is required to make the weld.**
- **Which yields an energy transfer efficiency (absorption) of 17% (83/475) for the defocussed weld.**

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Important Potential New Applications – Ready for Open Source Collaboration in SmartWeld

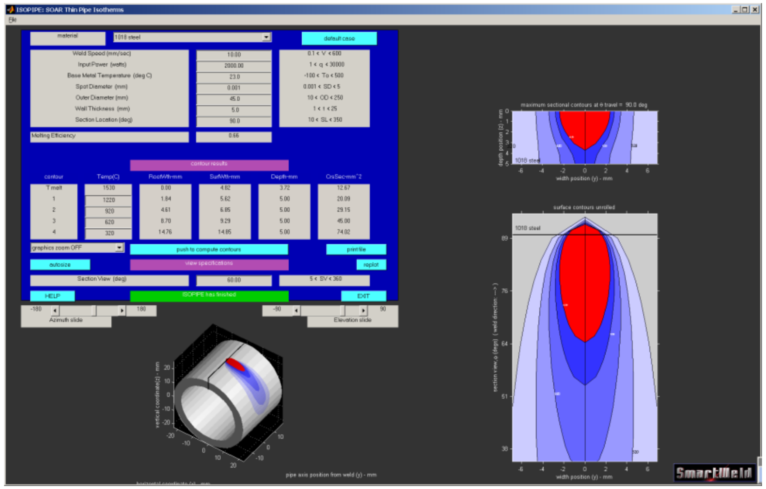
<u>Continuous Pulse Welding</u>

Mirlin, G. A. and P. V. Denisov (1968). "Heating in Pulsed Arc Welding of Sheet Steel." <u>Svar. Proiz.(4): 4-7.</u>
Vishnu, P. R., W. B. Li, K. Easterling (1991). "Heat flow model for pulsed welding." <u>The Institute for Metals: 649-259.</u>

<u>Pipe Welding</u>

Lho, T. J. and S. J. Na (1995). "A Study of Mathematical Modeling of Parameter Optimization in Gas Tungsten Arc Welding of Thin Pipes." <u>Trans. ASME 117(2): 78-83.</u>

Matsutani, T., F. Miyasaka, et al. (1997). "Mathematical Modelling of GTA Girth Welding of Pipes." <u>Welding International 11(8): 615-620.</u>



Unfinished Pipe App. !

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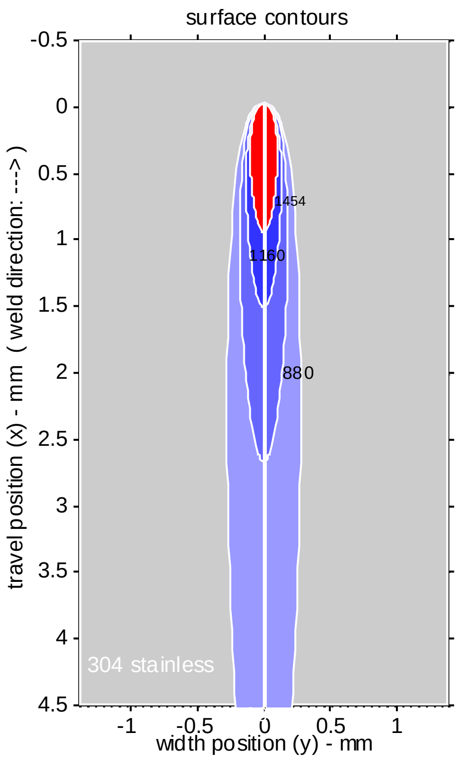
SmartWeld - A Virtual Manufacturing & Process Simulation Technology

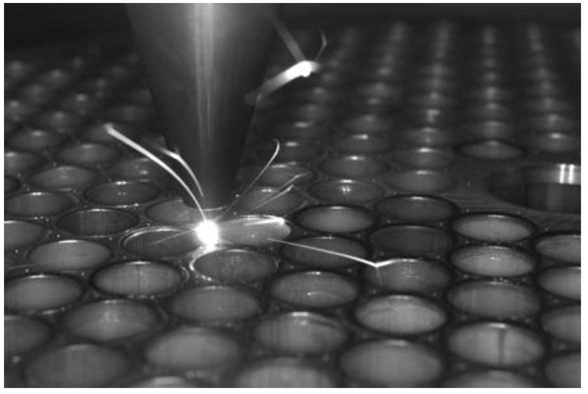
http://sourceforge.net/projects/smartweld/

or

http://smartweld.sandia.gov/



Weld Temperature Contours



Laser Welding

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Backup Slides

Tutorial –

Metals and Alloys in SmartWeld

- **All thermal property values measured calorimetrically.**

304 stainless -	18Cr-8Ni austenitic stainless steel, widely used.
15-5PH stainless-	15Cr-5Ni, precipitation hardened martensitic stainless steel.
17-4 stainless -	17Cr-4Ni, precipitation hardened martensitic stainless steel.
1018 steel -	0.18C-bal Fe plain carbon steel. 60 ksi tensile strength.
HY130 -	0.12C-5Ni-0.6Cr-0.5Mo-bal Fe high yield strength steel(min. 130 ksi).
HY80 -	0.18C-2.6Ni-1.4Cr-0.4Mo-bal Fe, high yield strength steel (min. 80 ksi).
tin -	A low melting point pure metal for comparative purposes.
molybdenum -	Pure metal with excellent high temperature strength.
nickel 200 -	Commercially pure nickel, 99.5% min.
Kovar -	29Ni-17Co-Bal Fe low expansion alloy for glass and ceramic seals.
1100 aluminum -	Low strength with 99% min. aluminum.
6061 aluminum -	Precipitation hardened structural alloy.
110 copper -	Also called ETP copper, oxygen bearing with 99.9 % minimum purity.
Hastelloy C4 -	Ni-16Cr-16Mo alloy with good elevated temperature properties.
Hastelloy C22 -	Ni-22Cr-13Mo-3W-3Fe. Ni based alloy with resistance to corrosion.
Hastelloy B2 -	Ni-28Mo. Ni based alloy with resitance strongly reducing chemicals.
Inconel 718 -	52.5Ni, 19Cr, 18Fe, 5Nb, 3Mo, 0.9Ti. High strength Ni based alloy.
Inconel 625 -	61Ni, 21.5Cr, 9Mo, 3.6Nb. Ni based alloy with high strength.
Ti-6Al-4V -	Heat treatable alpha-beta titanium alloy for aerospace.

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Tutorial -

Energy Transfer Efficiencies (ETE) for Fusion Welding Processes

Welding Process	Reported ETE	Recommended ETE	Reference
EBW, Electron Beam Welding	90%	90%	[1]
GMAW, Gas Metal Arc Welding. (MIG)	85%	85%	[2, 3]
GTAW, Gas Tungsten Arc Welding. (TIG)	67-80%	75%	[4-6]
CO2 Laser Beam seam welding.	20-90%	See OSLW or reference	[7]
Nd:YAG Laser Beam spot welding	38-67%	50%	[8]
PAW, Plasma Arc Welding	47-75%	60%	[3, 5]
SAW, Submerged Arc Welding	90%	90%	[2, 3, 9]
VPPAW, Variable Polarity Plasma Arc Welding, aluminum	41-62%	50%	[10]
SMAW, Shielded Metal Arc Welding (Stick)	75%	75%	[2]

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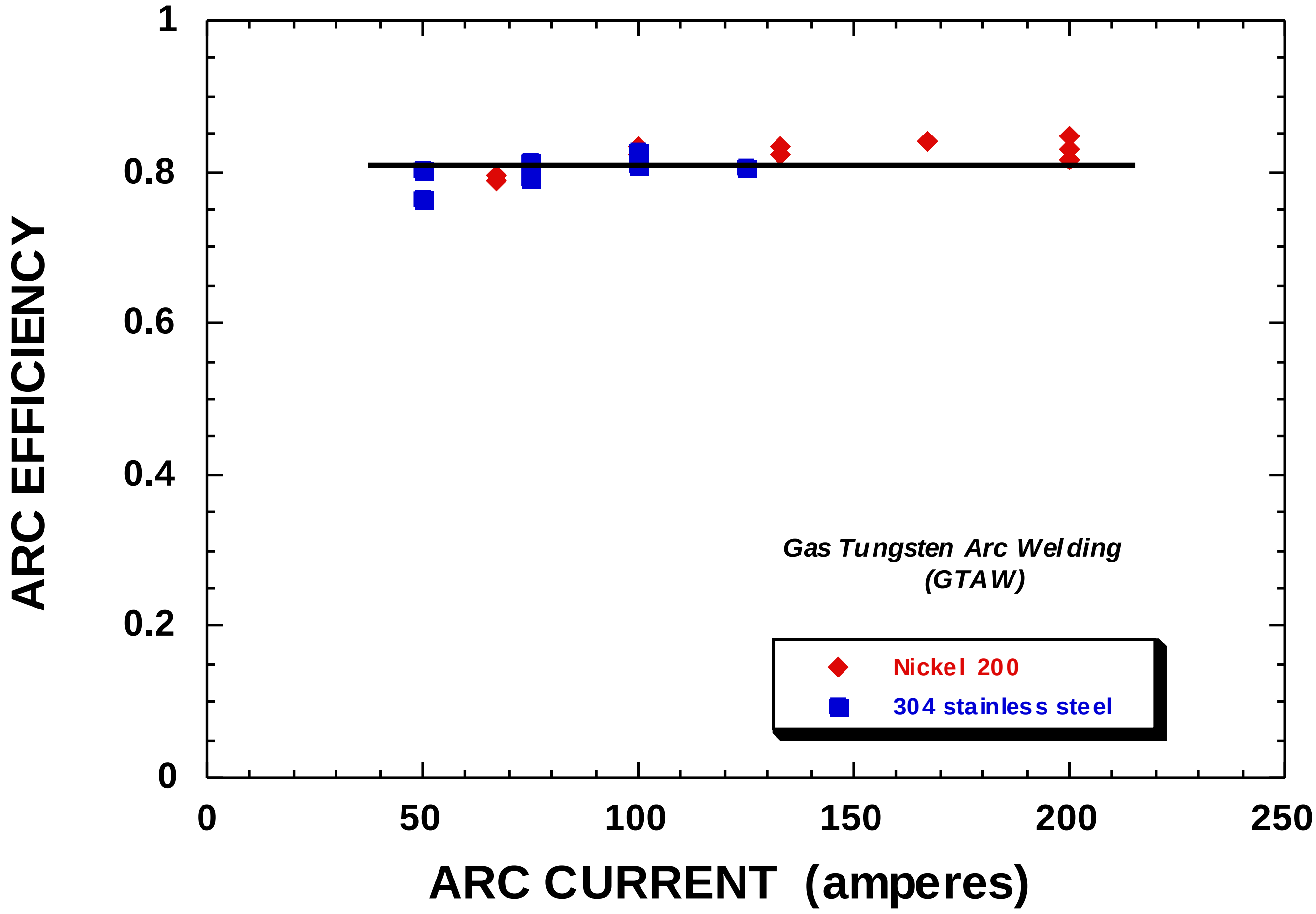
Tutorial –

Consistency in Arc Energy Transfer



From Fuerschbach and Knorovsky, Welding Journal, vol. 70, pp. 287s-297s, 1991.

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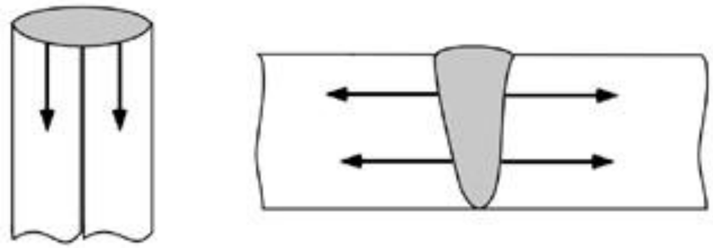
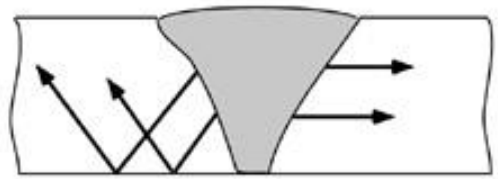
Tutorial -

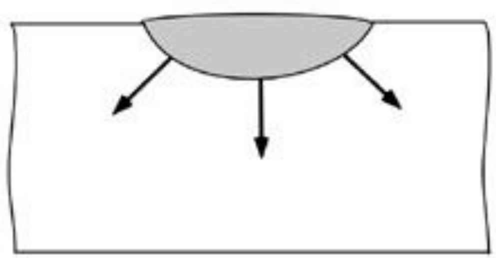
Welding Heat Flow Geometry



2D Heat Flow



2.5D Heat Flow



3D Heat Flow

Spot Welding Applications

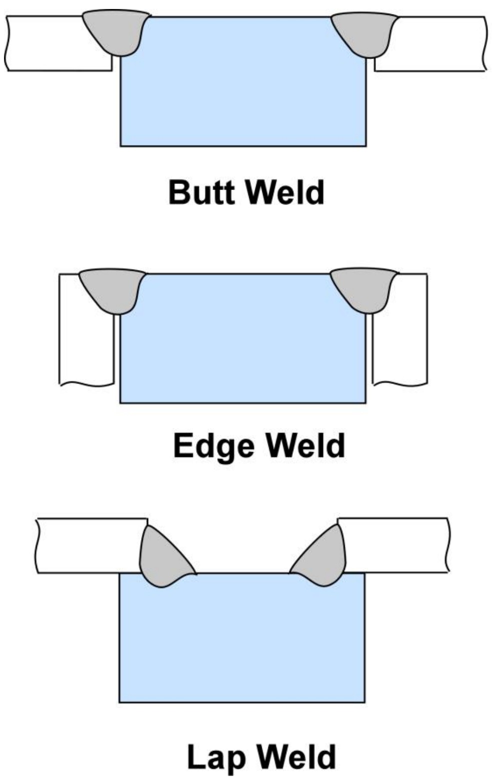
- "Three software programs for spot welding are available from Sandia National Laboratories' SmartWeld project.

- These programs can be used for many different metals and alloys, including 1018 , HY80, and HY130 steels, 304 and 17-4PH stainless steels, 6061 aluminum, Ti-6Al-4V , and Inconel 718.

- The programs are applicable for 2 or 3-dimensional heat flow spot welds, and will determine adjacent temperatures, optimal pulse parameters, and spot weld sensitivities to variations in thickness and base metal temperature.

Lap weld joint has advantages for laser spot welding

- Butt and edge joint geometries require tight tolerances to avoid weld joint gaps.
- Joint gaps become problematic for these weld geometries since the laser beam may pass through the joint resulting in insufficient melting.
- Fillet lap welds have no gap and can be visually inspected unlike piercing lap welds.



Tutorial –
Important Efficiencies Defined

$$Melting\ Efficiency\ (\eta_m) = \frac{Enthalpy\ of\ Weld\ Volume}{Net\ Input\ Energy}$$

$$Enthalpy = [\,\Delta h_f + \int_{T_r}^{T_l} c_p(T)\,dT\,] \times Volume$$

$$Arc\ Efficiency\ (\eta_t) = \frac{Net\ Input\ Energy}{Arc\ Output\ Energy}$$

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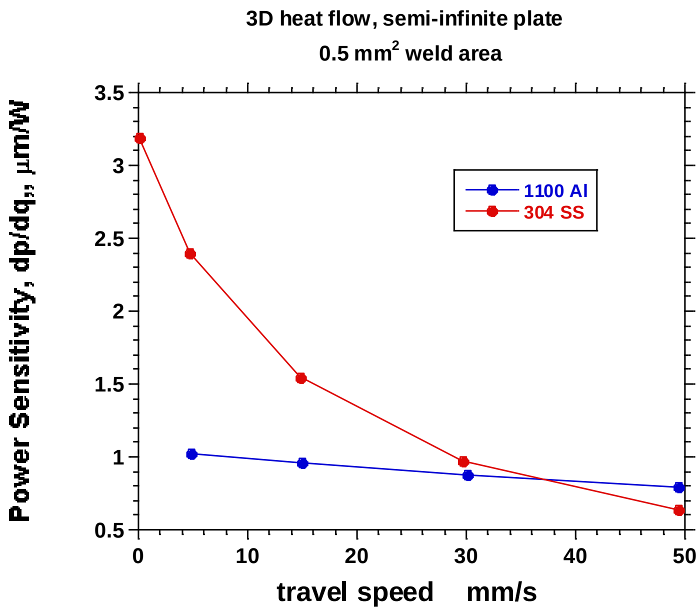
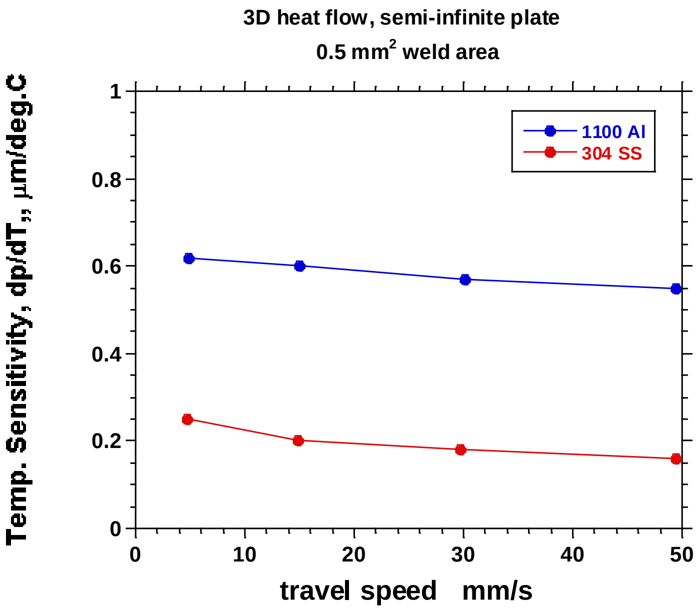
Sensitivity Parameters in SmartWeld

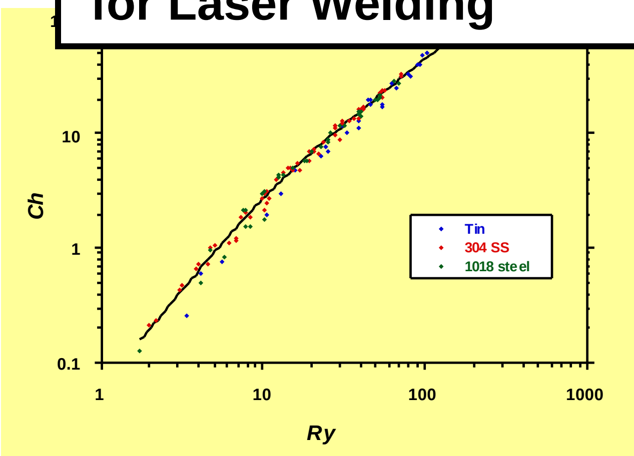




- **Weld pool size will naturally vary with changes in the arc power or base metal temperature.**
- **The magnitude of variation will depend on the weld procedure used.**

Tutorial - Dimensional Analysis of Fusion Welding

Experimental Validation for Laser Welding

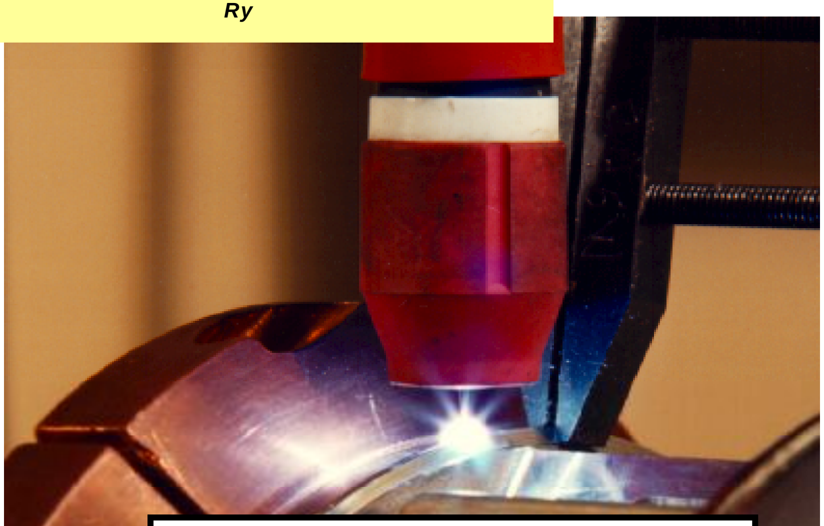


$$Ry = \frac{q_i \upsilon}{\alpha^2 \delta h}$$

$$Ch = \frac{\upsilon^2 A}{\alpha^2}$$

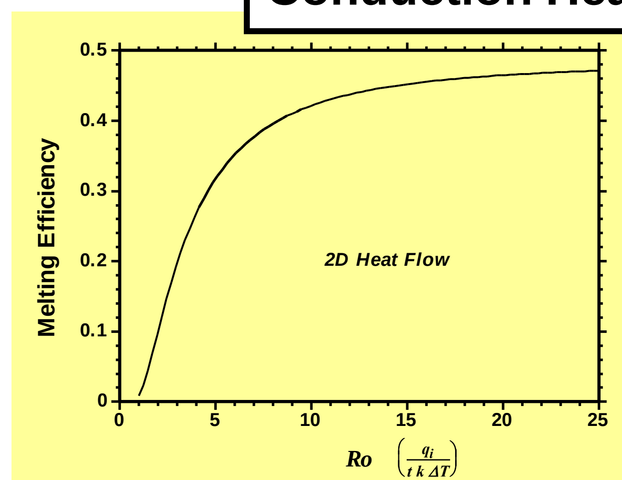
$$Ro = \frac{q_i}{t\, k\, \Delta T}$$

where:
q_i = net power into the workpiece
υ = travel speed
t = characteristic length
k = thermal conductivity
α = thermal diffusivity
δh = the enthalpy of melting
A = the weld cross-sectional area
Ch/Ry = melting efficiency

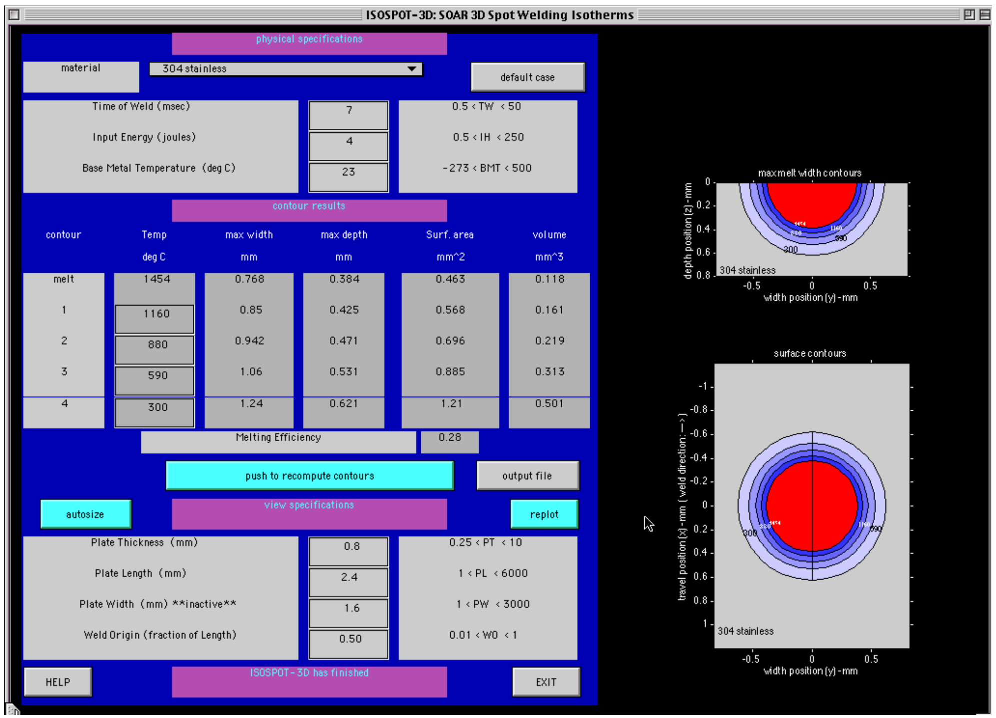


All Welding Applications

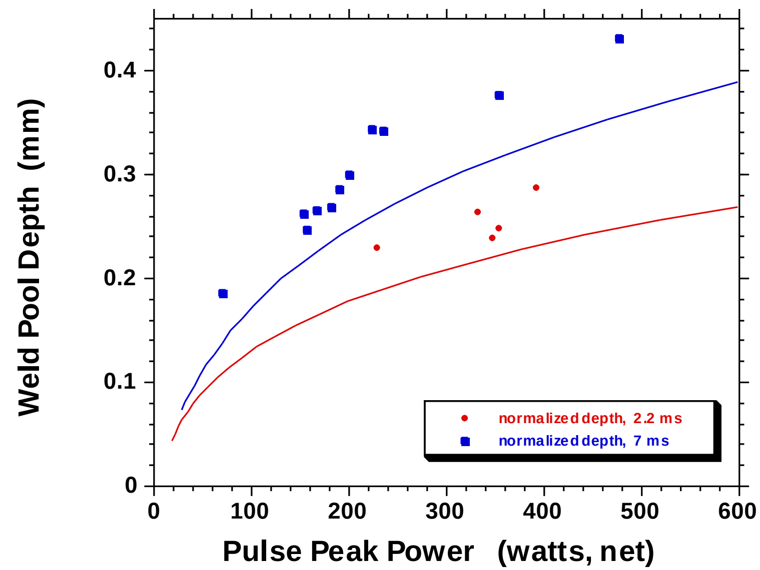
Conduction Heat Flow



Laser and Resistance Spot Welding
ISOSPOT-3D



experimental validation



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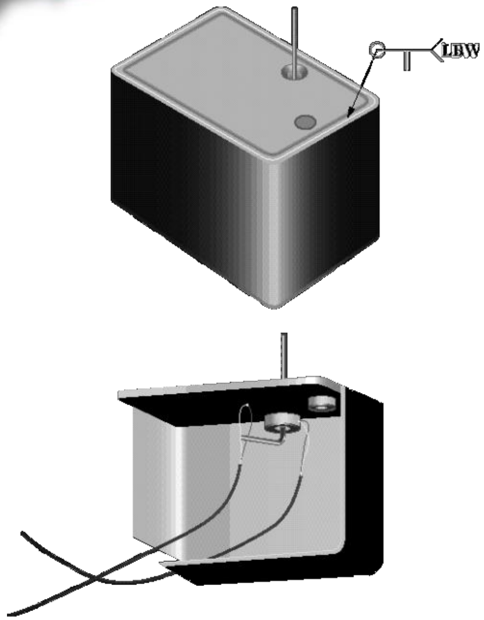
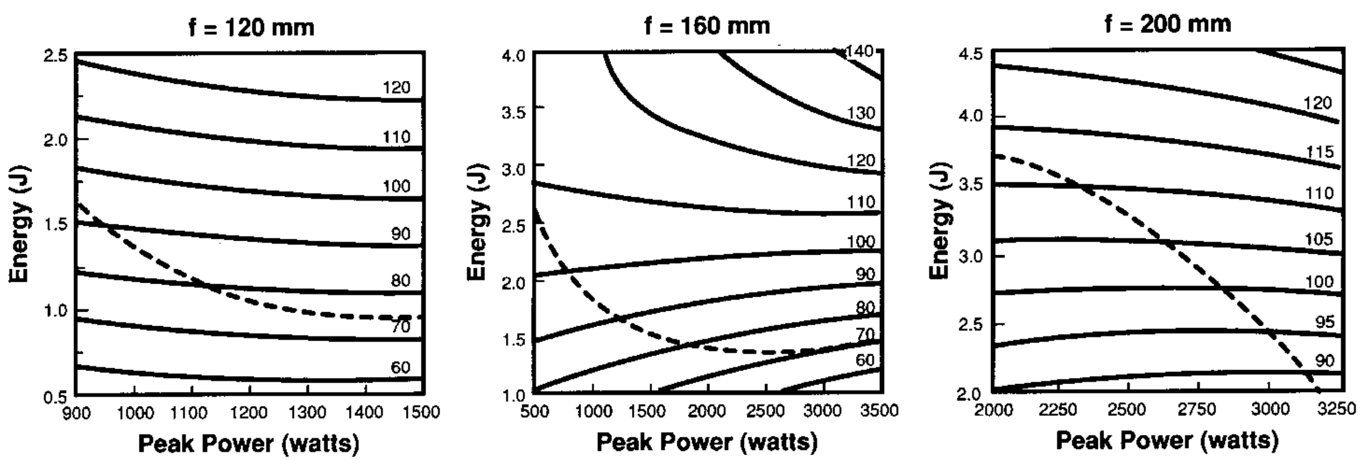
Pulse Nd:YAG LBW of Cardiac Pacemaker Batteries

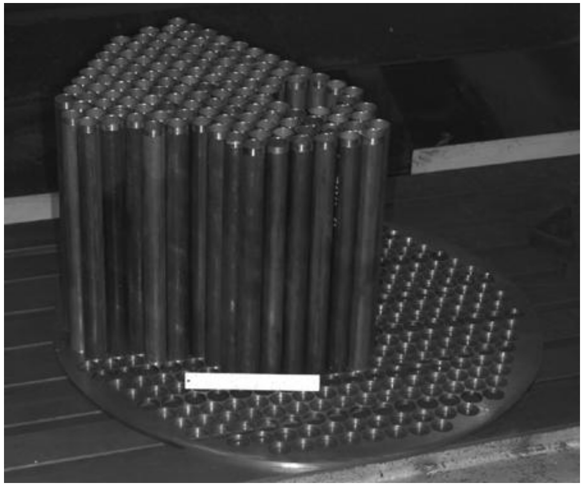


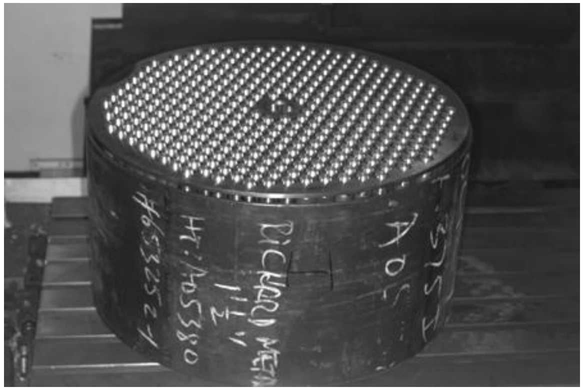
- A customized SmartWeld application for a specific welded product.
- Contour plots indicate optimized procedure for lowest temperature weld.
- Dashed line represents required weld penetration.



Example – Predictive
Fasthawk Nozzle at NAWC, China Lake, CA.

- **Pressure vessel with 372 one inch diameter by 0.065 in tubes welded to a 1/4 in thick tubesheet.**
- **Small (.050 in) spacing between tubes required a deep narrow weld with minimal distortion.**
- **Substantial distortion could result on the one of a kind unit if the laser weld schedule parameters were not chosen correctly.**





Example – Predictive
Customer Expressed Appreciation for the Timely Response and Quality of Welds

- **SmartWeld recommended 1300 watts at 29 mm/s to meet the penetration depth of 2.4 mm required.**
- **Melting efficiency of 0.44 kept distortion to a minimum.**
- **Estimated cost savings just in set up costs were $6000.**