

# SmartWeld : A Knowledge-based Approach to Welding

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## Abstract

SmartWeld is a concurrent engineering system that integrates product design and processing decisions within an electronic desktop engineering environment. It is being developed to provide designers, process engineers, researchers and manufacturing technologists with transparent access to the right process information, process models, process experience and process experts, to realize "right the first time" manufacturing. Empirical understanding along with process models are synthesized within a knowledge-based system to identify robust fabrication procedures based on cost, schedule, and performance. Integration of process simulation tools with design tools enables the designer to assess a number of design and process options on the computer rather than on the manufacturing floor. Task models and generic process models are being embedded within user friendly GUI's to more readily enable the customer to use the SmartWeld system and its software tool set without extensive training. The integrated system architecture under development provides interactive communications and shared application capabilities across a variety of workstation and PC-type platforms either locally or at remote sites.

## Introduction

Welding in the US is a \$50B per year business which generates upwards of \$7B of waste due to rework and scrap. Many of the problems associated with welding arise due to the high degree of "trial and error" that typically accompanies the development of weld processes and schedules, weld joint designs, and material selection. Sandia material scientists and engineers have decades of experience in welding. They have written hundreds of memos and papers addressing welding issues from part/problem specific memos to refereed journal and conference publications. In addition, Sandia analysts have developed weld process models and analysis tools that can predict thermal response and residual stress due to welding.

This knowledge should be an important contributor toward reducing scrap and rework, however, it was only embodied in a select group of experts and was not routinely integrated into the design of welded assemblies. The goal of the SmartWeld project is to collect and package legacy welding information, develop new welding models that advance welding from art to science, and to

make that legacy information and new science available at the fingertips of designers, weld engineers, and analysts.

The SmartWeld system supports users from conceptual design through final, detailed design by incorporating models of varying fidelity and complexity. During conceptual design, it is sufficient for the designer to know that acceptable weld processes exist. During final design, the details of the weld schedule are necessary and may have to be simulated within a 3D Finite Element Analysis code to quantify the design margin.

The SmartWeld system addresses two classes of welding problems. First, for a few, important Sandia product families we use object models to specify default attributes such as alternative weld locations, weld function, candidate materials, part topology, and a finite element mesh that can be changed parametrically by changing part dimensions. For this class of problem, SmartWeld can assist users from conceptual design through visualization of a 3D finite element analysis of heat dissipation during welding.

Second, users want advice on generic welds, such as welding a lid to a housing or welding two flat plates together. In these cases, the user must provide information that is defaulted in the object models of the modeled product families. SmartWeld advises on weld joint geometries, weld process, and weld schedules, but cannot aid in analysis without a user provided mesh.

In the first case, SmartWeld is more useful, but for a limited class of problems. In the second case, SmartWeld provides less, but to a far broader class of problems. In both cases, the goal of SmartWeld is to provide users with the best available data, information and knowledge to assist them in the design and analysis of welded assemblies.

SmartWeld can be accessed either directly or through a product-focused design environment to provide the welding perspective. In the standalone mode, a designer can enter SmartWeld early in the design conceptualization stage and rapidly perform "what-if" testing to estimate the impact of welding on the design. The user can access the weld advisor, the weld schedule database or the weld schedule optimization tools at any time during the design process without having to enter the overall SmartWeld

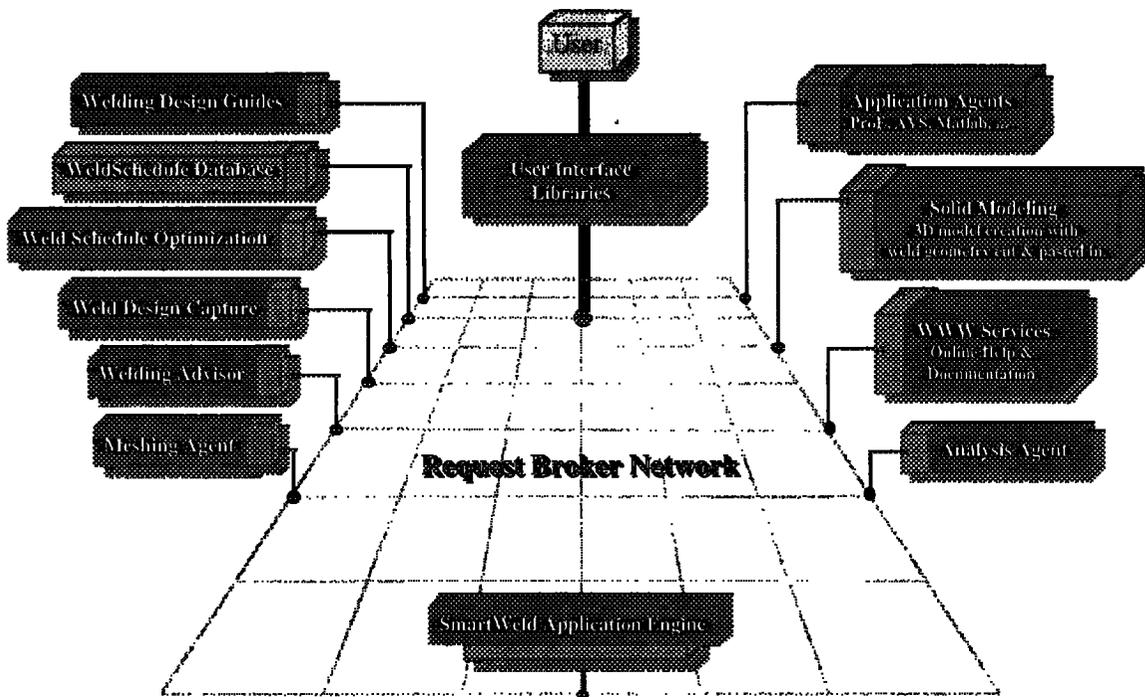


Figure 1. SmartWeld Architecture

architecture. Later, in a more detailed design mode, the designer can enter the system through the product design environment with many of the design decisions complete. SmartWeld then assists the user in developing a more detailed design of the weld. It automatically incorporates the weld and the joint geometry into the product solid model, and creates an executable weld specification.

### Weld Design Issues

The main issues that must be addressed to design a predictably good weld include:

- **Choosing a weld location.** Within product families, usually there are a few locations that are acceptable based on issues such as, reachability by welding machines and location of thermally sensitive regions.
- **Choosing a weld process and joint design.** Different weld processes and joint designs have different properties, such as, depth of metal penetration, heat input, residual stress, distortion, sensitivity to loading and sensitivity to corrosive environments. Choosing the weld process and joint geometry is a core problem. Currently, we are considering fusion welds and solid state welds consisting of six arc and beam welding options, six resistance and friction welding options, and approximately forty weld joint geometries.

- **Weld Schedule Development.** The details of the weld process, and geometry including speed, amps and volts, filler material feedrates, and a full geometric description of the weld joint are represented in the weld schedule.

- **Evaluating the effect of welding on product performance.** Welding joins metal by melting the metal of each piece and creating a fusion zone which is a composite of the original materials. The intense heat required for welding can cause both thermal and mechanical problems. One major concern during welding is damage to thermally sensitive regions near the weld. Changes in the mechanical properties of the part in the weld zone due to this heat treatment is a second major concern.

### System Design

SmartWeld is being built using a three-tiered client server architecture, see Figure 1. All communications between the user interface, the integrating application layer, and each of the tools are done through CORBA™ objects. The goal is to create a system that allows teams of developers to work together without interfering with each other. For example, the user interface can now be either Motif and X-windows or Java™ and Netscape™. The user interface is independent of the application layer. We want to negotiate an interface between the application layer developers and the analysis agent developers that can remain relatively invariant. The analysis agent developers can then improve and modify their code with no adverse effects on the application layer developers.

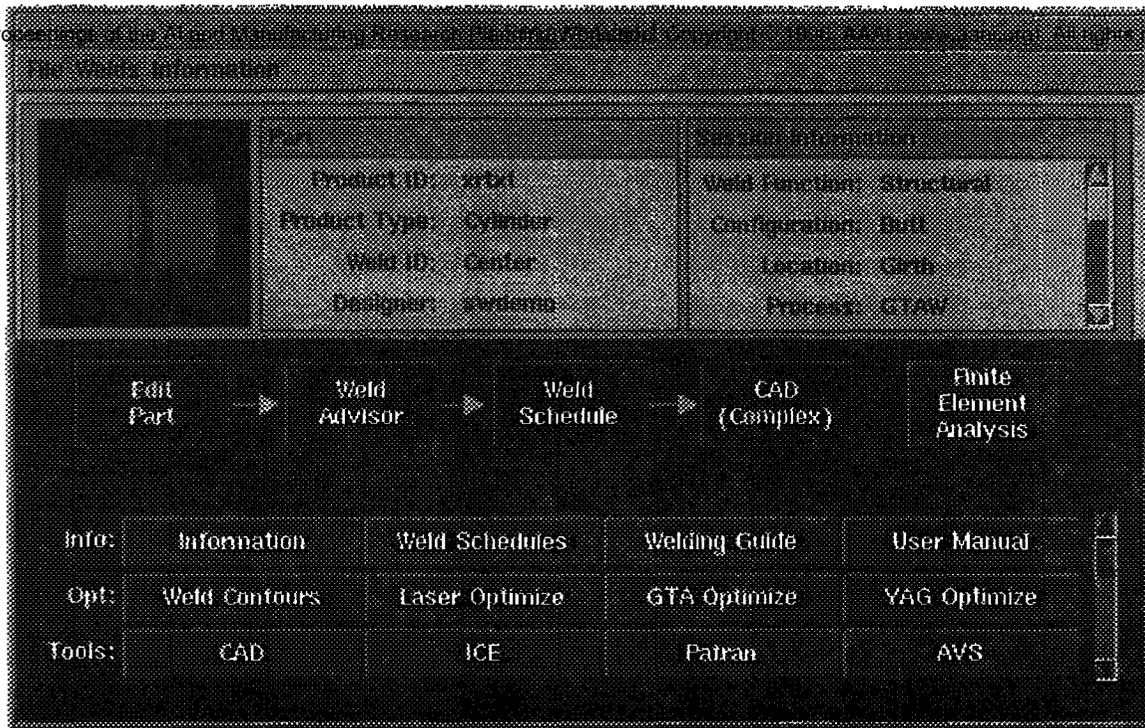


Figure 2. SmartWeld Graphical User Interface

The system consists of:

- A user interface layer – Motif/X-windows or Java™/Netscape™
- an intelligent, integrating application layer, which integrates, within a single desktop environment, the tools and information sources needed by the user to make robust decisions
- a Weld Advisor, which captures Sandia welding knowledge in an object base
- a Weld Schedule database that stores the details of weld schedules and joint geometries used successfully in the past
- a Weld Schedule Optimization tool built on Matlab™
- an integrated Pro/Engineer™ for CAD modeling
- PATRAN™ for meshing
- a simple 2D steady state heat flow model (Rosenthal's equation) that allows users to quickly and analytically evaluate temperatures near the weld
- new laser weld model for predicting thermal contours and residual stress using 3D FEA tools

- new GTA weld models for predicting thermal contours and residual stress for multi-pass welds using 3D FEA tools
- integrated visualization tools to see the results of the FEA analyses.

The SmartWeld GUI, shown in Figure 2, has three major components: The upper section records important attributes of the current problem solving state. The middle section is highly structured to guide the user through the weld design and analysis tools required to produce a predictably good weld. The lower section allows experts direct access to information and tools, such as the World-Wide-Web, hypertext design guides, CAD tools, Matlab™, and finite element analysis tools.

The middle section of the GUI is a network of nodes representing the steps required to design the weld, design the weld schedule, simulate the temporal temperature distribution during the welding process, and visualize the temperature distribution. This structure allows information to be passed seamlessly from one step to the next. The code in this area is able to both syntactically and semantically link all of the weld design and analysis codes. Each node is color-coded to immediately let the user know the status of the current problem - green nodes are available for execution; red ones cannot be performed because at least one precursor condition is not satisfied; blue ones represent completed tasks.

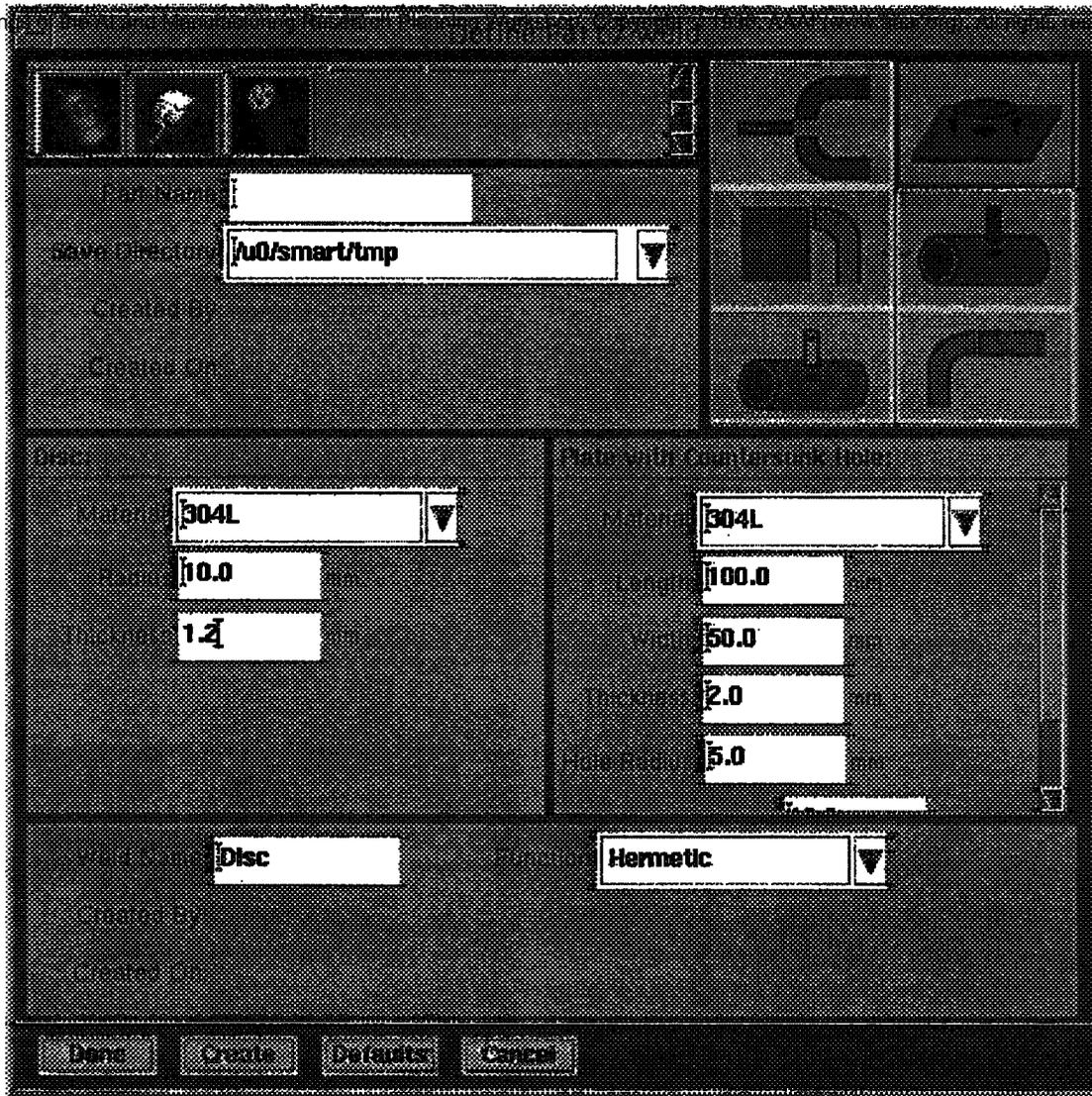


Figure 3. Define Part/Weld Window

### Using SmartWeld

The first step in the weld design and analysis process is the initial definition of the part and weld. When the user clicks on it, the window shown in Figure 3 appears. The user can either import a design at this point or graphically choose a product family by clicking on an icon at the top of the window. In this example the product family has six different welds. Default dimensions (or dimensions passed from the product design environment) are shown on the screen and can be edited for "what-if" testing.

The second step in the design and analysis process is the Weld Advisor. The Weld Advisor is an object-oriented knowledge base. Information about the weld location and function specified in Define Part/Weld starts the reasoning

required to determine plausible weld scenarios. The welds are determined to be plausible based on knowledge about compatibility between materials, weld processes and joint geometries.

The Advisor knows the default attributes of the product family when a part of that type is chosen in Define Part/Weld. The Advisor has both knowledge about welding in general and specific knowledge pertaining to product families. At this point, it begins to reason in the knowledge base. During the reasoning process, if information is required that is not available to the knowledge base, the user is queried. When all information requirements are met, the advisor ranks and scores each plausible weld scenario based on performance criteria.

Rank	Weld Process	Joint Geometry	Material	Temp	Speed	Cost	Quality	Weight
1	HighVoltageEB	Square Butt With Relief Notches	407	47.5	50	20.0	50.0	50
2	LowVoltageEB	Square Butt With Relief Notches	407	47.5	50	20.0	50.0	50
3	HighVoltageEB	Square Butt With Relief Notches And	405	47.5	50	20.0	50.0	50
4	LowVoltageEB	Square Butt With Relief Notches And	405	47.5	50	20.0	50.0	50
5	GTAW	Square Butt With Relief Notches	390	25.0	50	25.0	50.0	50
6	GTAW	Square Butt With Relief Notches And	387	25.0	50	25.0	50.0	50
7	CO2	Square Butt With Relief Notches	352	47.5	50	15.0	50.0	50
8	Nd:YAG	Square Butt With Relief Notches	350	50.0	50	10.0	50.0	50
9	CO2	Square Butt With Relief Notches And	350	47.5	50	15.0	50.0	50
10	PAW	Square Butt With Relief Notches	350	37.5	50	22.5	50.0	50
11	Nd:YAG	Square Butt With Relief Notches And	347	50.0	50	10.0	50.0	50
12	PAW	Square Butt With Relief Notches And	347	37.5	50	22.5	50.0	50
	LowVoltageEB	Square Butt Joint	367	47.5	Failed	20.0	50.0	50
	HighVoltageEB	Square Butt Joint	367	47.5	Failed	20.0	50.0	50
	LowVoltageEB	Square Butt With Backing	362	47.5	Failed	20.0	50.0	50

Figure 4. The Results Screen from the Weld Advisor

Each ranking criterion has an "importance" and a "weight" associated with it. "Required" criteria are hard constraints, and "desired criteria" are soft constraints. If a user wishes to omit one of the normal criteria from the evaluation function, the "don't care" importance for that criteria is chosen. Initially by default, all criteria have "required" importance as opposed to "desirable" or "don't care" and each has a weight of 50. Both the importance and weight of each criterion can be changed by the user to develop an understanding of the sensitivity of the weld scenario rankings to the importance and weighting of each criterion. This allows the user to rapidly perform trade-off assessments. In addition, an explanation facility exists which explains in detail how each weld scenario was evaluated.

Each ranked weld process and joint geometry are classified into one of three color-code categories. Green welds satisfy all of the hard and soft constraints. Yellow welds satisfy the hard constraints, but fail one or more soft constraints. Red welds fail at least one hard constraint.

Once the user selects a weld from the rank-ordered welds, the user can transparently access appropriate weld schedules from either a database or from optimization codes. The database of historical weld schedules describes in extensive detail all of the information needed to fully

specify the new weld on the new part. The SQL selection is based on the material, weld process, joint geometry and material thickness. Information is stored about the component being welded, its piece parts, details on the joint geometry, and extensive information on the machine parameters during the weld. The database is an implementation of a highly normalized relational schema developed using the information modeling methodology, NIAM. Once a weld schedule is selected, the information is mapped to objects for further usage downstream of the advisor.

At times, a validated weld schedule may not exist in the database, or the user may not want to use the weld schedules that do exist. In either case, SmartWeld includes validated optimization models of several weld processes and joint geometries that can produce the necessary weld schedule information.

The next step in the weld design and analysis process is to create the solid model of the part, if necessary, and to paste the selected weld joint into it. Pro//Engineer is our solid modeling CAD tool. A complex CAD model can either have been input into the SmartWeld system from a design environment or can be automatically generated from decisions the user made in the Define Part/Weld step. If generated from the specification in the Define Part/Weld step, the model is created on-the-fly and saved. Next, for finite element analysis the part, if complex,

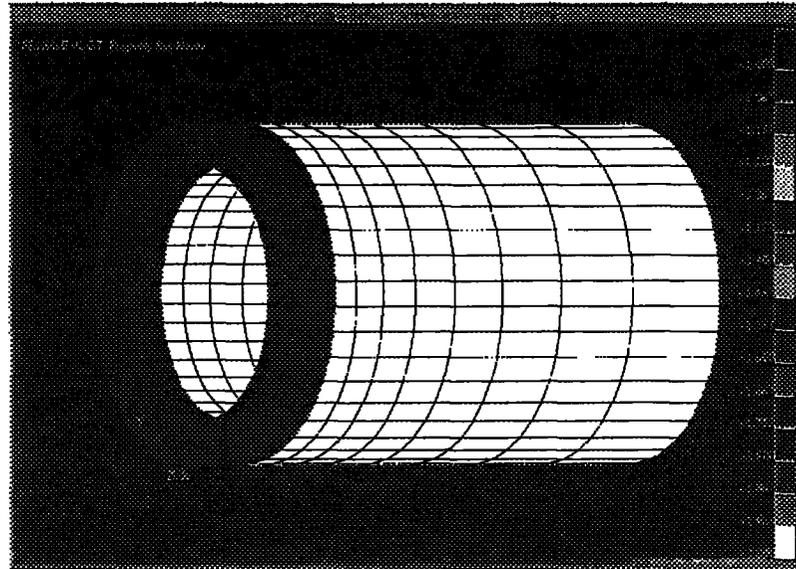


Figure 5. A meshed cylinder.

should be simplified to minimize meshing and thermal analysis calculations around features that do not impact the temperature and stress distributions generated by the weld. The system cannot automatically do this simplification, but does automatically bring up the model in *Pro/Engineer™* for simplification and then saves it in the appropriate place.

Next, a finite element mesh must be installed in the solid model. *PATRAN™* is used for mesh generation. An example mesh for a cylindrical part is shown in Figure 5. For each product family, an expert analyst designs the first parameterized mesh. Once this mesh exists, the user can modify the mesh parametrically within bounds for "what-if" testing. The user can also specify boundary conditions. For example, the user can decide to use a water-cooled fixture if heating is expected to cause a problem. With a water-cooled fixture, the surface temperature boundary condition under the fixture can be held to 30°C for the duration of the weld.

The next step in the weld design and analysis process is to validate the selected weld schedule by performing a 3-dimensional thermal analysis. To do this the user must choose the appropriate material model, and must specify the weld process schedule and setup conditions. For different weld processes, process specific heat flux models are applied. These models are typically

represented as either heating the surface under the arc or beam or heating the whole volume of metal under the arc or beam. For both material and process models, the most likely model is presented as a default, but the user must

confirm the choice and, if knowledgeable, can override it.

When these conditions are satisfied, the thermal analysis is performed automatically. All of the input to the thermal analysis code is modified on-the-fly based on the user's decisions. The thermal analysis code resides on several computers on our network so each computer bids and the one with the estimated fastest turnaround is given the job. We are using *JACQ*, an internally developed Sandia code for thermal analysis. *JACQ* simulates the evolution of the temperatures generated by the welding process over time, including the addition of filler material in the weld.

The final step in the weld design and analysis process is visualization, as illustrated in Figure 6. The output of the thermal analysis is automatically input into another Sandia code, *FEAVR* (Finite Element Analysis Viewer) for automatic creation of a movie of the evolving temperature distribution in the part. *FEAVR* is written in the *Advanced Visual Systems (AVS™)* code. The user can also pick a node in the mesh and watch the temperature for that specific point evolve over time. This is important if there is a specific thermally sensitive area that is of concern.

Another component of *SmartWeld* is random, direct access to information and tools. Expert users want to exploit the structure of the problem, but do not want to be locked in to that structure. They need random access to all of their tools and information sources. Access to the *World-Wide-Web*, the *Weld Advisor*, the *Weld Schedule Database*, and an *HTML Weld Design Guide* is built into the system. *Pro/Engineer™*, *AVS™*, *PATRAN™*, *XV™*, *JACQ*, *Matlab™*, video-teleconferencing, and application sharing are currently available from the *Tool Bar*.

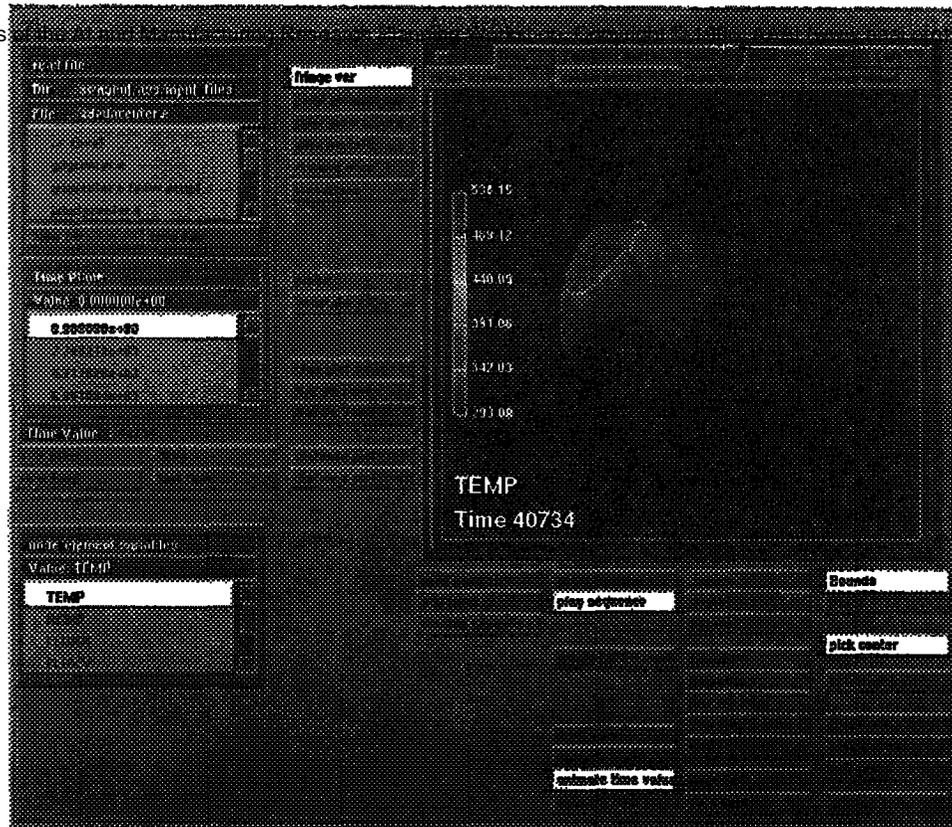


Figure 6. Visualization of Weld Temperature Distribution for a Flat Plate in FEA VR

Additional tools and information sources can be added easily.

All of these facilities are completely integrated into a point-and-click environment that seamlessly translates from one code to the next. The current system runs on a distributed network that links Sandia's sites in California and New Mexico. The user does not know the syntax of each code, the location, or even the machine that is running the code. The main code runs on a Sun workstation in California. The visualization code runs on a different machine in California. The database exists on a Sun workstation in New Mexico. All of this is completely transparent to the user. This distributed system is accomplished through an agent-based architecture. The code is written in C and Kappa, a product of IntelliCorp.

#### Future Work

Users of SmartWeld will drive the evolution of the system until it fully meets their requirements for weld design and analysis. We will continue to add knowledge to the system to improve the recommendations from the Weld Advisor and to further integrate all of the codes. Our goal is to not only make the integration of these codes mechanically seamless, but semantically seamless as well.

We are also extending the SmartWeld system to new product families and customers. As more and more knowledge is incorporated into the system, the addition of new product families should become faster and less expensive. We intend to make this system applicable to a broad spectrum of weld processes, product families and customers.

SmartWeld is the prototype for the SmartProcesses program. We are currently in the initial stages of development of a system that addresses a broader category of manufacturing processes. Additional new SmartProcesses include encapsulation, forging, soldering, design for machinability and a near net shape advisor.

#### Acknowledgments

The authors acknowledge the valuable contributions of Gregorie Gershanok, Ken Hicken, Gerald Knorovsky, Phil Fuerschbach, Artie Ortega, Jim Lathrop, Steve Gianoulakis, Richard Eisler, Charles Ray, Chris Montoya, Kristen Phillips and Larry Schoof to the SmartWeld project. We also acknowledge Duane Lindner, the Product Realization Backbone Manager at Sandia National Laboratories. This work is a component of his Product Realization program. This work was performed at Sandia National Laboratories supported by the U.S. Department of Energy under contract numbers DE-AC04-76DP00789 and DE-AC04-94AL85000.