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Weld Predictor App

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Abstract

Welding is an important manufacturing process used in a broad range of industries and market sectors, including automotive, aerospace, heavy manufacturing, medical, and defense. During welded fabrication, high localized heat input and subsequent rapid cooling result in the creation of residual stresses and distortion. These residual stresses can significantly affect the fatigue resistance, cracking behavior, and load-carrying capacity of welded structures during service. Further, additional fitting and tacking time is often required to fit distorted subassemblies together, resulting in non-value added cost.

Using trial-and-error methods to determine which welding parameters, welding sequences, and fixture designs will most effectively reduce distortion is a time-consuming and expensive process. For complex structures with many welds, this approach can take several months. For this reason, efficient and accurate methods of mitigating distortion are in-demand across all industries where welding is used.

Analytical and computational methods and commercial software tools have been developed to predict welding-induced residual stresses and distortion. Welding process parameters, fixtures, and tooling can be optimized to reduce the HAZ softening and minimize weld residual stress and distortion, improving performance and reducing design, fabrication and testing costs. However, weld modeling technology tools are currently accessible only to engineers and designers with a background in finite element analysis (FEA) who work with large manufacturers, research institutes, and universities with access to high-performance computing (HPC) resources. Small and medium enterprises (SMEs) in the US do not typically have the human and computational resources needed to adopt and utilize weld modeling technology.

To allow an engineer with no background in FEA and SMEs to gain access to this important design tool, EWI and the Ohio Supercomputer Center (OSC) developed the online weld application software tool “WeldPredictor” (https://eweldpredictor.ewi.org). About 1400 users have tested this application. This project marked the beginning of development on the next version of WeldPredictor that addresses many outstanding features of the original, including 3D models, allow more material hardening laws, model material phase transformation, and uses open source finite element solvers to quickly solve problems (as opposed to expensive commercial tools).

Statement of Objectives

The development focused on arc welding processes including gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and submerged arc welding (SAW) for steels, aluminum alloys, and titanium alloys.

The original objectives of the project were as follows.

Objective 1 – Front-End Interface Development

In this task, OSC, with EWI support, will design and build the modern web user interface (UI) for the new version of WeldPredictor. The UI will encapsulate the workflow of defining a weld simulation, including specifying (1) welding process, (2) geometry and welds (building from interface or importing a CAD model), (3) material selection for both base and filler materials, (4) material property customization, (5) weld parameter input including preheating and inter-pass temperatures, (6) weld fixture definition and inspection via a 3-D interface with interactive rotation and zoom control, and (7) Optional user defined outputs. An executable weld simulation will be created from the simulation definition by populating one of the computational templates with input from the user forms. Once a simulation is created, the UI will provide controls to execute and inspect the weld simulation. Once a simulation is completed, the UI will provide controls to output simulation results, including display of notable plots, interactive analysis and a summary PDF report.

Objective 2 − Automatic Mesh Generation

A computer program will be developed to create finite element mesh automatically based on the geometry information collected in the UI developed in Task 1. The user-defined weld fixture conditions in the web interface in Task 1 will be converted to numerical boundary conditions. Thermal and mechanical boundary conditions will be applied in the model. User input files will be created for running the analysis.

Objective 3 − Develop Thermal-Analysis Solver

A thermal-analysis solver will be developed based on open-source finite element codes to predict temperature during weld and cooling. The heat source models for GMAW, GTAW, and SAW will be implemented in the solver to calculate heat flux at a given time and at a given location in the weld joints based on the defined welding parameters in Task 1.

Objective 4 − Develop Microstructure Prediction Code

Microstructure prediction codes will be developed to predict microstructure phases and hardness resulted from welding process for steels, aluminum alloys and titanium alloys based on predicted thermal cycles in Task 3 and user defined chemical compositions and CCT diagram.

Objective 5 – Develop Mechanical-Analysis Solver

A mechanical-analysis solver will be developed based on open-source finite element codes to predict stress and distortion by inputting the predicted temperature in Task 3 and predicted microstructure change in Task 4. The solver allows isotropic, kinematic, and combined isotropic/kinematic hardening laws and is able to model material phase transformation induced plasticity. The solver can also handle the different coefficient of thermal expansion during heating and cooling. Material melting will be modeled in the mechanical-analysis solver.

Objective 6 – Automatic Post-Processing

The analysis results will be post processed automatically by developing software codes and using open source code such as Paraview. The results will include distributions of temperature, stress, and distortion, which will be presented using contour plots. The temperature history and cooling rate will also be provided as line plots. The results will be assembled into a PDF file to allow a user to download. Animations will be created based on a user's request.

Objective 7 – Software Integration

The new version of WeldPredictor will be launched by integrating the front-end (Task 1) and back- end software codes (Tasks 2-6). OSC will be responsible for the software integration and software function testing.

Objective 8 – Software Testing and Validations

The developed new version of WeldPredictor will be tested by EWI for predicting temperature, residual stress, and distortion and comparing the model predictions with the experimental data and public literature data to validate the model.

Objective 9 – Software User Manual and Training

OSC will work with ORNL will develop a user manual including software theory, implementation, user guidelines, and simulation examples. OSC and ORNL will conduct a software training (workshop) class to users.

Benefits to the Funding DOE Office's Mission

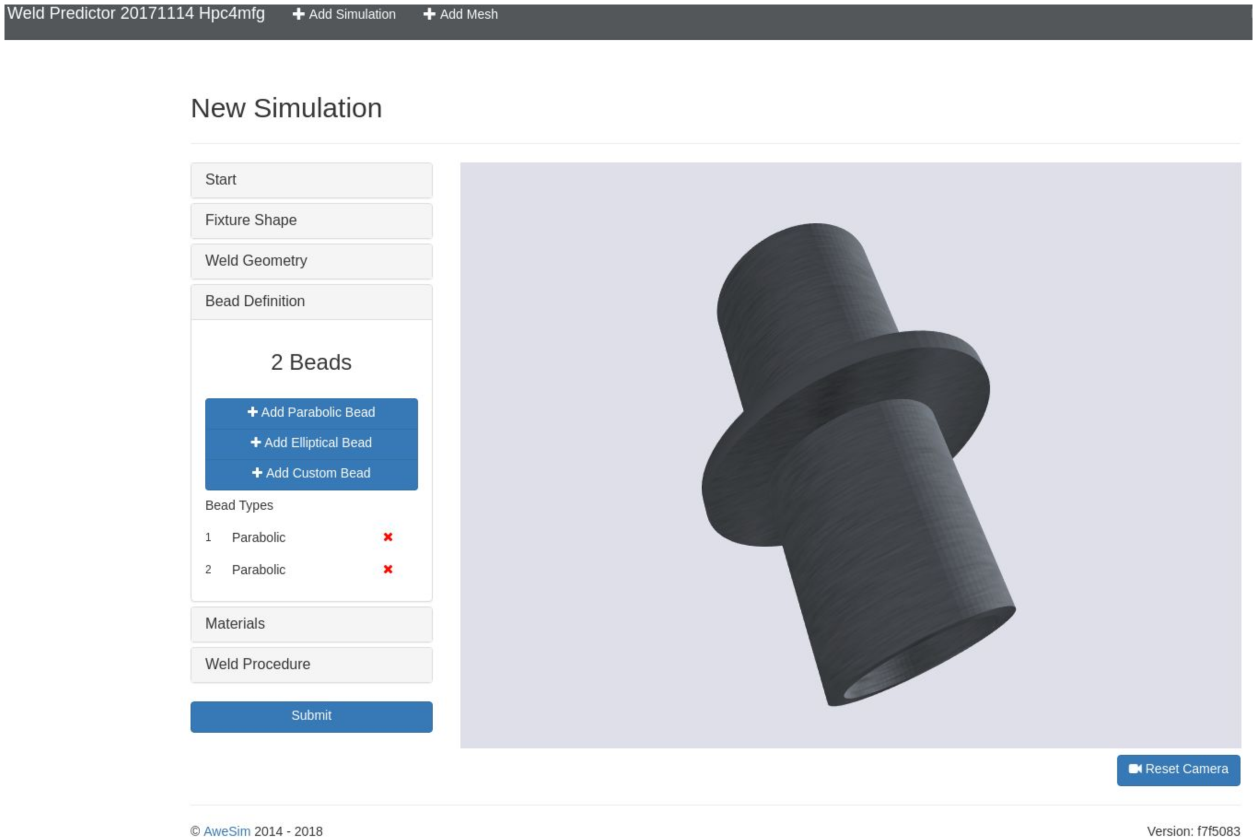
The project was supported as part of a Phase I award in the High Performance Computing for Manufacturing (HPC4Mfg) program from the Advanced Manufacturing Office within the Office of Energy Efficiency and Renewable Energy of the US Department of Energy. This program seeks to connect industry partners who need high performance computing to laboratory researchers with expertise in high performance computing for challenging manufacturing problems. This project directly benefited both the sponsor and the partner by beginning development on a next generation tool for predicting weld performance, which provides significant cost savings across industries. To use the marine industry as an example, based on a presentation at the 2004 ShipTech conference, it costs about $4.2M for a deepwater warship, $13M for an LPD warship and $5.6M for an DDG warship to correct welding-induced distortion. If distortion can be controlled to meet the designed tolerance by optimizing the welding process and fixture, and assuming 25% cost is the energy cost (electricity, inert gas, etc.), the energy saving is $5.7M for building one of each of these ships.

Technical Discussion of Work Performed by All Parties

ORNL, OSC, and the Edison Welding Institute (EWI), who acted as a subcontractor on this work to OSC, completed objectives 1-3, and 5, and made progress on objectives 6-9, with objectives 6 and 7 nearly completed at the time of this report. An insignificant amount of progress was made on task 4 and mid-way through the project ORNL staff decided to focus more on the other tasks it was assigned. A number of changes were made to the frameworks used in this project. Specifically, MOOSE and Eclipse ICE were not used. The team determined that MOOSE was not a good fit for the welding problems because of challenges related to the way that code handles non-linear mechanics. MOOSE was replaced with WARP-3D (http://www.warp3d.net), which is both HPC and currently used by a number of large industrial companies to study welding problems. Although there were no problems in principle using Eclipse ICE, it was not used because it was easier to Open OnDemand from OSC for the front end tasks.

Objective 1

The figure below shows the new WeldPredictor UI with support for 3D models and running in a web browser. The geometry pictured is a “T-Pipe” geometry with two pipes welded together on a flange using a triangular weld line. Users can configure the geometry, the shape, the bead definition, the materials, and the weld procedure. Support is currently in development so that users will be able to upload and view meshes for arbitrary geometries.

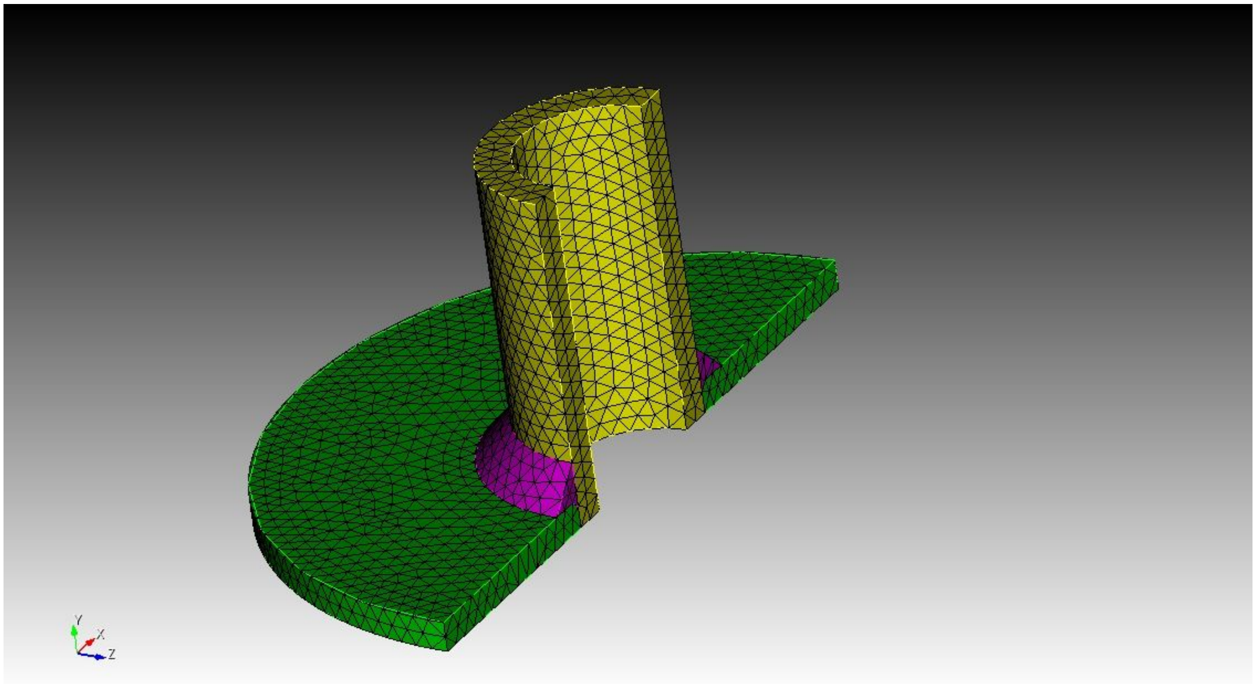


Weld Predictor 2.0

Objective 2

The team produced an automated meshing program, named Ganjiang, based on the Netgen that can generate meshes in parallel by combining parts in a STEP file. The tool uses Netgen and OpenCASCADE to merge and mesh the parts based on simple user instructions provided in an INI input file. The tool has been tested out to 32 processors successfully at which point scaling stopped for even large meshes because tetrahedral elements are easy to generate. The figure below shows a clipping of plate-and-flange part with a triangular weld pattern around the circumference. This part was meshed in less than 0.1 seconds on ORNL's CADES cluster using 32 cores.

The primary purpose of developing this tool was to streamline mesh generation, which can be an expensive and dominating part of the modeling and simulation workflow. Instead of requiring users to spend significant amounts of their own time generating and then uploading the mesh, Ganjiang will automatically perform joining, merge, and minor repair operations on the geometry before attempting to generate a mesh in parallel.

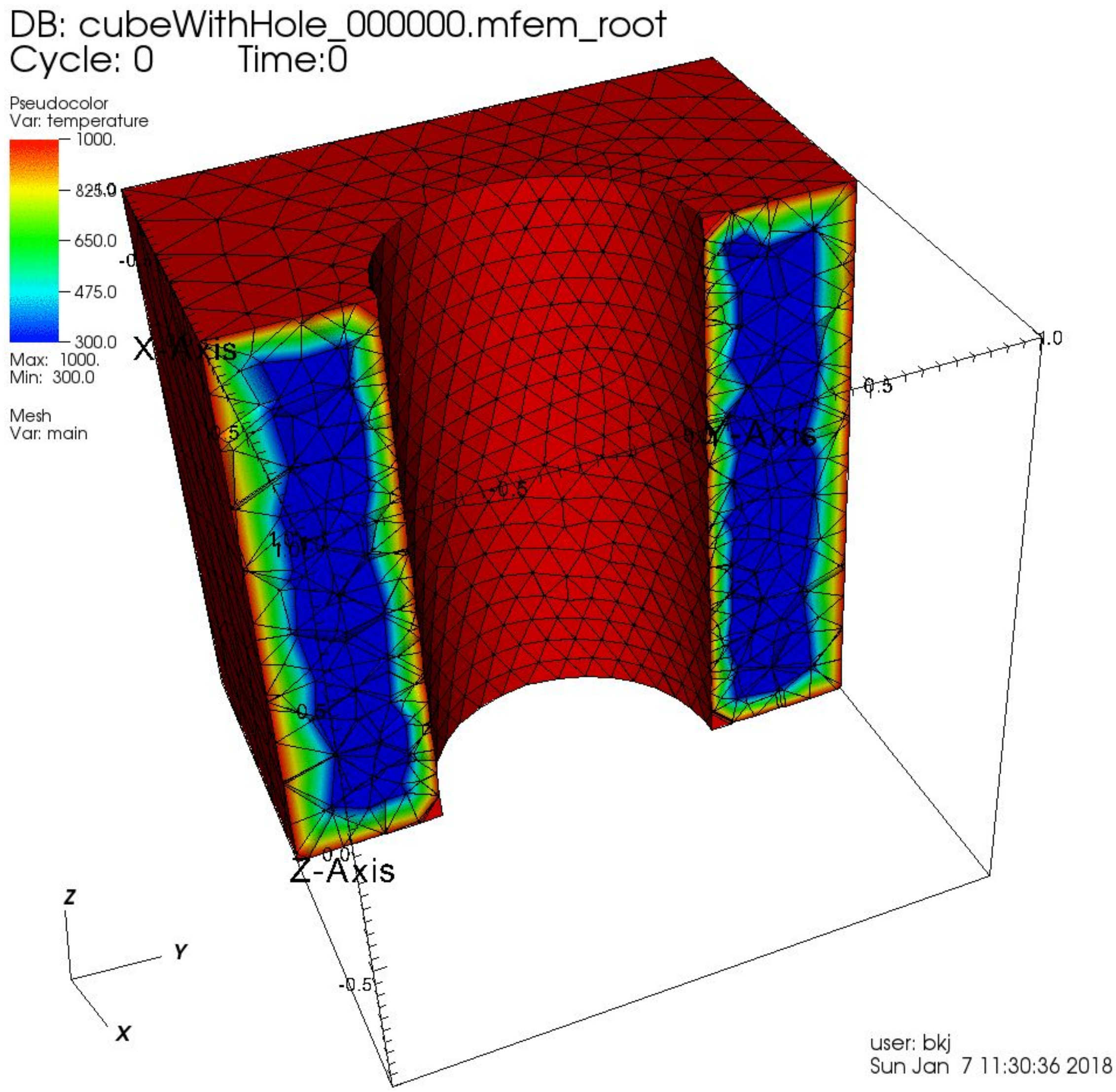


The Ganjiang Automated Meshing tool developed as part of this work.

Objective 3

The team produced a new thermal analysis solver using the Modified Finite Element Framework (MFEM, http://mfem.org) that can accept user-provided subroutines to represent welding torches. Heat source routines can be added easily for GMAW, GTAW, and SAW weld types and boundary conditions are easily configured through the input file to predict both heating and cooling.

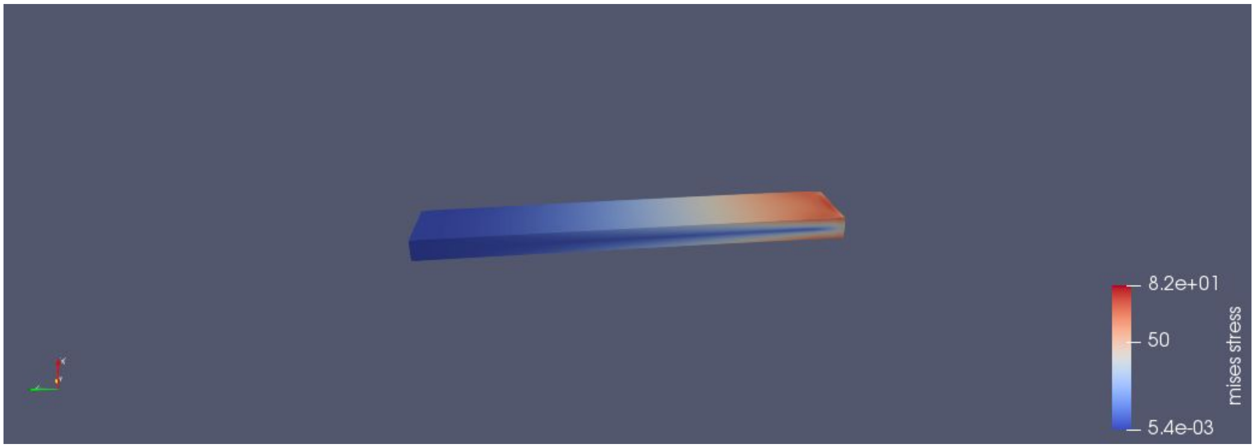
The image below shows the thermal analysis code, Kelvin, on a moderately fine mesh of a cube with a hole drilled through the center, which was used as a test problem in early development. This test problem demonstrates uniform heating on the boundary from a heat source at 1000K and the diffusion of the heat across the interior domain, initially at 300K.



The Kelvin Thermal Analysis Solver

Objective 4

The team was able to successfully deploy Warp 3D on OSC and ORNL machines for the nonlinear mechanical analysis required by WeldPredictor 2.0. The figure below shows the results of a simple test problem where the Mises Stress is reported for deformation due to both the weight of the beam and thermal creep effects calculated by Warp 3D. The inclusion of Norton-Bailey (Secondary) creep affects is an example of the advanced types of physics available in Warp 3D but not available in other tools and which would require an inordinate amount of work to duplicate.



A simple beam in Warp 3D showing distortion due to gravity and thermal creep.

Subject Inventions (As defined in the CRADA)

None.

Commercialization Possibilities

OSC is currently investigating commercialization possibilities as part of their AWESIM and Open OnDemand platforms.

Plans for Future Collaboration

ORNL and OSC staff have continued to work on the project since the expiration of the CRADA because of the strong collaborative bond that has developed on the team. The team is currently working with the HPC4Mfg leadership team to identify and explore possibilities for Phase II funding within that program that would continue and expand work on and expand the scope of WeldPredictor.

Conclusions

This project has started development on WeldPredictor 2.0. While only part of the objectives were met and work remains, the ORNL+OSC team made significant progress in the development of the new backend and frontend elements of the tool to predict weld distortion in parts using advanced, 3D HPC modeling and simulation technologies. No new inventions were produced as part of this work, but OSC is investigating options to commercialize the technology as part of a new center-wide cost recovery model. OSC and ORNL are continuing to work on WeldPredictor 2.0 and look forward to a release in the future, possibly as part of Phase II work for the HPC4Mfg program.