How Can Computational Weld Mechanics Help Industry?

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Prediction of distortion and residual stresses are just two examples of how computational models may be used in welding right away

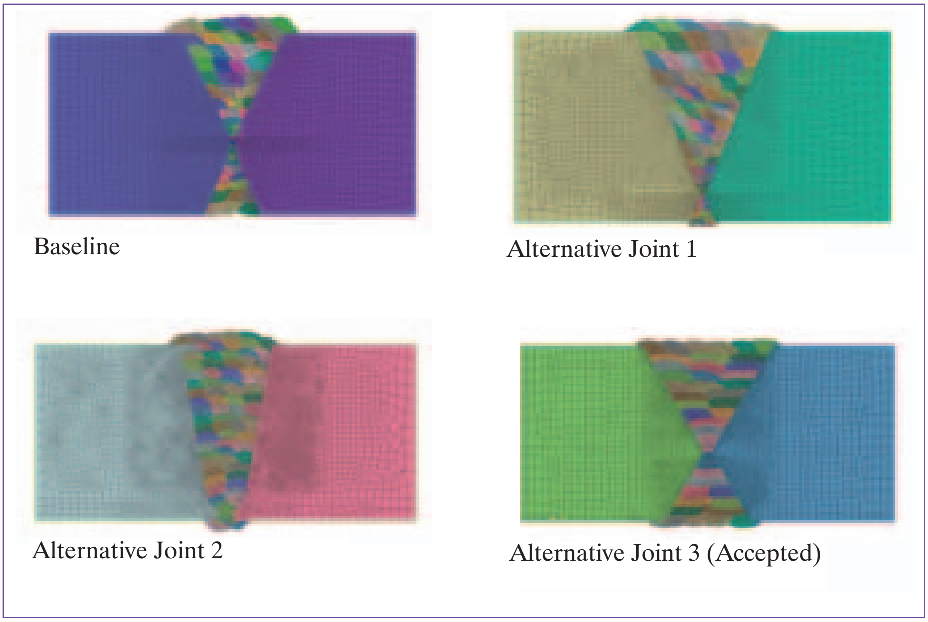

Fig. 1 — Illustration of thick-plate weld joint geometry, multipass weld-bead shape, and placement in a baseline condition, as well as three other alternative designs.

With an increasing focus on energy efficiency, sustainability, and cost, there is also an increased focus on advanced materials usage for a wide range of applications (Ref. 1). For example, the automotive and energy exploration industries are implementing new materials that are stronger to meet higher operating conditions (Ref. 2). In both applications, the use of new materials is often done with a limited knowledge of a materials' welding characteristics. Since weldability of these next-generation steels is affected by local changes in material behaviors due to a wide range of welding processes, the assumption of bulk properties for the joints may not be valid. This can lead to three potential challenges. First, if too aggressive, the assumption of bulk properties for joints may lead to an underdesigned part resulting in premature failure under loading conditions. Second, if too conservative, the design engineer may underestimate the joint strength and require thicker components, which defeats the purpose of leveraging advanced materials. Third, the design engineer may require certain mechanical properties from welding leading to expensive trial-and-error optimizations. For example, in shipbuilding, fabrication of an 8000-ton ship has a conservative estimate of 16,000 labor hours allocated for flame straightening of weld-induced distortion, which excludes alternative mechanical straightening methods and increased fit-up costs (Ref. 3). These challenges are not new; they have existed since the introduction of welding in a production environment. This leads to a fundamental question: Why can't we use some mathematical and computational tools to address these challenges?

Utility of Computational Weld Mechanics Tools

To make a case for developing computational weld mechanics (CWM) standards, the predictive utility of CWM tools is briefly presented in the following examples.

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Minimizing Welding Distortion in a Heavy-Section Joint

Goal: To deliver a product that meets flatness specifications while minimizing fabrication costs. Due to their geometry, these weld joints require a high amount of labor to weld, rework, and flame straighten. This is especially acute when mechanical pressing is not feasible.

The original procedure called for multiple gas metal arc welding (GMAW) passes in the root with follow-on single-wire submerged arc welding (SAW) until approximately 75% of the first side was completed. The structure was then flipped and backgouged to sound metal, with multiple layers of GMAW placed in the root.

This was followed by single-wire SAW to close out the second side. The structure was flipped back and double-wire SAW used to close out the first side. Initial attempts resulted in exceeding the out-of-flatness tolerance, requiring the joint to be thermally cut apart and ground down to sound metal and rewelded. Computational weld mechanics was used to solve this fabrication issue.

Results: Multipass welding simulation was used to develop a baseline and conditions to compare alternative geometry and welding. Two alternative designs changed the joint geometry while a third altered both the joint geometry and the welding process — Fig. 1. Distortions were measured at a point 101.6 mm from the weld centerline. The results are shown in Fig. 2 and Table 1. Simulations of Alternative Joints 1 and 2 predicted less distortion and saved 84 and 96% of the backside welding, respectively. However, during the simulation, Alternative Joint 2 generated more in-process distortion, indicating higher process stresses.

Alternative Joint 3 not only altered the joint geometry but also the process. It called for completely welding one side of the joint with double-wire SAW, then flipping the structure and, using the same process, completing the weld joint. Although this geometry required more backside welding, analysis predicted less distortion with a mechanical process that reduces labor by depositing higher volumes of metal per pass and requiring less fitup. This joint design has now been implemented into production. It is important to note that, in this work, experimental welds were produced after the simulation without model calibration, showing a truly predictive application of CWM. This example clearly shows the reduction in experimental trial-and-error welding procedure development.

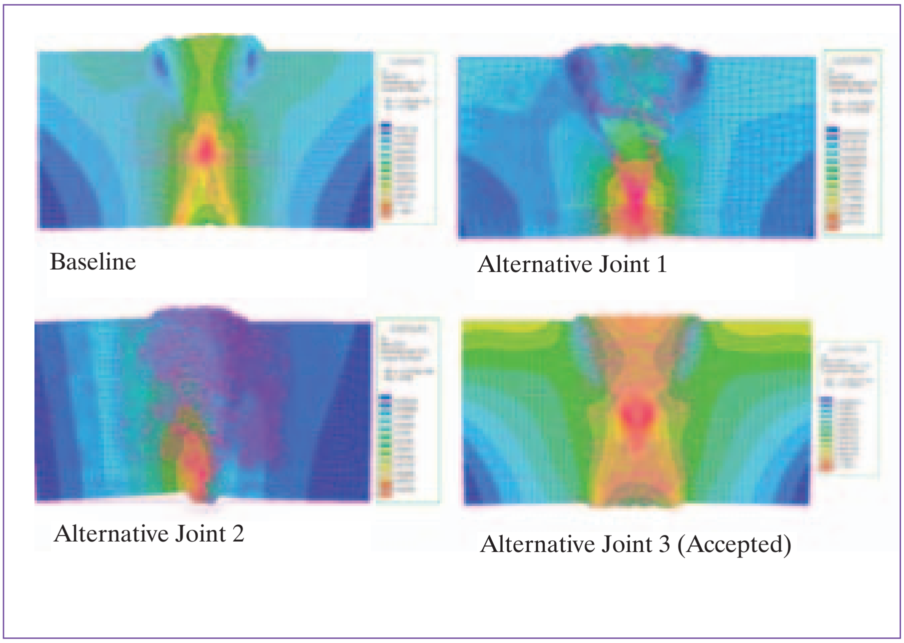


Fig. 2 — Deformed shape after completion of "virtual" welding per the model conditions shown in Fig. 1.

Rapid Prediction of Welding Distortion in Large-Scale Assemblies

Goal: Although the previous example clearly showed the benefit of CWM, the setup and running of simulations for large-scale welding with multiple attachments and optimization of the same to minimize residual stress and distortion is often complex. Goldak (Ref. 4) addressed this problem. The goal in this example was to minimize the time taken to apply the CWM tools for large-scale structures shown in Fig. 3. As shown in Fig. 3, the geometry of the welded structure consists of a cylindrical pipe 2680 mm long, 228 mm in diameter with a 6-mm wall thickness. Six quadrilateral plates with a 12-mm wall thickness are wrapped around the cylindrical pipe. In each of the six plates, 12 circular holes are welded to the pipe with fillet welds. Circular disks are welded to close the ends of the pipe. The total number of welds is 74. The material is low-alloy steel.

Results: The first step in the CWM analysis is to import into the weld analysis program VrWeld®, the CAD-created

Table 1 — Results Summary of Predicted Weld Distortion from the Analyses Models

Analysis	Maximum Distortion (mm)	Max. Production @ Corners (mm)	Distortion @ the Corners (mm)	Backside Welding Reduction (%)
Baseline	0.285	0.285	0.018–0.057	0
Alternative Joint 1	0.311	0.176	0.029–0.043	84%
Alternative Joint 2	0.651	0.458	0–0.035	96
Alternative Joint 3	0.130		0.016	36.7

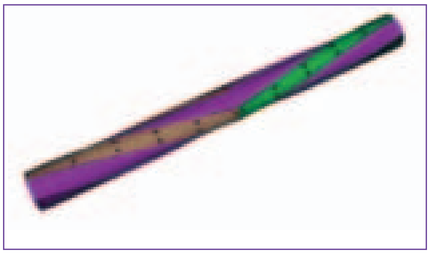


Fig. 3 — Schematic of a welded assembly that was analyzed using CWM tools.

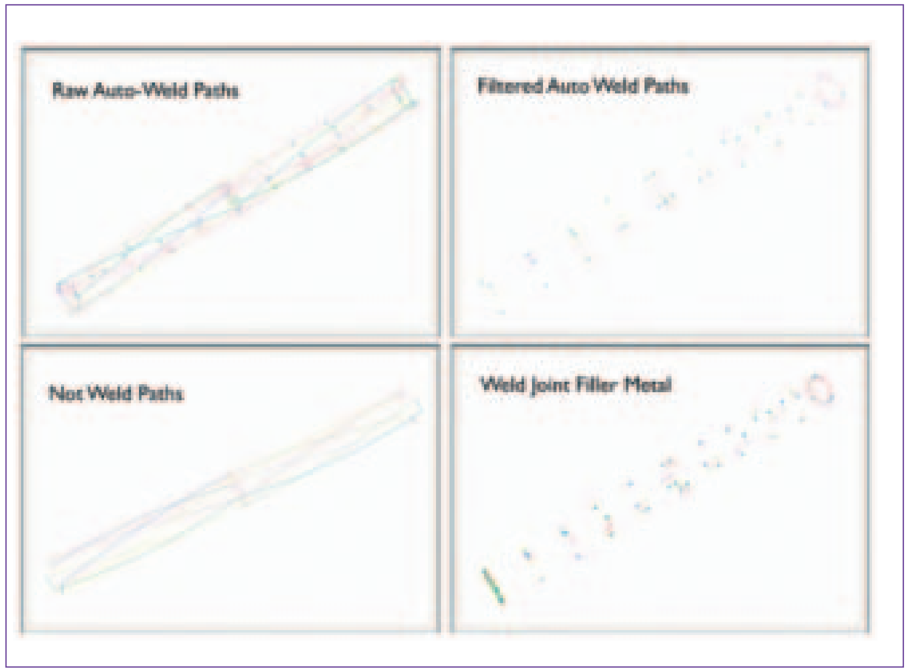


Fig. 4 — The complete set of candidate auto-weld paths is shown in the upper left; the set of auto-paths that are circular is shown in the upper right; the set of auto-weld paths that are not circular is shown in the lower left; the mesh for the filler metal for the circular weld paths is shown in the lower right.

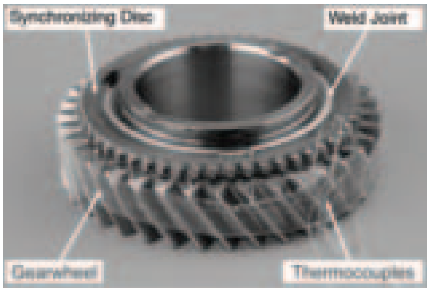


Fig. 5 — The photo of the gear wheel that is the target of this demonstration is shown with thermocouples, which are used for evaluating the heat source model.

stereo-lithographic files that define the geometry of each part with a user-assigned material type for each part. The next step is to create a set of candidate weld paths automatically by computing the adjacency of all parts and checking where the geometry would permit a weld to join a pair of parts. The candidate weld paths are shown in Fig. 4.

In the second step, the software classifies the candidate weld paths by parameters such as the following: 1) weld path length; 2) whether the weld path is a closed or open loop; 3) whether the weld path is a circle. In this example, the designer chooses welds that are circles and have a weld path length corresponding to the circumference of the small circles. The appropriate weld procedure is assigned to all 72 weld paths. Next, the two larger circular welds on the ends of the pipe are chosen and the appropriate weld procedure assigned. The weld paths not chosen are deleted. The weld procedures define welding speed, current, voltage, arc efficiency, and double-ellipsoid semi-axes lengths. The welds can be ordered and assigned a start time automatically based on the weld sequence, welding speed, and a delay time between the end time of one weld and the start time of the next weld. In the third step, the parts and weld joints are meshed, largely automatically — Fig. 3. In the fourth step, the designer assigns boundary conditions to constrain the rigid body modes for stress analysis and applied tack welds. Then the user sets the fields to be processed and checks "run." After the analysis is complete, the user visualizes the results such as displacement, residual stress, microstructure, and hardness. The significance of this work is the time it takes to set up this analysis, 15 min, with only a few days of training.

Your Input Is Needed

Current AWS Activities to Develop CWM Standards. The American Welding Society has established a technical committee (A9) with members representing academia, industry, nonprofit consulting organizations, and government national laboratories in order to develop a standard for CWM. To limit the task ahead to a reasonable scope, an initial survey of the committee members was conducted and resulted in a decision to focus on developing a recommended practice for CWM of fusion welding of metallic materials to predict residual stress and distortion. The necessary background information is being collected for incorporation into this AWS standard. A draft version of the standard is expected to be developed within two years. The committee has posted an open survey for the general public and welcomes any additional input. You can access the survey at *www.aws.org/1Y2X*.

Reduction of Welding-Induced Distortion in an Electron Beam Welded Gear Wheel

Goal: An automotive gear wheel (Fig. 5) is welded with an electron beam allowing for high flexibility in the weld plan configuration. The current weld plan takes advantage of this fact and uses three simultaneous heat sources generated by a single electron beam, which is able to jump to three or even six positions nearly simultaneously. Despite the fact that this configuration already enhances the deformation behavior favorably, it was not sufficient as the pitch of the gear wheel was altered too much resulting in high wear and cracks. A manual trial-and-error optimization using numerous welding experiments generated no significant advantages. In order to solve this problem effectively, a numerical welding simulation was done (Ref. 5).

Results: First, a validated temperature field was simulated to begin the welding simulation. Thermal simulation results were relative to the measured data. Hence, the numerical model of the temperature field is suited for subsequent calculation of the welding-induced distortions. Baseline simulations (Fig. 6) showed that the circularity of the weld changes as the weld progresses.

Before welding (t = 0.0 s), the geometry of the synchronizing disc is an ideal circle. With the start of the welding procedure, the heat input into the workpiece leads to a high local temperature rise resulting in thermal expansion of the material. This creates a bulge in the circumference of the synchronizing disc that moves together with the advancing heat sources (t = 1.0 s to t = 2.0 s). The above deformation remains during the subsequent part cooling to room temperature (t = 5.0 s to t = 5000 s). Further investigation of the results indicated that the geometrical grooves create a heat accumulation at the end of the weld joints because of the smaller volume fraction in these regions and the already existing heat of the welding start point from the adjacent section. This further intensifies the radial distortion created by the electron beam heat input. Using this knowledge, modified welding direction and procedures were developed. The target was a more uniformly distributed temperature field in the workpiece which, in this special case, did not correspond with a more uniformly distributed heat input because the geometrical features had a significant influence. The direct optimization approach using CWM showed that a welding configuration with six simultaneous heat sources moving in different directions generated by the electron beam had the most positive effect on the resulting distortions. Pitch variations in the gear-tooth were reduced (Fig. 7) by 35% with these modified welding procedures.

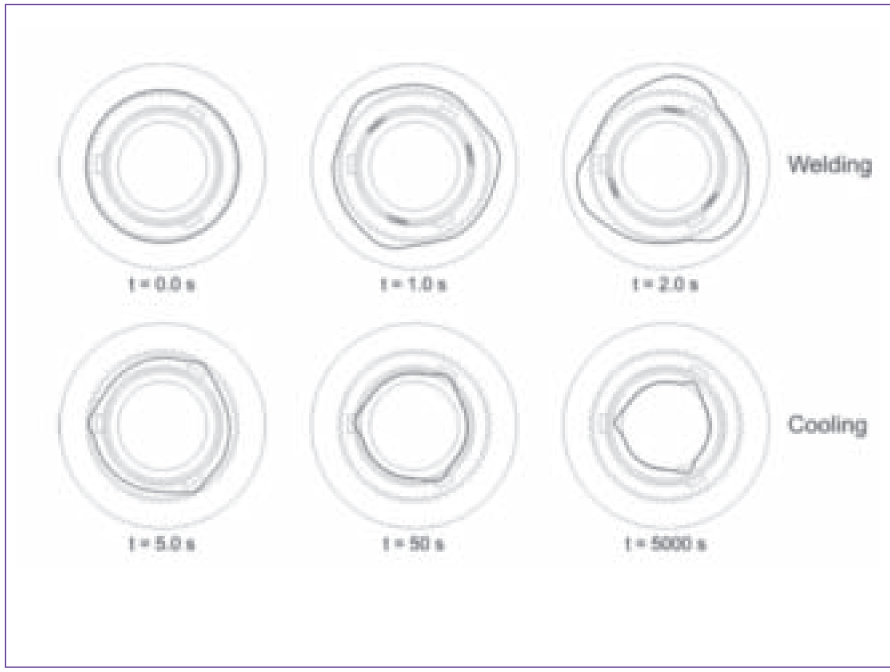


Fig. 6 — Transient behavior of the calculated weld-induced radial distortions of the gear wheel; all distortions are scaled with a factor 250 for better visibility.

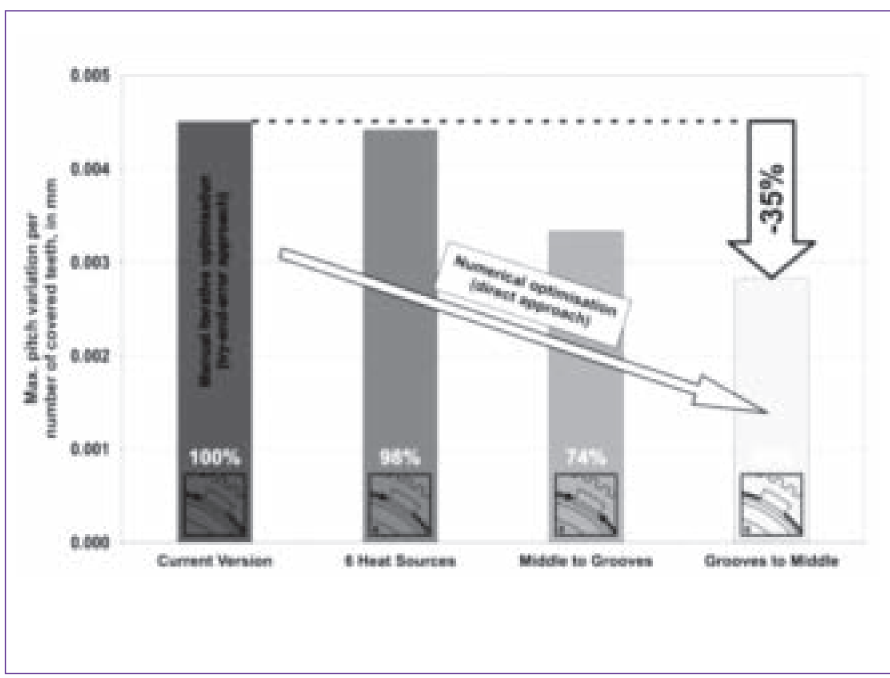
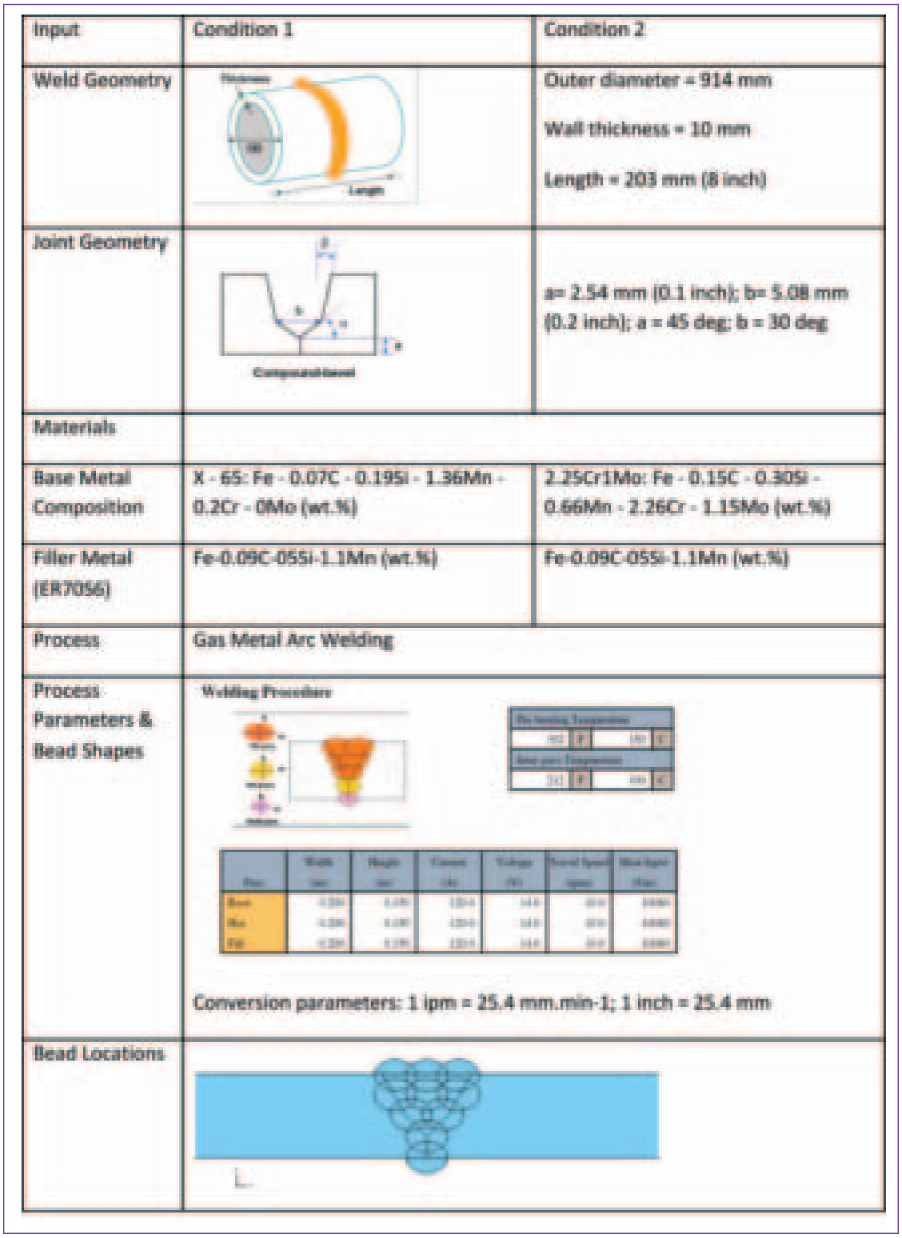


Fig. 7 — Optimization to reduce the weld-induced distortion in a welded gear wheel.

Technology Transfer of CWM to Welding Engineers

Goal: The previous examples clearly show that CWM can be used as a tool to perform virtual trial-and-error welding experiments. However, this work still requires a design engineer who is well versed in computational methodologies. There is a growing need to transfer this technology to welding engineers who have a limited background in computational methodologies. These tools can be used for routine weld geometries to evaluate some of the "what if" scenarios. Recently, Zhang et al. (Ref. 6) developed E-Weld Predictor™, a CWM tool that leverages weld modeling, supercomputer, and Internet technologies to transfer the CWM tools for specific applications such as plate and pipe welding. This is demonstrated with a material substitution problem. While welding a 2.25Cr1Mo steel pipelinewith ER70S6 filler metal, a hard zone was observed in the heat-affected zone. The case study focus was to substitute traditional X-65 steels in lieu of the 2.25Cr1Mo steels using the same process and welding wire conditions without adverse residual stress and distortion effects.

Results: The individual steps in running the simulations and input parameters are shown in Fig. 8. The results obtained based on these inputs are summarized in Fig. 9. Thermal calculations indicated that there are no significant differences in the HAZ width, residual stress, or distortions by substitution of the 2.25Cr1Mo with the X-65 steel — Fig. 9A, F–H. The most important difference was the formation of martensite in the HAZ of the 2.25Cr1Mo steels compared to bainitic microstructure in the X-65 steels. The above microstructural distribution is also reflected in the reduction of peak hardness in the heat-affected zones of the



Input	Condition 1	Condition 2
Weld Geometry		Outer diameter = 914 mm Wall thickness = 10 mm Length = 203 mm (8 inch)
Joint Geometry		a= 2.54 mm (0.1 inch); b= 5.08 mm (0.2 inch); a = 45 deg; b = 30 deg
Materials		
Base Metal Composition	X - 65: Fe - 0.07C - 0.19Si - 1.36Mn - 0.2Cr - 0Mo (wt.%)	2.25Cr1Mo: Fe - 0.15C - 0.30Si - 0.66Mn - 2.26Cr - 1.15Mo (wt.%)
Filler Metal (ER7056)	Fe-0.09C-055i-1.1Mn (wt.%)	Fe-0.09C-055i-1.1Mn (wt.%)
Process	Gas Metal Arc Welding	
Process Parameters & Bead Shapes	Welding Procedure Conversion parameters: 1 ipm = 25.4 mm.min-1; 1 inch = 25.4 mm	
Bead Locations		

Fig. 8 — Typical inputs needed for the E-Weld Predictor software used in the demonstration.

X-65 steels. With this tool, the range of other process parameter and material combinations can be evaluated and some key conditions are being considered for detailed experimental evaluations.

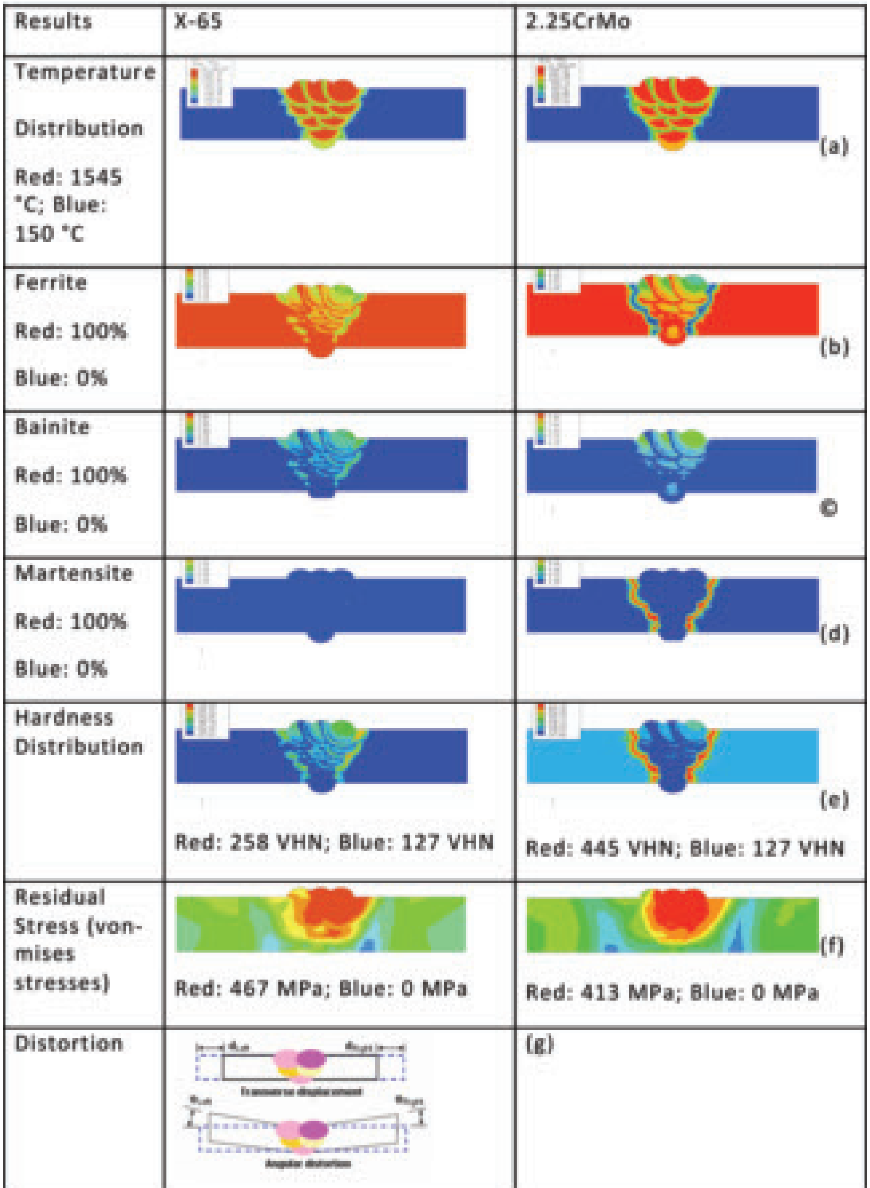
Although the examples shown here are focused on the fusion welding processes, there are numerous examples of applying CWM to other joining processes such as resistance spot welding, inertia welding, etc., published in the literature. Computational weld mechanics tools can be used to reduce the number of trial-and-error optimizations. Based on the authors' experience, the reduction in number of experiments is expected to be 50%. This reduction will result in cost savings for the potential application. Currently, the above tool is not comprehensive for a wide range of geometries (fillet welds), boundary conditions (restraints), processes (resistance, laser, friction stir welding, etc.), alloy (aluminum, titanium, etc.) systems, and performance (toughness, creep, fatigue, etc.). However, the above framework can be modified for these needs with the development of sub models for these processes, materials, and performances by interfacing with researchers in this area.

Challenges to Deploying CWM to Welding Industries

Even with the success stories mentioned here, the introduction of CWM has been limited in the welding industry. In contrast, computational fluid dynamics and computational solid mechanics models have been used routinely in industry to great advantage for more than three decades. Perhaps the most dramatic example of how computational models can impact an industry are the computational models that make it possible to design electronic circuits that are the heart of modern computer and cell phone technology. This use of computational models suggests that industry has confidence and trust in their accuracy and expects to reduce costs and delivery times and improve quality. Currently, CWM models are not yet used routinely in the welding industry. This is related to both business and technical reasons. Business reasons are related to managers' perception that CWM usage does not lead to costs reductions and improved delivery times and quality for welded construction. Although much of the published literature includes demonstrated case studies that counteract this perception, the widespread adoption of these tools is also plagued by technical challenges. This is to a large extent due to a lack of standard verification and validation tests to build the technical case for the use of CWM tools.

The process for developing trust and confidence in a computational model is called Verification and Validation. Verification tests that the computational model solves the mathematical equations that are the essence of the model with sufficient accuracy, robustness, and reliability. Validation tests that the computational model predicts the reality relevant to the decision maker with sufficient accuracy, robustness, and reliability. In welding, the reality relevant to a decision maker might be distortion, residual stress, microstructure, and the risk of in-service failure. A computational model that has been verified and validated for a given application area can be used as a predictive tool before any experiments are performed. Computational models that must be fitted to experimental data before they can be used are called calibrated. These calibrated models cannot predict the reality relevant to a decision maker before the required experimental data are provided. This is the reason that computational models that are verified and validated are much more valuable and more useful than calibrated computational models.

Compared to the linear elastic analysis of structures such as bridges, the simplest welding examples are more complex, involve nonlinear-coupled equations, a larger range of length scales and time scales, and are more sensitive to microstructure evolution. It is for these reasons that CWM emerged about two decades later than computational solid mechanics.



Transverse Displacement	Left 0.19; Right 0.07	Left 0.27; Right 0.08
Angular Distortion (deg)	Left 0.53; Right 0.54	Left 0.61; Right 0.63

Fig. 9 — Typical results from the E-Weld Predictor calculations for evaluating the substitution of 2.25Cr1Mo steel with X-65 steel.

At this time, CWM is rapidly rising from an emerging technology to one approaching maturity. ASME has developed standards for verification and validation for computational fluid mechanics and for computational solid mechanics (Ref. 7). AWS is currently working on developing a verification and validation standard for CWM. The objective of this paper is to increase awareness of the current state of CWM and to encourage a dialogue with the welding community such that these tools can be used routinely in industry in the near future.

Conclusion

Computational weld mechanics can become an active field of scientific research that not only could leapfrog the welding science and technology but also bring much needed new talent into the welding community.◆

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