MODELING THE WELD PROCESS

Can the science behind welding become available to practicing engineers?

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Associate Editor

Welding processes largely have been developed empirically, and consequently many are not well characterized from a scientific point of view. Welding itself is not a dicipline, but a process, and therefore a fundamental science has not developed around this field. However, like many processes, welding involves scientific principles from many diciplines including physics, chemistry, mechanics, electronics, and materials. Welding researchers are applying the principles of this already existing science base to weld modeling with the hope of achieving higher quality and more consistent welds through automation and robotics.

Why model?

A mathematical model represents a process or some aspect of a process by a set of differential or algebraic equations derived from fundamental chemical and physical laws. A model can provide quantitative relationships between key process parameters — an invaluable component of any process study. This is critical for planning and interpreting experiments and for process control and optimization. In addition, a properly developed model is a basic requirement of artificial-intelligence studies.

Weld modeling is aimed at relating processing conditions to the structure and properties of weldments, thereby defining optimum welding conditions. Such models ultimately will provide welding engineers with the means to obtain highest quality welds through process control. The accuracy of model prediction of microstructural and property changes in welds depends on the accuracy of defined boundary conditions of heat transfer and stress analyses.

According to Prof. Julian Szekely, M.I.T., the rapid growth in weld-modeling research is a result of more readily available computer facilities, software packages, and computational fluid mechanics. In addition, this growth is stimulated by an industrial need for consistently higher quality welds produced by automated operations.

U.S. research in recent years has produced major advances in modeling of arc and other welding systems. With respect to arc behavior, electron flow is the principle contributor to the overall heat flux. Consequently, it is essential to know current distribution precisely to model the welding arc. Reportedly, the factors governing welding arc behavior and arc-to-anode heat transfer are well understood. Models have been developed that show reasonable agreement between experimentally measured and predicted temperature profiles (10-mm arcs at 100 and 200 A). In addition, research by several investigators shows good agreement for theoretically predicted maximum anode current density and measured values using a water-cooled anode. Radial current density also is predicted quite well, while there is less agreement between theoretically predicted and experimentally measured heat fluxes. The anode region needs to be defined more precisely. Unsolved problems remain in the areas of plasma-jet stability, behavior of the near-cathode region, and plasma-jet weldpool interface.

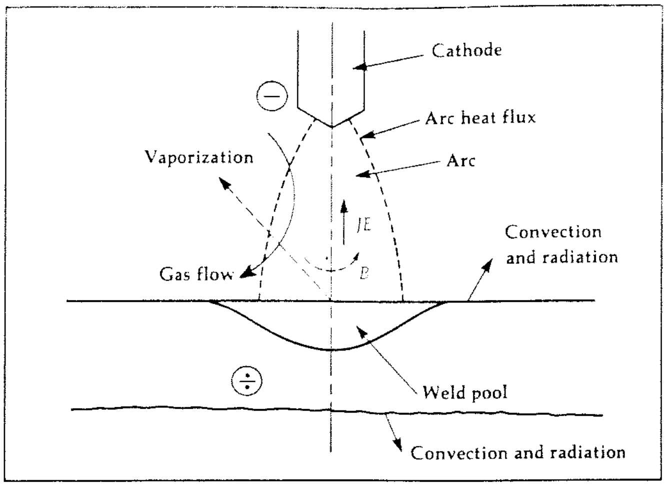
Weldpool phenomena are studied because weldpool shape and circulation play key roles in determining the properties and thus the quality of welds. Weldpool characteristics can be estimated from simple algebraic relationships; this provides a general appreciation of the system and is a necessary first step before machine computation.

Although early modeling of weldpools ignored convection completely, a quantitative description of weldpool shape was reasonable. Knowledge of convection is important, however, because this will define precise weldpool shape, which affects weld structure and properties.

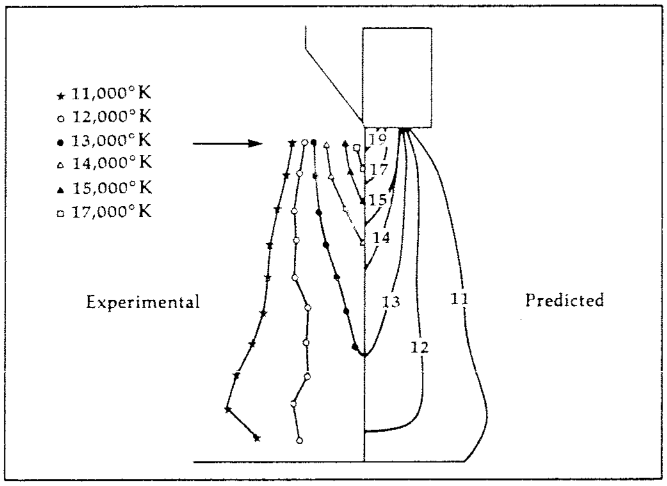
Modeling moving heat sources

Until recently, most modeling work on weldpool behavior has involved spotwelds including weldpool circulation and solidification. Spot welds are easier to analyze because they have axial symmetry and are mathematically two-dimensional (with time dependence).

Now there are some useful results in the attempt to model a moving weldpool (moving heat source). The M.I.T. approach to modeling continuous welding operations was to initially look at a two-dimensional slice in a travelling weldpool, which shows the gradual distortion of the weldpool and reduced penetration with increasing welding speed. The model also shows relatively little convection in the melting zone, while



A general model for fusion welding requires the integration of sophisticated heat-transfer, stress, and microstructural models to adequately represent the complex process. Critical boundary conditions include the heat-flux distribution to the arc, the interaction of the arc with the surface of the material, convective heat transfer due to fluid flow in the molten pool, and thermal conduction into the solid.



Predicted temperature profiles generated from modeling work at M.I.T. agree reasonably well with those measured experimentally, as shown in this example for a 10-mm arc operating at 100 A.

the solidifying region is highly agitated. Three-dimensional studies are expected to reveal some interesting effects from continuous welding operations.

Researchers feel that work done so far lacks both a systematic correlation with experimental work and a correlation of weldpool behavior with weld structure and properties. Major challenges ahead include the need for a more precise definition of plasma-weldpool interactions with special attention to deformation and surface stabilities.

According to researchers at Sandia National Laboratories, Livermore, Calif. and Lawrence Livermore National Laboratory, their general computer model for fusion welding has contributed significantly to obtaining reliable thermal histories for a stationary gas tungsten arc weld (GTAW). The model also incorporates a vaporization model (to improve temperature predictions under the arc) and a method for modeling the effect of weldpool geometry without the need for computing fluid flow.

This work shows that thermal history of the weld can be modeled with a minimum number of assumptions. The accuracy of the computed results are improved with experimental determination of the shape of the heat-flux distribution and the arc efficiency; experimental accuracy is a must.

While calculated thermal distortion values agree quantitatively with experimental measurements, calculated stress and strain distributions are only qualitatively correct. A lack of an adequate materials model and experimental high-temperature property data limits the accuracy of stress analysis. Work is currently underway to develop these key items.

Researchers at General Electric Co., Schenectady, N.Y., formulated a mathematical model to simulate GTAW of thin sheetmetal. The model is based on two-dimensional solutions of the heat-conduction equation for a distributed heat source moving at a constant velocity. In the method, closed-form solutions of the governing partial differential equation provide a simple functional expression that can be used to develop the welding process-control algorithms.

The aim of modeling the GTAW process was to obtain the weldpool envelope and associated shape and geometry. The weldpool solid-liquid interface is determined from the temperature distribution; a computer program calculates the weldpool perimeter, area, maximum width, length, and aspect ratio.

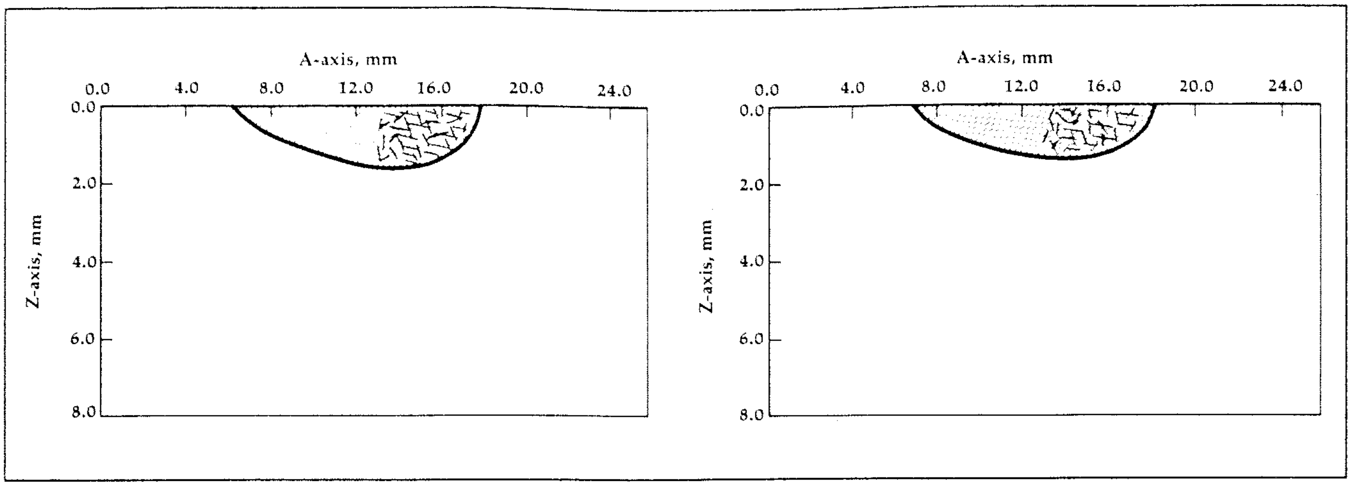
Process test data were obtained with a GTA welding torch provided with a vision system to allow observation of the dynamic features of the weldpool during a welding run; single images of the weldpool were analyzed on a video monitor.

According to researchers, the predictions from a simple two-dimensional process model compare favorably with process test data. The process tests not only provided weldpool geometric data to validate the analytical process model, but also established set points to conduct experiments for different materials and welding parameters. The model determined discriminants for most effective use in a welding adaptive control system based on optical sensing of the weldpool. The study shows that weldpool maximum width and area are the most sensitive discriminants measured from the weldpool image to control the GTAW process.

A model for a three-dimensional transient heat-transfer analysis was developed by researchers at the University of Illinois Urbana-Champaign. The finite-element method was applied to predict the thermal history of a weld joint produced by the gas metal arc welding (GMAW) process. Although the size of finite-element mesh grows continuously in time (from the addition of filler metal), the work shows that this does not cause a problem in applying finite element method (FEM) to the GMAW process.

The size of the heat affected zone (HAZ) calculated from FEM agrees closely with the experimentally measured value from one test; however, the predicted temperature distribution was not completely verified experimentally. The analysis reportedly gives a good spectrum of over-all heat-transfer phenomena in GMAW.

The model solves only the problem of temperature distribution in the plates; no calculations are made to



Three-dimensional modeling (continuous welding operation) is more complex than two-dimensional modeling. As a first step in approaching this problem, M.I.T. researchers modeled a 2-D slice through a travelling weld pool, which clearly shows the gradual distortion of the weld pool and decreasing penetration as the welding speed is increased from 1.5 mm/sec, left, to 2 mm/sec, right.

predict residual stresses and distortions, and vaporization is not considered. The temperature model derived from this work will be used as input to the residual-stress analysis, yielding a complete thermomechanical model.

Characterizing weld microsegregation

Weld performance largely depends on factors such as weld-cracking susceptibility, phase equilibria, and mechanical properties. All of these are, in turn, strongly influenced by microsegregation that occurs during weld solidification. Although microsegregation plays an important role in weld performance, very little data reportedly are available for measured and modeled weld microsegregation.

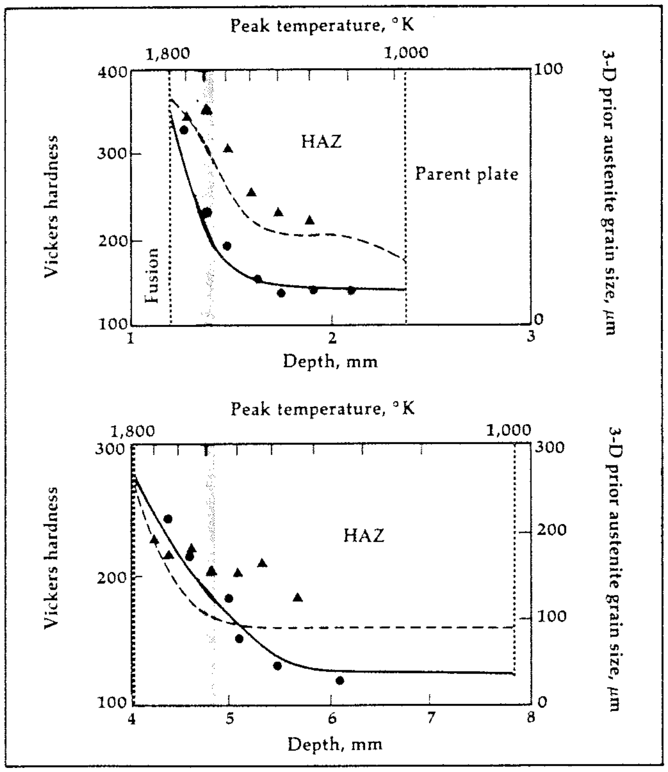
Researchers at Sandia National Laboratories, Livermore, Calif., have taken a step to enlarge this data base by characterizing and modeling the solidification behavior of two binary alloy systems (Al-Cu and Fe-Nb) using finite-difference analysis. Their work shows that the detailed mechanics of solidification are not necessarily apparent in the weld microstructure observed at room temperature.

Although the constitutional diagrams for both alloy systems are similar, the degree of microsegregation in the welds of similar solute content is very different. For example, in Al-Cu welds made by GTA and electron beam welding, dendrite-tip undercooling increases with both increasing solidification velocity and composition; which reduces the degree of segregation. However, solid-state diffusion is slow, which minimizes additional solute homogenization.

By comparison, solid-state diffusion in Fe-Nb welds reduces the degree of microsegregation and significantly affects the final temperature and phases of solidification. Agreement between predicted and measured results is good. This type of analysis, researchers feel, will provide a better understanding of the physical metallurgy of welding. Furthermore, the analysis will yield information about the evolution of weld structures, weld properties during solidification and cooling, and solidification in cracking behavior. These analyses also can be used as a tool to control weld behavior, both through alloy design and welding practice.

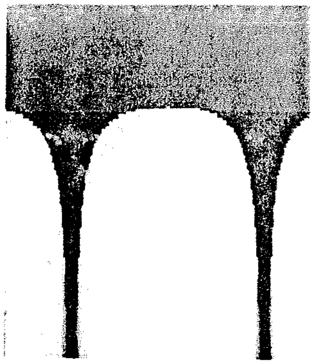
Phase transformations in weldments

A model developed by researchers from the University of Cambridge, England, and ESAB AB, Sweden, predicts a primary microstructure of low-alloy steel weld deposits that agrees well with published experimental data on the effect of large variations in silicon and manganese on weld microstructure.

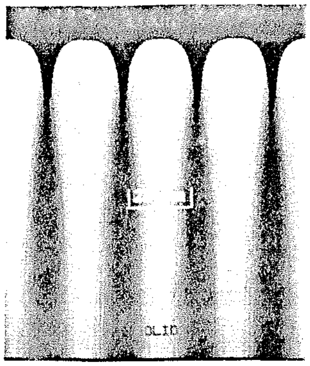


Modeling studies show that grain size (solid lines) and hardness (dotted lines) predictions are in good agreement with associated plotted experimental values in these two different gas metal arc welds of Nb microalloyed steel. The shaded regions represent NbC particle dissolution.

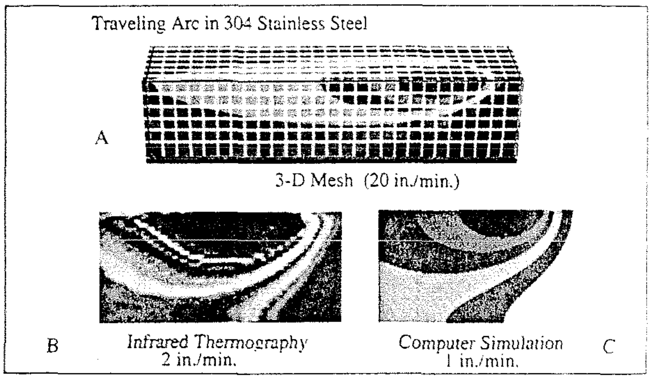
Even though welding is a complex metallurgical process involving many variables, this model, requiring the input of only chemical composition and welding conditions, yields the appropriate part of the phase diagram for steels containing C, Mn, Si, Ni, Cr, Mo,



Computer-graphic results of an Al-2% Cu GTA weld show the tips of solidifying cells extending into the liquid weld pool. For the concentration profile near the cell tip, the Cu isoconcentration lines in the solid are nearly parallel to the cell axis. This condition illustrates the lack of a significant amount of solid-state diffusion. The length-to-width of cells has been reduced by a factor of 100. Courtesy, Sandia National Laboratories, Livermore.



Computer-graphic results show concentration profiles in an Fe-2% Nb GTA weld. The curved isoconcentration lines in the solid indicates the occurance of diffusion during weld solidification and cooling. The intensity of color represents the Nb content and shows the nature of solid-state diffusion. Courtesy, Sandia National Laboratories, Livermore.



Lawrence Livermore National Laboratory-developed finite-element computer-codes produce 3-D and 2-D temperature profiles for a travelling arc on 304 stainless steel at travelling speeds of 20 in./min, a, and 1 in./min, c. In the 2-D calculation, a travel speed of 1 in./min in the computer simulation produces a 50% penetration weld, similar to that measured experimentally by infrared thermography at a travel speed of 2 in./min., b. Courtesy, Sandia National Laboratories, Livermore.

and V, in any combination. The resulting phase diagram is required to define the relevant para-equilibrium tie-lines for detailed kinetic analysis. TTT and CCT curves and various transformation start and finish temperatures also are computed. Volume fractions of ferrite phases are estimated from these data.

The model predicts that information obtained from simple isothermal experiments can be misleading in predicting the effects of alloying elements on the primary microstructure of manual metal-arc welds. Experimental work confirms this prediction.

Researchers at Alcoa Laboratories accurately modeled the HAZ of Al-Mn-Si alloys using an arc-welding heat-transfer model based on finite-differencing techniques in conjunction with kinetic analysis. The kinetic relationships were developed to represent precipitation during welding. The model provides accurate representation for the major portion of the HAZ; however, it does not account for the dissolution of precipitates near the weld fusion zone. There is good agreement between measured and predicted hardness values in the HAZ with the exception of the fusion zone.

Several models are described by Prof. K. E. Easterling (University of Sydney, Australia and University of Lulea, Sweden) for the temperature distribution during arc welding and the resulting microstructural changes in microalloyed steel. Included in the models are the phenomena of dissolution and coarsening of carbonitrides, phase transformations and grain growth, estimations of volume fractions of various eutectoidal constituents, and the hardness distribution in the HAZ.

The overall shape of predicted thermal cycles of submerged arc and gas metal arc welds agrees well with experimental data; the main discrepancy is in the heating rate. Poor response from thermocouples in experimental work, or changes in thermal properties as a function of temperature or surface heat losses not taken into account, may account for this discrepancy.

Experimental measurements of grain size agree well with those predicted, considering the wide range of input energies. In the case of hardness comparisons, agreement between computed and experimentally measured values also is good.

Prof. Easterling sees the need for further research in several areas of weld modeling. In the case of precipitate dissolution, present work is based on the assumption that carbonitrides are binary compounds, which is not true. In microalloyed steels, particle composition is a complex function of chemistry and heat treatment. Analysis of at least quarternary particle compositions (two metal components plus nitrogen and carbon) would be useful. As with complex particle dissolution, precipitate-coarsening models also require further theoretical and experimental work.

A model of weld-bead and joint geometry that takes into account the transfer mode of metal drops, surface energy, and the effects of heat loss on the shape of the melt is needed. In addition, the type of weld joint — such as butt, fillet, or edge — must be considered. A possible approach may be to assign a "thermal-severity grading" to the various weld joints, plate thicknesses, or other components based on the possible heat-flow paths. Further, it would be useful to incorporate the effects of multipass welds (which anneals the weld metal and HAZ of the previous pass) into the modeling procedure.

Finally, a method for determining how hydrogen is redistributed in the HAZ is needed, since hydrogen-induced cracking in welds is an extremely important phenomenon. Incorporation of hydrogen levels into the model could provide a warning or recommendation in the computer program to implement special welding-process controls. ■

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