



Guide for Verification and Validation in Computation Weld Mechanics



American Welding Society®



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An American National Standard

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Guide for Verification and Validation in Computational Weld Mechanics

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Prepared by the
American Welding Society (AWS) A9 Committee on Computerization of Welding Information

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This standard provides guidelines for assessing the capability and accuracy of computational weld mechanics (CWM) models. This standard also provides general guidance for implementing verification and validation (V&V) of computational models for complex systems in weld mechanics.



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Foreword

This foreword is not part of AWS A9.5:2013, *Guide for Verification and Validation in Computational Weld Mechanics*, but is included for informational purposes only.

A task group was formed in 2007 under the AWS technical committee structure to investigate the need for computational weld mechanics standards. The task group was reorganized as the AWS A9 Technical Committee on the Computerization of Welding Information and began work in 2008. This is the first standard publication by this committee with more related topics on computational weld mechanics (CWM) planned.

Program managers need assurance that computational models of weld mechanics are sufficiently accurate to support programmatic decisions. As there are multiple acceptable approaches to analyzing the welding process using computational models, a step-by-step Verification and Validation (V&V) process is not practical. However, this guide will provide the CWM community with a common language and conceptual framework to enable communication to non-users of CWM to gain a sense of credibility of the CWM models. This guide will cover a wide range of V&V activities, including simplistic and complex model development, verification of numerical solutions, attributes of validation experiments, accuracy requirements, and quantification of uncertainties. Remaining issues for further development of a V&V protocol are identified.

The AWS A9 Committee plans to pursue the publication of additional standards on computation weld mechanics after this standard. Among those planned are:

- Recommended Practice for Describing Thermal Boundary Conditions
- Recommended Practice for Modeling Thermo-Mechanical Phenomena
- Recommended Practice for Describing Clamps and Fixtures
- Recommended Practice for Modeling Microstructure
- Recommended Practice for Integrated Models
- Recommended Practice for Verification, Uncertainty Estimation, and Sensitivity
- Recommended Practice for Documentation
- Exceptions and Modifications with reference to Materials 1: Steels
- Exceptions and Modifications with reference to Materials 2: Aluminum
- Exceptions and Modifications with reference to Fusion Welding—Arc
- Exceptions and Modifications with reference to Fusion Welding—Laser
- Exceptions and Modifications with reference to Fusion Welding—Resistance
- Exceptions and Modifications with reference to Thin and Thick Plate Geometry
- Exceptions and Modifications with reference to Large Scale Geometries

It is noteworthy that this document is in alignment with similar activities pursued by other international standards organizations such as the German Institute for Standardization (DIN) and the International Institute of Welding (IIW). For example, the readers of this standard are also requested to refer to DIN SPEC 32534–1, *Numerical welding simulation—Execution and documentation—Part 1: Overview*, published in 2011.

Annex A lists the in-text citations referenced throughout this document.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS A9 Committee on the Computerization of Welding Information, American Welding Society, 8669 Doral Blvd., Suite 130, Doral, FL 33166.

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Guide for Verification and Validation in Computation Weld Mechanics

1. General Requirements

1.1 Scope. This guide introduces computational weld mechanics methodology through an overview of the current technology. It presents current practices for heat transfer, microstructure, residual stress, and distortion calculations. In addition, a framework for developing verification and validation (V&V) procedures for these models is presented through an example related to the prediction of thermo-mechanical conditions. This document establishes the foundation for future V&V operations to allow for other emerging computational weld mechanics tools.

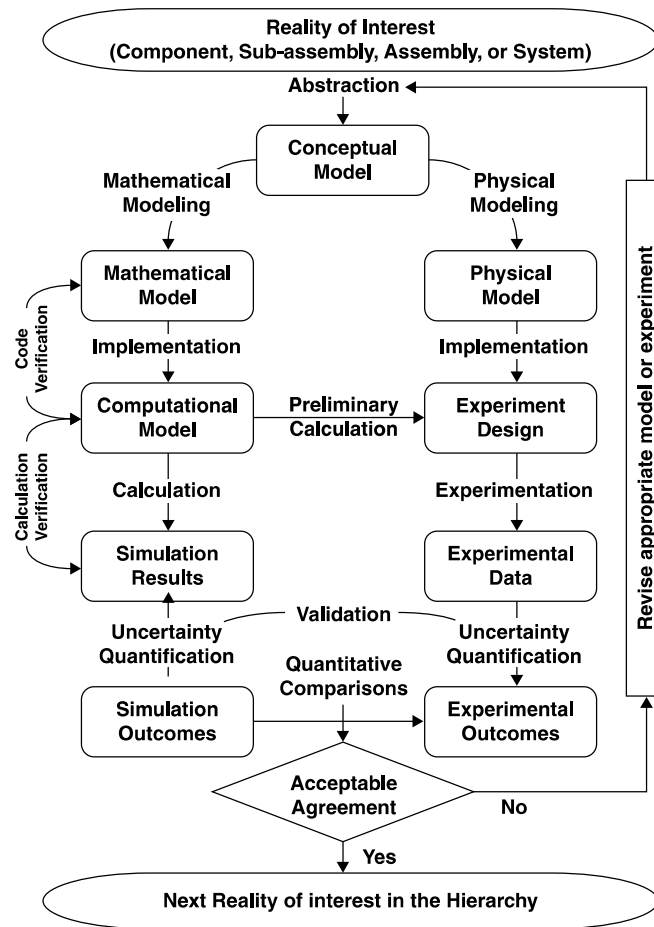
1.1.1 Preface. Computational models have been used routinely to great advantage for more than three decades. This technology has been used in many industries to analyze and assist in the design of many items. From architecture to telecommunications, computational analyses (structural to thermal to fluid) have been used to develop objects from the most complex to commonplace everyday items. Numerical analysis has given engineers the capability to make products better, safer, and more functional with less development costs. The growth in the use of computational models shows that commercial industries have confidence in the accuracy of the codes to reduce costs and delivery times while improving quality. In manufacturing, computational solid mechanics (CSM) and computational fluid mechanics (CFM) have been fully adopted; yet, the use of computational weld mechanics (CWM) has not. It has been suggested that the same level of confidence in CWM analyses does not exist due to relative newness of the tools and the lack of experience in their use. In comparison CWM is quite complex involving a coupled phenomena of thermal and nonlinear, transient structural analyses. Information regarding material responses due to thermal inputs, microstructure evolution, and to stresses and strains are needed to perform this type of analysis. It is for these reasons that CWM has emerged about two decades later than CSM.

The process to develop confidence in computational modeling can be expedited by a process called verification and validation (V&V). Verification testing ensures that a computational code solves the mathematical state equations that describe the phenomenon with sufficient accuracy, robustness, and reliability. Validation tests that a particular computational model predicts a particular event with accuracy and reliability. Such V&V has been developed for computational solid mechanics [1]¹ with Figure 1 illustrating a typical methodology used to develop V&V documents for creating models throughout the design process. This approach can be applied to CWM as well. In welding, the relevant phenomenon might be distortion, residual stress, microstructure, or risk of in-service failure. Once through this process, a computational model can be used repeatedly without physical experimentations with confidence that the output will be accurate and reliable.

Computational models fitted to experimental data before being used are called calibrated models. These types of models cannot be used to predict a particular outcome unless the input values are the same range as the original 'calibrated' model. Any changes in the model require the repetition of the calibration process resulting in multiple computational models and experimental tests. As one can easily see, computational approaches that utilize validated codes and verified approaches are much more expansive and usable in multiple cases than their calibrated computational model counterparts.

1.2 Units of Measurement. This standard does not require units of measure. Therefore, no equivalents or conversions are contained except when they are cited in examples.

¹ See Annex A for in-text citations.



Source: Reprinted, with permission, from ASME, V&V 10–2006, New York: American Society of Mechanical Engineers, Figure 1.

Figure 1—Verification and Validation Activities and Products

1.3 Safety. Safety and health issues and concerns are beyond the scope of this standard and therefore are not addressed herein. Safety and health information is available from the following sources:

American Welding Society:

- (1) ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*
- (2) AWS Safety and Health Fact Sheets
- (3) Other safety and health information on the AWS website

Material or Equipment Manufacturers:

- (1) Material Safety Data Sheets supplied by materials manufacturers
- (2) Operating Manuals supplied by equipment manufacturers

Applicable Regulatory Agencies

Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous, and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety

and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1 should be considered when developing the safety program.

2. Normative References

American Welding Society (AWS) standards:²

AWS A2.4, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions*

American Society of Mechanical Engineers (ASME) standards:³

ASME V&V 10–2006, *Guide for Verification and Validation in Computational Solid Mechanics*

German Institute for Standardization (DIN) standards:⁴

DIN SPEC 32534–1:2011, *Numerical welding simulation—Execution and documentation—Part 1: Overview*.

3. Terms and Definitions

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*, provides the basis for terms and definitions used herein. However, the following terms and definitions are included below to accommodate usage specific to this document.

For a detailed glossary relevant to finite element methods and computational weld mechanics, readers are referred to classic textbooks on the same topic [1, 2].

angular distortion. The out-of-plane movement of the welded structures along the axis of the weld perpendicular to the welding direction (i.e., rotation about the weld line).

axisymmetric. An axisymmetric structure is represented by two coordinates (e.g., x, y) in a finite-element model and assumes symmetry along the welding direction.

boundary conditions. Conditions imposed at the spatial boundary of a computational model that describe the interaction between the modeled and unmodeled domains. Complete boundary conditions provide a unique solution to the specific mathematical problem being solved.

buckling distortion. The out-of-plane distortion in thin section welds when the longitudinal residual stress exceeds the buckling strength of the welded structure. Buckling occurs when an unstable state changes to a stable state. The fact that something is wrinkled does not at all imply that it has buckled.

calibration. Determination of the variable parameters for the mathematical model as part of the implementation, related to a concrete application case.⁵

computational weld mechanics. A mathematical framework to solve a set of physical equations that describe the thermal, mechanical, and metallurgical process that occur during welding to predict the outcome as a function of initial, boundary, and processing conditions.

constitutive model: In the context of this document, a mathematical model giving the relationship between stress, strain, and other state variables (such as temperature, accumulated plastic strain, accumulated creep strain, etc.)

² AWS standards are published by the American Welding Society, 8669 Doral Blvd., Suite 130, Doral, FL 33166.

³ ASME standards are published by the American Society of Mechanical Engineers, Three Park Avenue, New York, NY 10016–5990.

⁴ DIN standards are published by the German Institute for Standardization (DIN Deutsches Institut für Normung e.V.), Burggrafenstrasse 6, 10787 Berlin, Germany.

⁵ Adopted from DIN SPEC 32534–1:2011, *Numerical welding simulation—Execution and documentation—Part 1: Overview*.

deviatoric plasticity. The presence of non-uniform stresses in three directions in a localized region, leading to localized plasticity when the resolved shear stress increases above the yield point.

elasto-visco-plastic: A type of constitutive model that accounts for basic linear stress-strain behavior (“elasto”), time-dependant creep and swelling (“visco”) and time-independent nonlinear stress-strain response (“plastic”). Within this broad description, many examples of widely varying complexity exist.

finite element analysis. A numerical method for solving partial differential equations that describes the response of a structure to external loading (thermal and mechanical) conditions.

heat flux. The rate at which the energy is transferred through a unit area of surface, for example, during welding of a plate.

plane strain. The out-of-plane strain components are zero everywhere in a 2D structure.

plane stress. The out-of-plane stress components are zero everywhere in a 2D structure.

power density. The amount of power absorbed or generated per unit volume in the neighborhood of a point.

residual stress. The stresses that remain in the structure after the completion of welding after all external forces acting on the structure are removed.

simulation result. The final result of the performed simulation in terms of the selected welding specific characteristics.⁵

solution method. An approach to solving a generated mathematical model using numerical algorithms.⁵

validation. The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

validation experiment. An experiment designed specifically for validating the calculation results with maximum possible coverage of all relevant data and uncertainty.⁵

verification. A methodology to test consistency between the physical model, the mathematical model, and the solution method in which, as opposed to the validation, no experimental data are employed.⁵

4. Approach

This guide extends the ASME V&V 10–2006 standard’s philosophy on CSM to CWM. The specific approach utilized here is to produce a general V&V document (this standard) supplemented by more specific and nonmandatory guidance contained in recommended practices. The relationship between V&V and recommended practices is shown in Figure 2. These recommended practices for CWM will provide guidelines and for both verification and validation methodologies for different modeling procedures relevant to welding. With these methodologies, a practitioner of CWM will be able to develop and deploy CWM for different aspects of welding.

As per the methodology, the first step identifies the intended use and priority for this activity. A simple overview of welding processes, materials, and intended applications indicates that this standard could have a wide reaching impact. Clause 5 describes a V&V document for residual stress and distortion. It is important to note that some of the methodologies and procedures to be developed may crosscut other V&V documents for microstructure and performance prediction to be developed in the future.

Predictions of residual stress and distortion require different modeling procedures and the V&V methodologies are described for each of the following procedures. In this document, first the verification of the methodology for residual stress and distortion is presented. The validation clause will follow this clause.

5. Discussion of Computational Weld Modeling Methods and Influences on Analysis

5.1 Overview. In a thermo-mechanical welding simulation (i.e., CWM), the welding conditions and joint configuration are the input to the thermal analysis, where the heat flow, molten metal flow, and phase transformations may be analyzed. The output from these analyses is the temperature history and microstructure. In the mechanical analysis, which may

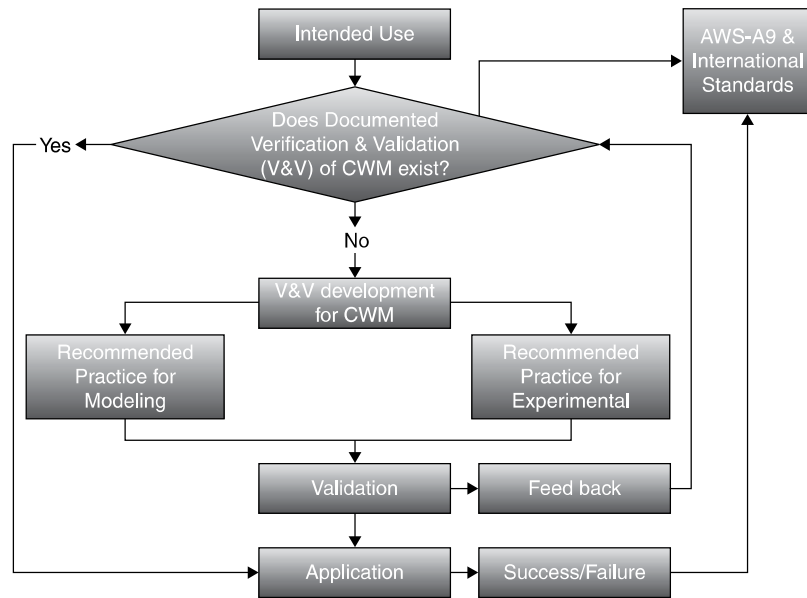


Figure 2—Proposed Methodology to be used for Development of V&V Documents for Different Aspects of Computational Weld Mechanics

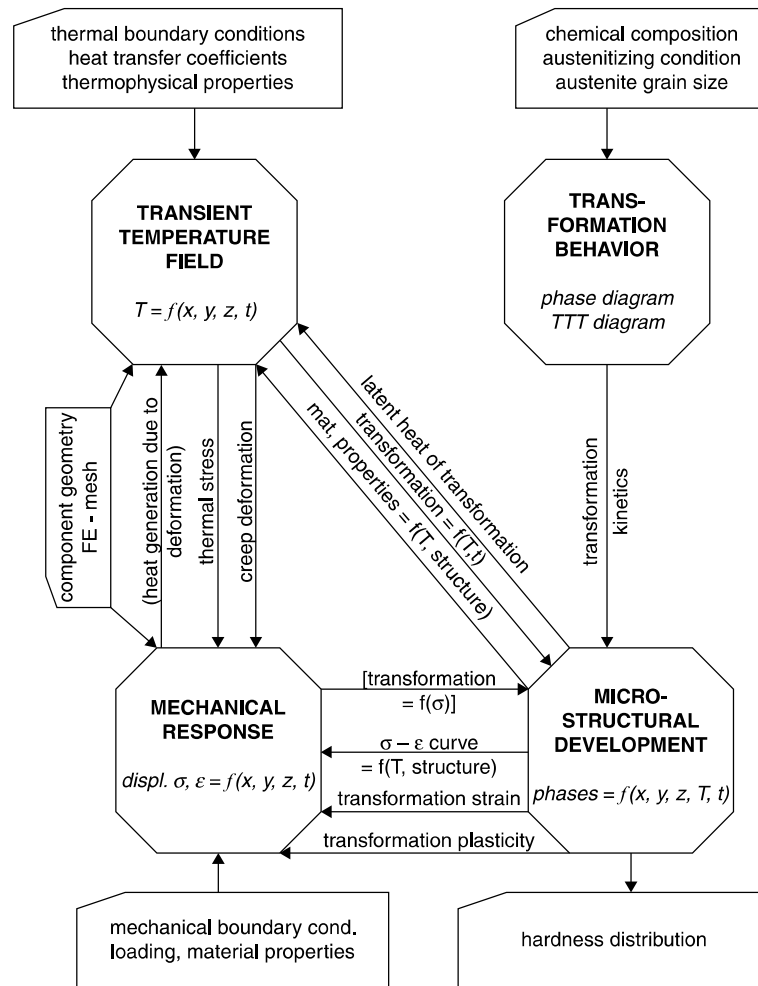
follow or be coupled with the thermal analysis, the elastic-plastic deformation, creep, and transformation plasticity are analyzed. The distortion and residual stresses are the output of the mechanical analyses.

Clause 5 addresses the various components that make up a CWM, including common or key simplifications, and their qualitative impact on analysis accuracy. There are a wide range of analysis possibilities within CWM, with a corresponding range in accuracy. Underlying this clause is the assumption that a CWM problem may be thought of as falling in a continuum between analysis complexity and required verification and validation (V&V).

5.1.1 Clause Organization. This document is intended for a range of users, from engineers performing CWM to project managers responsible for the incorporation of the results into the larger project framework. Clause 5 is written in a format of increasing technical information within each subclause. As a convenience, essential high-level information is written at the beginning of each subclause rather than dispersed throughout them. The basic organization of this clause is as follows:

- Current State of the Art
 - Key Analysis Inputs
 - Material properties
 - Model Scale and Scope
 - Thermal, microstructural, and mechanical analysis couplings
 - Modeling of multiple pass welds
- Analysis components
 - Thermal analysis
 - Microstructural analysis
 - Structural analysis

5.1.2 Intent of Clause. Prior to verifying a CWM model (described in Clause 6), the model itself must be chosen. The choice of model is driven by the problem to be solved. The most general and complex CWM problem is simultaneous prediction of temperature, microstructure, distortion, and stress histories at all points in a structure for the complete welding process. These phenomena and their couplings are illustrated in Figure 3 and constitute an extremely demanding multi-physics problem.



Source: Reprinted, with permission, from Scandinavian Journal of Metallurgy, Wiley [2]

Figure 3—Schematic Illustration of Integrated Computational Weld Mechanics Approach

Currently, industry problems that are likely to come before project managers and engineers will represent simplifications of some kind. Any simplifications will increase uncertainty in the solution. This uncertainty may be compensated by increasing the amount of V&V required (as described in Clause 6) to achieve the same level of confidence in results. Alternately, if the increased uncertainty can be bounded, it may be accepted and addressed as part of the larger project-based decision making process. Within the current state of CWM, uncertainty and error due to problem simplifications can range from minimal to great, and are problem dependant. However, with some understanding of the specific simplifications that can be made, and a proper V&V strategy problems of practical importance can be solved using CWM, with a corresponding substantial increase in safety and quality and a decrease in cost and risk.

5.2 Current State-of-the-Art in CWM. A first principles simultaneous solution of all phenomena is still an active research area. The most rigorous commercially available numerical solution procedure would be a three-dimensional solid element model employing a traveling power density heat source with simultaneous calculation of temperature, microstructure, and displacement, utilizing elasto-visco-plastic constitutive models based on material properties ranging from room temperature to beyond the melting temperature. Solutions of this complexity are generally only available in welding-specific software. General purpose commercial finite-element software typically can only solve a subset of these problems “out-of-the-box;” extensive user programming is typically required to approach the level of detail captured in many welding-specific software packages.

The development of integrated thermo-mechanical-metallurgical models is indeed challenging due to the complex interaction between physical processes during welding. Some of these physical processes include heat and mass transfer, phase transformations, electro-magnetic phenomenon, plastic strain, and reactions with environment during welding. Researchers have developed a framework for linking thermo-mechanical histories to microstructure development and mechanical heterogeneity in welds (see Annex B—Part C). These developments are again summarized in Figure 3.

According to Figure 3, by integrating individual sub-models for heat, mechanical, and material models, one can predict the overall performance of welded structures. The approach starts with a heat-transfer model that simulates temperature distributions in three-dimensions [$T = f(x, y, z, \text{time})$] as a function of process parameters and time. Thermal cycle data will be used by material models to predict the microstructure evolution and its impact on transient mechanical (σ - ϵ relations) properties. The transient changes in temperature and mechanical properties will be fed into a finite-element structural model to predict plastic strain distribution. This information allows for the prediction of final properties, residual stress, and distortion in a complex welded geometry. This interdisciplinary approach may appear simple; however, it requires collaboration between experts in metallurgy, finite element analyses, welding process, and computer science [62, 63]. To a limited extent, this vision has become a reality by pioneering work in many organizations and commercial software companies (see Annex B—Part D). There exist several conference proceedings that provide a detailed progression of integrated weld modeling and its capability for a wide range of joining processes (see Annex B—Part E). In addition, there are several useful classic textbooks related to modeling of welding processes (see Annex B—Part F).

5.3 Key Analysis Inputs. Key inputs are those that are either fundamental to the analysis, or that the analysis will be particularly sensitive to them. A CWM may contain thermal, metallurgical and structural analyses, and inputs and assumptions are addressed with respect to each.

5.3.1 Material Properties. Accuracy of the prediction by CWM relies on the accuracy of thermal, physical, mechanical, and metallurgical properties used by the models. Universally accepted, codified material properties for a wide range of materials do not exist as they do in other technology areas (e.g., the NIST Database of chemical properties, or the ASME Boiler and Pressure Vessel Code Section II, “Material Properties”). This unfortunate combination of sensitivity and uncertainty is largely counteracted by the use of a concept called the cutoff temperature; this concept is addressed in 5.6.1. For a certain subset of analyses, greatly simplified material properties have been found to be adequate when used in combination with test data. Examples are contained in the methods described in 5.7.

Some of the properties required for a general CWM include thermal conductivity, the coefficient of thermal expansion, density, specific heat, heat of fusion or transformation, elastic modulus, Poisson’s ratio, yield strength, tensile strength, strain hardening exponent, total elongation or ductility, and fracture strain. It is important for the analyst to understand the implications of material model selection. The selection of any of the above approaches must be related to the end goal of an accurate CWM analysis. In the published literature, many approaches have been used for selection of the above properties. Some of these are:

(a) The most common approach is to assume that these properties do not change with ensuing temperature and strain (or stress) during welding. Here the analyst has instant access to these from standard literature and minimizes material data development costs while reducing computational impact. However, some of the process physics may not be fully depicted as seen in (b) and (c) and may introduce accuracy errors.

(b) The second approach is to introduce additional complexity of temperature dependence of these properties. However, a much more complicated material model must be developed—greater accuracy in the results should be obtained. Generating the data requires significant investments in cost and testing. However, greater accuracy may lead to higher confidence in software results and may drive further optimization efforts. Additionally, material model selection may force the type of required representative model required. To accurately capture the entire phenomena that are occurring, 3D elements may be required, thus increasing the complexity of the modeling, the computational time, and the post-processing efforts.

(c) To support the previous statement, it is well known that during welding of steels, the thermal expansion coefficient and density changes as a function of temperature and is different for the heating and cooling cycles. This is related to hysteresis in ferrite to austenite (on heating) and austenite to ferrite (on cooling). These solid phase transformations that occur during the thermal cycle produced by welding lead to irreversible plastic deformation at the microstructural scale known as transformation plasticity. This phenomenon is driven by the volume change during solid-state phase transformations [3, 4, 5, 6, 7] and transformation plasticity (a term proportional to the deviatoric stress tensor) [3, 4, 5, 6, 7]. The above effects are shown to be inherently 3D [8].

The third approach relies on describing these properties as a function of the history or path dependence during welding. This approach is highly dependent on the process used. It requires model calibration to the empirically collected data. For example, during welding of steels, variation of thermal expansion coefficient and density change as a function of temperature during the heating cycle will be different compared to that of the cooling cycle. This hysteresis is metallurgical in nature and related to the transformation of ferrite to austenite (on heating) and austenite to ferrite (on cooling). The selection of either one of the above approaches is related to the end goal of the computational weld mechanics. Recent literature has demonstrated that this process or path dependent approach may lead to only small improvement in accuracy in the prediction of residual stress and distortion of ferrite-pearlite steels. Earlier work has shown that if the austenite-martensite transformation in high strength steels is neglected, the residual stress predicted is equal to the yield stress, but the experimentally measured residual stress is near zero [9]. For the new generation of steel weld consumables, a sensitivity analyses on simple weld geometry is needed to understand the sensitivity of final predictions for these new steels. This is because these new steels are designed to induce compressive stress in the weld toe by leveraging the transformation of austenite to martensite very close to room temperature. Recent papers address these sensitivities [10, 11] through numerical modeling.

5.3.2 Model Scale and Scope. One of the first choices to be made for a CWM model is the scale and scope of the model. In this context, scale and scope refers to 3D vs. 2D analyses. 3D modeling and analysis is the most rigorous approach for CWM as the welding process is inherently 3D and intensely local for all but the fastest welding speeds or thinnest sections. It is very important to note that power per unit length is not sufficient to characterize weld; welding speed should be specified. However, from a practical standpoint, simplified axisymmetric analysis of piping and pressure vessels is widely documented to produce weld residual stress results within the scatter band of experimental results that are themselves subject to interpretation. A recent example is given in reference [12]. As long as the simplifications used in a given CWM analyses are understood, the degree of simplification may be perfectly acceptable for the specific problem being studied. In terms of general guidance, items such as detailed through-thickness stresses, metallurgical effects, or moving arc information will require a 3D model.

Simplifications from 3D analysis include idealizing key solution variables as varying only in a single (flat) plane. These are cross-sectional models; that is, the model appears to be a slice through the weld and parts being joined, and are often referred to as 2D solid element models. This class of model includes axisymmetry, plane stress, plane strain, and generalized plain strain.

The other primary analysis simplification applies to structures that have two dimensions much greater than the third. Examples of this are a very wide thin plate or very large pressure vessels with thin walls. Further clarification on what constitutes “thin” is available in a host of mechanical textbooks. Structures such as this can be geometrically represented by surfaces and computationally modeled with shell elements. Shell elements are still 3D because they provide an assumed behavior in the thin direction and deformations and rotations are allowed in all directions. Deformation is not restricted to a single plane as in the 2D case.

The quality of the solution and magnitude of the approximation are strongly a function of part size, thickness, and the welding inputs. A more detailed discussion follows.

5.3.2.1 Axisymmetric Analysis. In axisymmetry, all theta sections are loaded and behave identically, as illustrated in Figure 4. A common example would be a cylindrical pressure vessel under uniform internal pressure. One could model the cylinder and pressure loading in 3D, but there would be no variation in results around the cylinder. In this case, the assumed behavior matches the actual behavior, and the axisymmetric solution is the exact solution.

In welding, axisymmetry assumptions are typically based on axisymmetric geometry (though to be rigorous, the assumption must be equally valid for the geometry, loading, and boundary conditions); the simplification then relates to how 3D the actual welding effects are.

In an axisymmetric mechanical welding analysis, there is no direct restraint in the hoop (or out-of-plane) direction, as every cross section or plane is assumed to behave identically. It assumes that the entire weld is laid down instantaneously. Start and stop effects are inherently neglected, and hoop stress is developed as the band of the weld pass contracts as it cools. The contraction of the weld pass is resisted by the adjacent bulk material in a single plane; excluding the free surface of the pool. The actual restraint for the instantaneous condition is quite different, as the weld pool is surrounded by relatively cold metal. Product geometry and welding conditions influence the actual result, but studies have shown axisymmetric models may produce results that differ significantly from a corresponding 3D analysis.

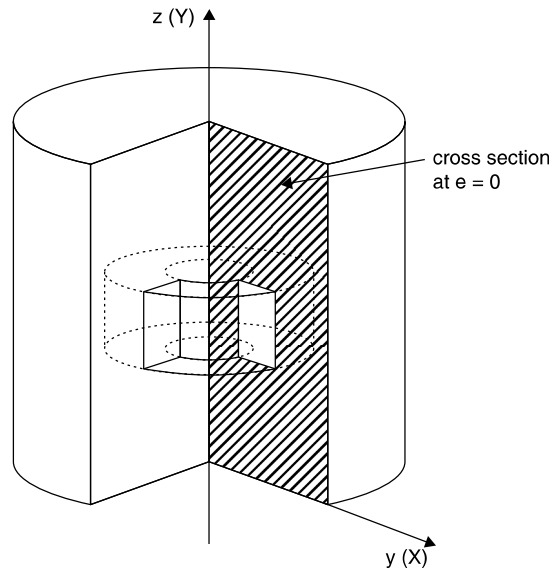


Figure 4—Schematic Illustration of Axisymmetry

On the other hand, while axisymmetry does not represent reality for most practical welding situations, it has been widely shown to produce yield level hoop residual stresses consistent with measurement and qualitatively in agreement with observed distortions. However, note that a temperature distribution of only a fraction the magnitude of that produced in welding is sufficient to produce yield level residual stresses. Said another way, simply shrinking an area of material in an axisymmetric analysis, without any refined material models, or even thermal analysis, will produce this result. Only slightly more complex analyses will begin to produce qualitatively meaningful axial (transverse to welding direction in this case) stress results. If this is an acceptable result, then the simplest analysis possible could be appropriate.

5.3.2.2 Plane Stress Analysis. Plane stress says there is no stress in one direction (i.e., there is no restraint or non-uniformity in load or geometry in this direction). This type of assumption is not generally employed in 2D planar analysis of welding, and is not discussed further.

5.3.2.3 Plane Strain Analysis. Plane strain says there is no deformation in one direction (the direction perpendicular to the plane modeled). Early analysis of butt-welded flat plates used a plane strain cross-sectional model; however, it has been recognized that these models are overly stiff in the welding direction. This type of CWM analysis has been largely replaced with a modified form of plane strain analysis called generalized plane strain.

5.3.2.4 Generalized Plane Strain Analysis. Generalized plane strain is a special case of plain strain where the out-of-plane strain is not forced to be zero, but rather a single displacement and rotation value of the entire cross section is allowed—see Figure 5). This method is widely used for the thermal stress analysis of thick sections or plates, and is always less stiff than the plain strain assumption. The degree of reduced stiffness is largely dependent on the geometry modeled however. For example, if the heated portion of the plate is small, relative to the total dimension of the modeled cross section, there will be very little benefit as the cold plate will dictate the (near zero) displacement for the entire cross section. Additionally, these models are typically inadequate to capture the nontransverse stress history, such as longitudinal stress, and overall distortion. In those cases, 3D models are required. A recent study has shown that the deformed shape of a cross section near the middle of a welded plate clearly exhibits warping, especially near the weld zone [13]. Thus, both the plane strain condition and the “generalized” plane strain condition in the 2D model might not be accurate as 3D analysis.

5.3.2.5 2D Planar Model Advantages. The preceding descriptions apply only to 2D planar structural analysis. In 2D thermal analysis (either planar, or axisymmetric where area is weighted by radial position), heat transfer analysis in some cases is reasonably accurate and comparable to 3D analysis results. While 2D planar models may be less rigorous than full 3D analysis, they have many attractive and beneficial aspects as well. Two-dimensional models take less

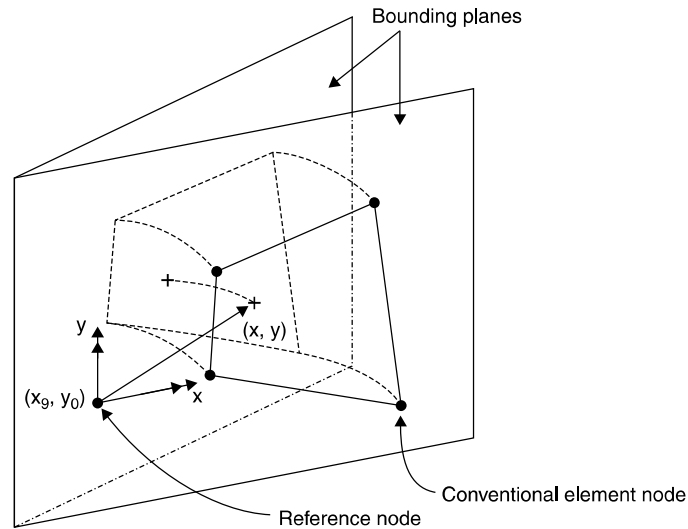


Figure 5—Schematic Illustration of Generalized Plane Strain

computational resources to run and simulation results are easier to visualize. The savings in computational resources have been shown to be especially significant for multiple pass weld simulations. For example, a 2D, twelve-weld-bead model can be analyzed in an hour while a similar 3D analysis may take days or weeks to complete, allowing rapid access to often qualitatively meaningful results. As predicted temperature profiles can be consistent between 2D and 3D models [14], 2D models are often adequate for first order studies due to the minimal computational resources. Two-dimensional models are also useful for heavy section multipass welds to qualitatively investigate the impact of weld sequence changes and major geometric changes (e.g., evaluating mock-up configurations). Additionally, if a 2D model is calibrated to match observed behavior for a particular class of problem over a period of time, the cost and time-savings may be obtained with an acceptable level of accuracy.

5.3.2.6 Shell Model Analysis. As discussed previously, a structure that has two dimensions much greater than the third can be geometrically represented by surfaces and shell elements. Shell elements (see Figure 6) usually assume linear stress variation in the thin direction—if the behavior is nonlinear (like at a nozzle/shell intersection), they are not as appropriate. However, shell elements can model complex thermal stress distributions in the through-thickness direction. A primary application where shell element analysis is well-suited is in obtaining global distortion predictions of complex, thin structures, particularly where single pass welds are employed. In this case, a shell analysis can be a useful approximation and results in some cases can be comparable to 3D solid analysis. Shell analysis of multipass welds generally requires calibration and specialized modeling techniques.

5.3.2.7 Multiple Pass Welds. For multiple layer welding, the numerical simulation requirements become more complex. First, the size of the numerical model can exceed reasonable simulation times or processing capacity. Secondly, multiple heat cycles affect the microstructure so that additional metallurgical characteristics have to be considered such as multiple phase changes, material tempering, and the appearance of inter-critically reheated zones. These issues along with the selection of a 2D or 3D approach must be made.

It is possible to perform a multiple layer welding simulation with either a 2D or 3D approach, depending on the simulation objectives. Subsequently, the possibilities of different methods of multiple layer simulation will be outlined.

The 2D approach is characterized by a short calculation time reducing the computer resources required. While helpful to obtaining convergence, simplifications made to use 2D models affect simulation quality for determining items such as hydrogen diffusion, hydrogen assisted cold cracking (HACC) [15], stresses limited by planar stress states, and neglected local effects [16, 17].

Using 3D models is necessary to obtain accurate simulations of complex geometries, 3D stress and deformation states, and metallurgical results [18]. The use of 3D solid element models result in a long computational time due to the

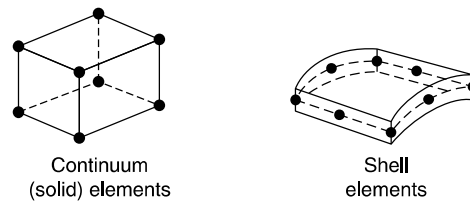


Figure 6—Schematic Illustration of Shell Elements

high number of elements and nodes. There are different approaches of 2D and 3D modeling depending on the required accuracy level [19, 20]. The model should be chosen in relation to the specific problem being and the desired predictive results.

5.3.2.8 Application of Simplified Models to Distortion Analysis. Two-dimensional, 3D small deformation, 3D large deformation, and 2D/3D decoupled applied plastic strain analyses have been evaluated in terms of predicting welding induced residual stress and distortion in thin panels. Experimental residual stress and out-of-plane distortion measurements were used as reference [21]. The following conclusions are drawn based on the results obtained:

- (a) Two-dimensional generalized plane strain analysis cannot capture welding distortion accurately in real life conditions. In thin plates, it does account for longitudinal buckling. In thick plates, the angular distortion is incorrect.
- (b) The 2D/3D applied plastic strain method predicts the onset and magnitude of buckling distortion accurately. However, it is not suitable for computing angular distortion.
- (c) The 3D small deformation analysis predicts correct values of longitudinal residual stress and distortion if there is no buckling. When buckling occurs, the 3D small deformation analysis corresponds to the unstable equilibrium state.
- (d) The longitudinal stress distribution predicted by the 2D analysis correlates to the unstable equilibrium state of long panels that approximate the 3D small deformation results.
- (e) The 3D large deformation analysis can predict the correct magnitude of distortion and longitudinal residual stress distribution in case of both angular and buckling distortion. It also captures end effects.
- (f) Geometric or load imperfections are needed in large deformation buckling analysis. In thermo-elasto-plastic analyses, the torch offset acts as a load imperfection. Add-on geometric imperfections are needed in the structural analyses of the applied plastic strain method.
- (g) The distortion magnitude has a high sensitivity to the imperfection magnitude for residual stresses near the critical buckling stress.
- (h) When buckling occurs, the residual stresses relax and reduce in magnitude.
- (i) There are multiple equilibrium configurations in a buckled panel. In computational models, the configuration can be switched by switching the imperfection sign. The configuration of the experimental panels can be switched by applications of momentary external forces. Therefore, when buckling occurs, the buckling mode and absolute value of distortion magnitude are of significance. The 3D large deformation method becomes computationally very expensive with model growth. Thus, the 2D/3D applied plastic strain approach may be used as an effective tool to predict buckling induced welding distortion instead of the 3D large deformation method.

5.3.3 Analysis Couplings. A majority of the published thermo-mechanical models are based on the sequentially-coupled approach. In this approach, the thermal model is run first as a pure heat transfer analysis. The thermal model typically takes into account the latent heat due to metallurgical phase transformation especially the latent heat of melting. The phase transformation temperatures and latent heat need to be known before solving the thermal model. In the second step, if the detailed metallurgical effect is of interest, the predicted temperature vs. time profiles (thermal cycles) at each node is input into a microstructure model to predict the phase evolution during welding. Finally, the thermal cycles and the microstructure history at each node are input into the mechanical model to calculate the residual stress and distortion. The sequentially-coupled approach is usually valid because the coupling of thermal, metallurgical, and mechanical

effects is mostly one-way in fusion welding. For instance, the mechanical stress and plastic deformation are expected to have very little influence on the temperature distribution; nor do they affect most phase transformations.

In a fully-coupled approach, the governing equations for heat transfer and those for mechanical stress and displacement are solved simultaneously. Though fairly rare, there are cases where the fully-coupled approach is required for accurate simulation results. For example, if a flat coupon is tack-welded to a stiff plate, then the coupling between thermal and stress analyses for a bead-on plate weld can be very strong through the contact stress and thermal contact between the coupon and the stiff plate. Additionally, when the components to be welded are unrestrained, large distortions may lead to a full thermo-mechanical coupling as the fit up and weld location may be altered [22].

The sequentially-coupled approach is much less demanding computationally than the fully-coupled approach. Because many more variables are solved at the same time, the fully-coupled analysis requires much more physical memory and computational time. Hence, the sequentially-coupled approach can be especially advantageous when multiple thermal runs with different heat input parameters are needed to validate the thermal model.

In summary, the heat transfer analysis and the mechanical stress analysis can be sequentially coupled in many, perhaps most, fusion welding problems. However, there are cases when they should be coupled.

5.4 Modeling of Heat Transfer During Welding. Thermal analysis of modeling is perhaps the most fundamental part of performing CWM; this is because the thermal analysis is generally required to generate any subsequent metallurgical, residual stress, or distortion results. There are many options available for thermal analysis of welding, covering a range of complexity; the appropriate choice of procedure is closely tied to the desired final result. For example, classical and simple closed form solutions for the welding temperature field from the 1930s and 1940s are often adequate for many simple metallurgical calculations. On the other hand, detailed prediction of through-thickness stress in a heavy and irregular section would tend towards requiring the most complex of the methods described below. Note that when stress or distortion are of interest, the molten weld pool is not directly resolved (e.g., using computational fluid dynamics), but rather replaced with an equivalent energy source.

5.4.1 Analytical Models for Prediction of Temperature Fields. In welding simulation, a precise description of the transient temperature field governs all subsequent analyses such as microstructure evolution, residual stress, and distortion. For CWM, the complex weld pool physical phenomena can be approximated by an equivalent heat source model based on the partial differential equation of heat conduction [23].

The major task in simulating the global temperature field is the development of numerical values (e.g., the power density distribution) so that the simulated temperature field is in agreement with experimental data. This problem cannot be solved directly because the physical process parameters cannot be used as model parameters to achieve a successful virtual weld. Therefore, the optimal model parameters have to be determined inversely. It is common practice to solve this inverse heat conduction problem by multiple direct simulation runs in connection with optimization algorithms [24]. In the case of computational intensive models based on finite discretization schemes, this approach is limited and can be very costly with regards to time [25]. In contrast, analytical closed-form solutions offer the possibility of predicting global transient temperature field by order of magnitudes faster. This allows automation [26] of optimization algorithms to obtain the virtual model parameters that agree with experimental reference data.

Based on a Green's function approach, analytical solutions to the temperature field can be obtained for various volumetric heat sources. Furthermore, adiabatic or convective boundary conditions are considered [27]. It has been shown that the analytically calculated temperature field for a volume heat source that moves on an arbitrary shaped welding trajectory can coincide with the numerical counterpart based on linear finite elements [28, 29].

These methods for generating analytical temperature field models for simple geometries like plates of finite dimensions have been validated. Conformal mappings techniques enable the transformation of the temperature field from a rectangular bounded domain onto a polygonal bounded domain allowing the temperature field for fillet or overlapping joints to be modeled analytically [27].

However, it should be noted that with respect to the applicability of analytical temperature field models for CWM, the influence of temperature independent thermo-physical-material properties on the temperature field and its affect on the resulting thermo-mechanical stress and displacement field needs to be investigated in comparison to the nonlinear numerical counterpart. In practice, going back to the pioneering work of Rosenthal at MIT in the 1930s and 1940s, full-field agreement of temperature distributions and histories has remained challenging when using constant material properties and the property values are typically tuned to give agreement in the region of primary interest.

5.4.2 Calibration of Heat Source Thermal Models. As described earlier, there are various approaches to develop heat source models. Many of the models described use 2D or 3D models with special exceptions or limitations. However, all of the models must be calibrated; the reader is referred to Clause 6 on validation for more details. Basic methods for calibration rely on matching measured thermal histories at points near a weld, near a reproduction of the measured spatial weld pool domain, or both. Proper implementation of these models is often directly tied to other modeling assumptions, such as the treatment of material properties and element activation strategies. Also note that calibration of a welding heat source alone does not ensure calibration of a computational weld model for a particular end use. Some of the commonly used calibration procedures are described below.

5.4.2.1 Prescribed Temperature Model (PTM). In this method, the temperature values are set for the weld pool region only. The analyst attempts to vary the heat source model's numerical parameters until the proper temperature profile is reached. There are multiple levels of complexity that can be used to develop a PTM from simplistic to complex. For example, a simple model could assume that a uniform liquidus temperature is achieved throughout the entire weld pool [29]. A more complex method involves prescribing a radial temperature profile [23]. Most recent models solve a simplified fluids problem to solve for the solid-liquid boundary in space and apply the resulting temperature to finite elements analysis (FEA), e.g., Sudnik/Ohji models (4th Generation heat source models) [30]. These models, like the prescribed heat power density models to follow, assume the liquidus boundary (weld pool shape and size) are known; thus the model is validated, at the very least, by reproduction of the known molten boundary in the computational model. Alternatively, the weld pool shape and temperature distribution are defined by computational fluid dynamics (CFD) models. CFD models are capable of predicting weld pool shape and size with consideration of buoyancy, surface tension, and magneto-hydrodynamics, but also require V&V.

5.4.2.2 Prescribed Power Density Distribution Model. In this approach, simple point-, line-, or plane-heat power densities are used. These methods are sometimes considered quicker than flux models and are often applied to large structures when distortions are of interest. The liquidus boundary is not usually reproduced or calibrated; temperature profiles and measured distortions are often the most appropriate validation for these types of models.

Many published models assume constant thermal material properties (i.e., not temperature dependent). Thus, matching a thermal history over all temperatures and distances from the weld pool can be challenging. Typically, assumptions are made about the spatial region and temperature range of greatest importance (e.g., it might be postulated that the HAZ less than 0.5TH is most critical for distortion prediction); these assumptions are ultimately validated in any case. Implementation of these models for finite thickness plates usually involves mirrored “imaginary” auxiliary heat sources that can be difficult to implement in arbitrary, complex shapes. See Annex B—Part A for further reading.

5.4.2.3 Prescribed Heat Input Model. The welding heat input to the weld pool can be modeled with either the heat flux ($\text{watt}/\text{meter}^2$) from the arc acting on the interface between the weld pool, or the power density ($\text{watt}/\text{meter}^3$) acting on the volume of the weld pool or by prescribing the temperature distribution in the weld pool. A model that only uses prescribed flux cannot generate realistic weld pools for many arc welds and obviously cannot generate the weld pools in laser or EB welds. One of the most well known power density models is the double-ellipsoid model by Goldak [31]. It models the heat input as a Gaussian distribution of power density applied over the weld pool volume idealized as two half ellipsoids. Cylinder, cone, and combination power density distribution models are frequently applied to generate weld pool shapes that differ from the usual ellipsoidal pool shape arc welds [32].

Model parameters to reproduce the melting isotherm of a known weld pool can be generated by prescribing an estimated temperature distribution in the weld pool. Then solve the heat equations with this known temperature distribution. The residual will be the power density distribution that is dual to the temperature and if the heat equation is solved with this energy equation it will reproduce this known temperature distribution. These models are often directly supported by commercial FEA software with minimal customization, whereas currently prescribed temperature models (within the weld pool) are typically not. These models can also be applied to either 2D or 3D models. For 2D “plane strain” models, the source is moved through the plane perpendicular to the weld paths. Such models ignore heat flow parallel to the weld direction. The error this causes becomes very large as the weld speed decreases [33, 34].

Two-dimensional “plane stress” models are based on a mathematical surface similar to thin shell models in stress analysis. They all approximate the heat flow through the thickness of the weld plate or shell by sinks or sources. For thin sheet or plate structures they can be very efficient. They can be very accurate if combined with a local 3D weld pool model near the arc where temperature isotherms may not be perpendicular to the sheet metal surface [25, 35]. Good overviews on modeling a heat source for welds can be found in recent books [30].

Arbitrary functions are used to define a distribution of flux on the surface of a weld and power density throughout the volume of a weld [30]. The double ellipsoid is one particular distribution function that provides a good approximation for many arc welds. However, it is not suggested that the double ellipsoid is more than a particular solution. If one has an exact solution of the temperature-enthalpy field, then one need only prescribe this solution to be Dirichlet and the associated flux and power density distribution are the Lagrange multipliers that enforces this exact solution. If the temperature field solution exists, then the associated flux and power density distribution must also exist.

5.5 Microstructural Analysis. Modeling of weld microstructures is indeed difficult due to complex (single or multiple) and spatially varying thermal and mechanical cycles. These variations influence the liquid to solid phase and solid-solid phase transformations, as a result, the final microstructure. The specific characteristics of this microstructure include dendrite morphology, grain size, grain shape, crystallographic orientations, compositional segregation, phase distribution, and defect density [37]. However, many researchers have addressed one or more aspect of the above microstructure evolution using phenomenological models. A review in the ASM Handbook [38] highlights various approaches for linking thermo-mechanical histories to microstructure development and mechanical heterogeneity in welds.

For example, for the welding of carbon steels, the models for microstructure evolution can be divided into models for heat-affected zone and weld-metal region. The models for heat-affected zone consider the formation of austenite from initial ferrite/pearlite microstructure during heating. The next step considers the austenite grain-growth during continued heating with and without pinning by small precipitates in the matrix. The third step considers the solid-state transformation of austenite to different morphologies (i.e., grain boundary ferrite, bainitic ferrite, and martensite during cooling). The relative volume fractions of these microstructures have been correlated to hardness. In the case of models for weld metal region, in addition to the above melting and solidification, inclusion formation is described. Some microstructure models are implemented within the computational weld mechanics (CWM) models as a post-processing step. This means that while solving for thermal and mechanical transients, the CWM models might not consider the effect of varying microstructure on the thermo-physical-mechanical properties. As a result, some of these models use the average properties as a function of temperature for both heating and cooling and ignore the history dependent properties. This approximation may be considered as acceptable for plain carbon steels that show phase transformation hysteresis [temperature at which 100% ferrite and 100% austenite present on heating and cooling] temperatures above 500 °C [932 °F] or above. However, for steels that transform close to the room temperature, the transformation induced plasticity effects may alter the ensuing residual stress and distortion drastically [39] (see 5.6.2).

Austenitic stainless steels and nickel alloys largely stay in the face-centered cubic (fcc) crystal structure in the solid state. Many models for predicting weld residual stresses do not include any solid-state transformation for those materials. On the other hand, recent studies have suggested that the dynamic recovery of dislocation could occur rapidly in the weld region exposed to high temperatures. Such dynamic recovery can influence the weld residual stresses especially for multipass welds, where the plasticity accumulated in the prior weld passes can be partially reset by the subsequent weld pass.

5.6 Modeling of Residual Stresses. Welding residual stress analyses typically involve applying the temperature results (see 5.4) from the thermal analysis to the computational model defined with mechanical properties and degree of freedom. The coupling between thermal and mechanical behavior is the thermal expansion, and stress is created by non-uniform temperatures and differential thermal expansion within the structure. Typically, a rate independent elastoplastic material response is assumed in the mechanical analysis allowing for the computation of residual stress due to plastic deformation during the welding heat cycle. This is a good approximation for temperature less than half the melting point. A detailed review of finite element modeling for welding residual stress and distortion modeling is available in Annex B—Part B. An overview of selected topics is presented in the following.

5.6.1 Material Modeling. The rate-independent, deviatoric plasticity model with the von Mises yield condition and the associated flow rule has been used with success in many welding simulations [20]. Some work has also used viscous-plastic models [39, 40, 41, 42] or combined rate independent plasticity at lower temperatures with visco-plastic models at higher temperatures [43]. The hardening behavior at lower temperature is important for the residual stresses. The materials near the weld experiences cyclic loading and choosing isotropic or kinematic hardening will affect the stresses in this region [44]. Extreme care needs to be exercised in reviewing the results based on any high temperature material model. Plastic strains inadvertently created at high temperatures (but below the solidus) can dominate the solution and are completely nonphysical (often produced as an unintentional by-product of the element activation scheme, i.e., when quiet element techniques are used). Unintentional material behaviors can also easily be created with non-isothermal

linear kinematic hardening models, unfortunate high-temperature combinations of elastic modulus and Poisson's ratio, or elastic modulus and material yield strength.

For temperatures that exceed the melting point, the modulus of elasticity and yield limit have zero value making viscous flow models more appropriate at these temperatures. However, elastoplastic or elasto-visco-plastic models may still be used in conjunction with the use of a cutoff temperature. This technique is used for two reasons: the properties at high temperatures are usually unknown, and a too soft weld metal in the model may give numerical problems or nonphysical plastic strains. In this technique, during the stress-displacement analysis, temperatures that exceed a cut off value are reset to the cutoff temperature. An appropriate choice of cutoff temperature will not affect the residual stresses [20, 45, 46].

The very low value of yield strength at high temperatures along with the use of elastoplastic models may result into artificial hardening and lead to higher than the actual residual stresses. To account for the annealing effect that naturally occurs in metals, either a creep model may be used or all accumulated plastic strains may set to zero above a critical temperature [47].

Careful compilation of material properties from a variety of sources, in combination with demonstration of results stability for a small range of reasonable cutoff temperatures indicates a well-posed high-temperature material model.

5.6.2 Solid-State Transformations. Solid phase transformations that occur during the thermal cycle produced by welding (see 5.5) lead to irreversible plastic deformation at the microstructural scale known as transformation plasticity [38]. This phenomenon is driven by the volume change during solid-state phase transformations [3, 4, 5, 6, 7] and transformation plasticity (a term proportional to the deviatoric stress tensor) [3, 4, 5, 6, 7]. The above effects are shown to be inherently 3D [8].

5.6.3 Eulerian Analysis. Thermal transport is discussed at length in 5.4. An approach for thermal transport analysis of welding is based on Eulerian reference frame attached to the welding torch with material flowing through the control volume. Because the heat source is fixed to the mesh, a very fine mesh can be used to capture the high-temperature gradients in the weld center. Furthermore, the mass conservation, momentum balance, and energy balance can be simultaneously solved to accurately calculate the temperature history in the presence of a molten weld pool. A viscous material response is typically assumed to eliminate the need for tracing and integrating the material response. As such, thermal transport analyses using Eulerian reference have primarily been used to model the temperature field and physical shape of the weld pool [31, 32, 33, 34, 35], the interaction between arc and material, buoyancy, surface tension, and magnetohydro-dynamic effects [48, 49, 50, 51, 52, 53, 54].

The thermal transport in Eulerian reference frame poses a special handling problem in the stress calculation. Computing residual stress requires modification of the constitutive model to account for the elastic component of stress, which depends on the deformation history of each particle. Furthermore, if the material evolution, such as hardening or transformations, is also to be considered in the computation of residual stress, the temperature, stress, strain, and internal variable history of each material particle needs to be computed. In Eulerian reference frame, this can be accomplished by computing backwards along the streamline of each particle and then integrating the material evolution along the flow-line [55, 56, 57]. Another approach is to use a mixed FEA formulation and enforcing the evolution in a weak form [58, 59, 60, 61]. Both approaches are quite specialized and require custom computer programming.

5.7 Distortion Prediction

5.7.1. Motivation. In today's world of welded structural fabrication, the standard method to developing good manufacturing processes is the trial-and-error method. The goal is to determine process parameters that produce a quality weld or weldment (a structure with multiple welds) in the most cost efficient manner. However, welding is a thermal process that when combined with metallic materials creates an inherent process issue—distortion.

Distortion is the end result of stresses being built up by the process and is influenced by many factors such as material, welding process, process parameters, joint geometry, bead and weld sequence, weld direction, and clamping conditions. Distortion can negatively affect the aesthetics, life cycle, strength, delivery time, and cost to produce the product. As the number of parameters in a welding operation is large, and exponentially larger for a weldment, creating an optimal process by the trial-and-error method can be too high in cost and time.

It is important for not only the end shape to be controlled but the mid-process distortions to mitigate intermediate operation costs. It has been shown that fitup costs downstream from a distorted product are dramatically increased, up to a factor of 2.4 times [62]. To avoid this cost, manufacturers usually take steps to mitigate distortion, using clamps, strong backs,

reinforcement structures, weld sequencing, or rework. All these methods except weld sequencing add additional processing costs. Many try to use weld sequencing to minimize distortion but often a structure will have multiple welds. This creates many possibilities⁶ often frustrating the manufacturer to revert back to the trial-and-error method. Manufacturers are left with a few cost effective methods to create optimized processes. The question facing the manufacturer is how to create an effective welding process without resorting to physical testing and to do this in a cost effective manner.

Recent advancements in computers have allowed finite element codes to be developed that are capable of simulating welding processes accurately. This capability is not only at the weld level but at the structural level too. With accurate virtual simulation based on process parameters, analysts can create multiple scenarios to develop comparisons leading to optimized welding processes.

5.7.2 Methods. Two approaches seem to dominate in the commercial codes to represent the loading of elements by weld induced thermal stresses. Other researchers have named these analytical methods the Equivalent Load Method (ELM) and Strain as Direct Boundary Method (SDB) [63]. These methods are further subdivided by the manner in which the applied loading is determined.

5.7.2.1 Equivalent Load Method (ELM). The ELM is the most simplistic and well-known method for weld distortion simulation by using methods to approximate the weld shrinkage. Theoretically, it is simple, but the application of the proper domain loadings with proper values and direction is relatively time-consuming process. ELM applies an equivalent lump of residual strains to represent the loads on the weld nodal or elemental sets, causing the structure to deform. The one lump representation includes all welding and material effects such as phase transformation, hardening, and quenching minus the elastic strain. The process does not require the strain to be numerically calculated but can be specified by the analyst from welding knowledge or experimental data.⁷ The loads are applied to the weld representative elements causing these elements to collapse or shrink. In other words, a set quantity of weld induced shrinkage is applied to the element nodes causing the nodes to undergo a strain or “shrinkage” effect. The final plastic strain tensor field, after welding is completed, is taken as data. From this, distortion and residual stress can be completed within a single elastic solver.

The structure undergoes macroscopic distortion based upon the “welds” shrinking and interacting with the constraints and other welds. However, it is often difficult to determine the amount of shrinkage due to the welding process because this value is greatly affected by the base material’s residual stresses and the combination of materials (base and filler), processes, and other external conditions. Often this loading condition is calculated numerically to avoid this issue. Once the process strains are calculated, the elastic strain calculated from the offset (elastic) condition is then subtracted from this value resulting in the residual strain that is applied to the elements representing the weld line.

5.7.2.2 Strain as Direct Boundary Method (SDB). The SDB method uses thermal contraction to create the loading criteria to place on the elements representing the welding material. By using the thermal contraction, this loading condition is calculated using a thermal expansion coefficient and the temperature difference as applied around the welding region. As with the ELM, the analyst, based on prior knowledge, could assign the thermal strain values or it can be calculated numerically. In this case, the coefficient of thermal expansion is dependent on the bulk material property as a function of temperature and the material phase (hereafter referred to as $f(T, \Psi)$), which is then applied to the elements or nodes found in the welding region to determine the distortion values. However, unlike the ELM method, the SDB method is typically a two part analysis; a coupled transient thermal and mechanical analysis. The coupling between thermal and mechanical analyses occurs in incremental steps. Thermal analyses (2D for shell elements and 3D for solid elements) determines thermal gradient. This information is used to define the spatially varying material properties that are relevant to mechanical analysis. With this update data, mechanical analysis determines the strains (i.e., distortions) from the welding process. That is, the residual stress from ELM should be equivalent to the thermal contraction strains developed by the SDB.

Using the SDB approach along with the LeBlond Material Model [3, 4, 5, 6, 7] and allowing the thermal strain to be determined numerically has often been termed as the full-physics approach. This is due to its accounting for all of the property changes and calculating thermal strain affects based on all the strain inducing characteristics using this material

⁶ It is related to the factorial of number of welds. For example, if a structure has 10 different welds, and each weld can be welded backward or forward, the factorial of $2^{10} \times 10^{10} = 1.0 \times 10^{13}$ is the total number of permutations.

⁷ This experimental data should include, at minimum, longitudinal, transverse, and out-of-plane shrinkage that should be treated as one shrinkage vector.

model. Others have used a modified version of this approach by considering only the bulk material properties [ignoring the effects of $f(T, \Psi)$]. This assumes that these strain-inducing characteristics are of a secondary or ternary influence on the overall developed strain. The differences in these approaches have been debated among software developers, and the total difference between the two approaches remains unresolved.

In the numerically calculated loading condition for the ELM approach, state equations representing phase transformation, hardening, and quenching effects are used to determine the amount of strain being created. Results are a function of the material properties specified by the analyst, of which there are two different approaches. One is to use bulk elastic modulus properties and the other is to use the LeBlond Material Model where the material is an $f(T, \Psi)$. In the ELM approach, this could affect the strain developed by the process as calculated from the strain influencing responses such as hardening or quenching. These differences might affect the developed process strains amounts thus affecting the amount of residual strain that is applied during the analysis.

5.7.3 Uses. Both ELM and SDB have been used to develop different commercially available codes. The predominant method has been the SDB method along with numerous finite element methods that reduce computational time yet remain accurate. The two major developers have created codes that utilize similar approaches except in the selection of the material model. For example, the bulk elastic modulus versus a material model with properties that are $f(T, \Psi)$. This difference has become a point of contention among users with focus of this on a cost versus accuracy discussion.

Both ELM and SDB use specialized methods to activate and deactivate elements to simulate the welding process. However, both require development time to create accurate thermal and sometimes mechanical models to represent the welding process. This is then applied using the SDB method to the weldment with good accuracy. On structures with a single weld joint, distortion analyses can be accomplished in a fair amount of time. However, if this continues beyond four or five joints, the transient analysis time can become computationally quite large⁸. Modified approaches have been developed combining the ELM and SDB methods to reduce computation time. For example, the ELM method of applying strains has been used to evaluate the applied loads by lumping thermal strains (SDB).

This calculation described in the previous paragraph provides the analyst with all the calculated information such as stresses, strains, metallurgy, and distortions. However, from a production standpoint, this information is not needed. Production typically is more concerned with the final condition of the structure and whether or not it meets the tolerances as stated on the drawings. Often a fabrication shop is required to use a particular weld joint geometry and welding process to fabricate a structure. Each of these specified joints has its own inherent distortion effects. Each specific welding process has its own inherent distortion effects. The fabricators have some control over these inherent distortion effects. Clamping conditions, weld direction, and weld order are some parameters fabricators can control to minimize overall distortion. Since the parameter interactions cannot be de-coupled, each parameter would have to be varied to determine the effects. This would create a test matrix that could not be solved in a reasonable amount of time with a transient calculation.

To alleviate this problem, a new approach has been created that further simplifies the use of a modified ELM and SDB method on just a shell-element-only model. This method calculates the transient thermal information and applies a temperature difference (room to melt). This, along with the coefficient of thermal expansion, allows a calculation of strain applied as a lumped load on the shell only model. This ELM-style approach is numerically efficient and results in a very quick solution convergence for each step of the welding sequence. This method then supplies the production line with the information that is required to optimize the welding sequence to minimize the distortion aspects.

Typically, most welding shops only care about the final shape of the structure and are more interested in optimizing the welding sequence. The modified ELM and SDB method can be used as a first-order and second-order calculation. The modified ELM and SDB method on a shell-only model can, relatively quickly, determine where the high stress production steps are, and then be used to developed methods to avoid this distortion affect. If the information for this modified analysis is not known, then an analysis using the transient method can determine the input values for the modified approach.

If this method is not sufficient to determine if a particular weld joint is a problem, and sequencing or clamping modifications are ineffectual, then a more detailed look at this joint may be required. At this point, the use of the coupled

⁸ Typically approximately 1:60 to 1:600. For every one second of welding, it can take 60–600 seconds to perform a transient analysis.

transient with solid element may be required. This would then provide much more detail to the analyst to determine other optimization techniques to modify the joint process, thereby minimizing distortion.

5.7.4 Summary. As one can see, there are many new methods to optimize the welding process to minimize distortion. It is incumbent upon the analyst to determine the best approach to achieve a solution to the problem at hand in a cost and time effective manner. The debate about which approach to use, either ELM or SDB, is without merit as they are equivalent in nature. However, the debate regarding the material model and its influence on the end results is valid and should be determined by the company or analyst before the problem is undertaken. Regardless of the numerical method used to represent the loading condition and regardless of the material model, it has become obvious to fabricators that using numerical models rather than physical tests results in a cost savings when trying to optimize a welding process to minimize distortion.

6. Validation of Residual Stress and Distortion Models

An experiment that is to be used to validate a weld model for particular phenomena of interest should be very carefully designed; see ASME V&V 10–2006 for a detailed explanation of general V&V principles [1] and Part G of Annex B regarding recent research. The experiment is best designed by first simulating the experiment with the weld model. The experiment should be repeated at least four times to estimate the repeatability of the experiment and the measured data uncertainties; this is explained in detail in ASME V&V 10–2006. The remainder of this clause provides recommendations for the design of an experiment to acquire data to be used for validating a weld model for a specified phenomenon of interest.

It is often not possible (and also not necessary) to test the entire weld structure for the purpose of validating the weld model. As discussed below, welds made in test coupons with similar heat sink capacity as the real structure are sufficient for validating the heat source model. For validating the stress model, a mock-up with stiffness and fixture representative to those in real structure may be needed. The design of a good mock-up requires a trade-off study of cost and time in building the mock-up vs. similarity of the mock-up to the real structure. The following practices are only relevant to the verification and validation of residual stress and distortion.

(1) For all data acquisition systems, one must stamp each data item with date (year/month/day) and time (hour/minute/second). All clocks in the data acquisition system must be synchronized. Operator should start acquiring data well before welding starts and run the data acquisition for a sufficiently long enough time to cool the structure to develop the residual stresses. This is typically to within 200 °F–300 °F [93 °C–149 °C] of room temperature that, dependent upon the structure size, may take up to 24 hours. Experimenter should not set start time to be zero and simply increment the time.

(2) **Recommend Practice**—It is recommended to have a video record of the welding process for use in the validation process for reference when comparing actual distortion occurrences to the virtual prediction. If a single camera is used, it is recommended to use a “video walk around” to capture fixtures, tack welds, and fitup at various stages during welding, including a far distance shot of the process. If multiple cameras are used, it is recommended to use the “video walk around” method as it will capture multiple angles of the process. If possible, it is recommended to capture the transient weld pool image. In all cases, it is recommended that frame-by-frame time stamping be used along with reference data such as a measuring tape to make data easier to use and apply.

(3) Install at least one strain gauge near the weld joint but sufficiently far from the weld so that the temperature excursion that the strain gauge sees is within the tolerance range of the strain gauge. The strain gauge is expected to accurately detect the time when each arc is struck and extinguished. It is recommended that a pattern of nine strain gauges be used but the number and actual locational pattern should be dictated by the structure and weld joint geometry as determined by the experimenter. The position of each strain gauge should be defined by its corner points. It is not sufficient to simply specify the position of the centroid of the strain gauge because the strain gauge can be sampling a region with a strain gradient. In that case, the strain gauge is sampling an area, not a point, and the model must know the sampling area. To test the strain gauge behavior in a transient temperature field, place a strain gauge on a flat unconstrained stress-free plate and heat it slowly from room temperature to 100 °C–200 °C [212 °F–392 °F]. The plate should remain stress-free with only thermal strain in the plate and on the strain gauge. This data should be provided for model validation.

Optical-based approaches have emerged as a powerful tool for both real-time and post-mortem measurement of surface deformation and distortion. They can provide evolution of strain distribution on the workpiece surface and final

distorted surface geometry after welding. The surface deformation data are useful in validating the stress and distortion model.

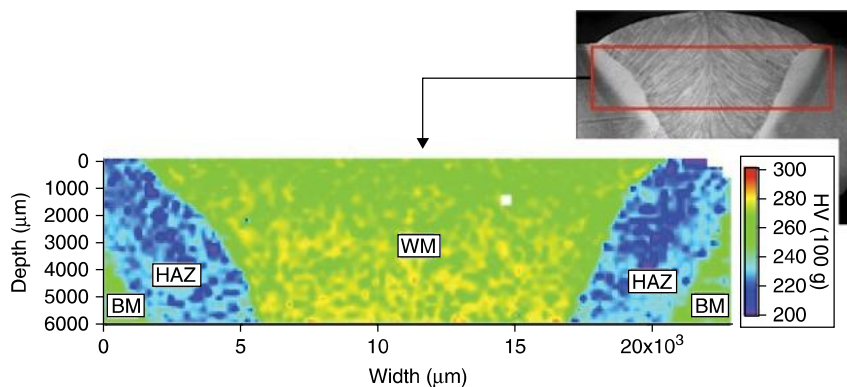
(4) Install at least one thermocouple near the weld joint at a distance from the weld joint necessary to detect maximum peak temperatures greater than 0.7 of the melting point. Plunging thermocouples into the weld pool or trying to place a thermocouple as close as possible to the boundary of the fusion zone is not effective. It is recommended that thermocouples be arranged in a pattern such that the welding direction and a good estimate of weld speed for each weld pass can be determined. It is estimated that nine or more thermocouples would provide sufficient coverage and pattern. Sudnik/Ohji models (4th Generation heat source models) indicate that the length of the 450 °C [842 °F] isotherm provides a good estimate of arc efficiency and hence net power into the weld [30]. It is also suggested to use at least four thermocouples, arranged perpendicular to the welding direction in order to get information about the temperature gradient perpendicular to the weld seam.

(5) The size and shape of the weld pool is best estimated from macrographs of cross sections of the weld. These can usually be done on test coupons. For multiple pass welds, the weld passes on a coupon can be arranged to resolve the fusion zone of each weld pass.

(6) The composition of base metal and weld metal (after welding) should be determined. This is needed to model the microstructure evolution.

(7) Measurements of residual stress by neutron and x-ray synchrotron diffraction should report carefully the geometry of the sampling volume for each measurement. Again, since these measurements are often made where the sampling volumes have high gradients, the models must know geometry and position of this sampling volume accurately in order to accurately predict the measured value. The position of the centroid of the sampling volume is not sufficient information.

(8) Hardness maps can be useful data for validating microstructure evolution models (see Figure 7). For example, measurement of Vickers hardness of 350 or above in the heat-affected zone (HAZ) of an alloy steel may suggest the predominant presence of martensite. However, it is important to note that similar hardness may be achieved by different strengthening mechanisms such as the formation of nano-scale copper precipitates in matrix. Therefore, for comprehensive validation of microstructure models, characterization in different length scales (μm to nm) using suit of microscopy tools is required [65].



Note: The map shows a soft zone formation close to the fusion line [64]

Figure 7—Hardness Map from a Metallographic Cross Section Made on a Longitudinal Seam Weld in a High-Strength Pipeline

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Annex A (Informative)

Cited References

This annex is not part of AWS A9.5:2013, *Guide for Verification and Validation in Computation Weld Mechanics*, but is included for informational purposes only.

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Annex B (Informative) Further Reading

This annex is not part of AWS A9.5:2013, *Guide for Verification and Validation in Computation Weld Mechanics*, but is included for informational purposes only.

Part A—Classical work performed by Rosenthal, Rykalin, Eager, and Tsai on simple point-, line-, or plane-heat power densities models. Radaaj provides exhaustive treatment of these, especially the Rykalin models while Nguyen provides detailed treatment of more recent analytical solutions. Readers are referred to WRC Bulletin 455, Report 2 and the VFT methodology for other examples.

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Annex C (Informative)

Guidelines for the Preparation of Technical Inquiries

This annex is not part of AWS A9.5:2013, *Guide for Verification and Validation in Computation Weld Mechanics*, but is included for informational purposes only.

C1. Introduction

The American Welding Society (AWS) Board of Directors has adopted a policy whereby all official interpretations of AWS standards are handled in a formal manner. Under this policy, all interpretations are made by the committee that is responsible for the standard. Official communication concerning an interpretation is directed through the AWS staff member who works with that committee. The policy requires that all requests for an interpretation be submitted in writing. Such requests will be handled as expeditiously as possible, but due to the complexity of the work and the procedures that must be followed, some interpretations may require considerable time.

C2. Procedure

All inquiries shall be directed to:

Managing Director
Technical Services Division
American Welding Society
8669 Doral Blvd., Suite 130
Doral, FL 33166

All inquiries shall contain the name, address, and affiliation of the inquirer, and they shall provide enough information for the committee to understand the point of concern in the inquiry. When the point is not clearly defined, the inquiry will be returned for clarification. For efficient handling, all inquiries should be typewritten and in the format specified below.

C2.1 Scope. Each inquiry shall address one single provision of the standard unless the point of the inquiry involves two or more interrelated provisions. The provision(s) shall be identified in the scope of the inquiry along with the edition of the standard that contains the provision(s) the inquirer is addressing.

C2.2 Purpose of the Inquiry. The purpose of the inquiry shall be stated in this portion of the inquiry. The purpose can be to obtain an interpretation of a standard's requirement or to request the revision of a particular provision in the standard.

C2.3 Content of the Inquiry. The inquiry should be concise, yet complete, to enable the committee to understand the point of the inquiry. Sketches should be used whenever appropriate, and all paragraphs, figures, and tables (or annex) that bear on the inquiry shall be cited. If the point of the inquiry is to obtain a revision of the standard, the inquiry shall provide technical justification for that revision.

C2.4 Proposed Reply. The inquirer should, as a proposed reply, state an interpretation of the provision that is the point of the inquiry or provide the wording for a proposed revision, if this is what the inquirer seeks.

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C3. Interpretation of Provisions of the Standard

Interpretations of provisions of the standard are made by the relevant AWS technical committee. The secretary of the committee refers all inquiries to the chair of the particular subcommittee that has jurisdiction over the portion of the standard addressed by the inquiry. The subcommittee reviews the inquiry and the proposed reply to determine what the response to the inquiry should be. Following the subcommittee's development of the response, the inquiry and the response are presented to the entire committee for review and approval. Upon approval by the committee, the interpretation is an official interpretation of the Society, and the secretary transmits the response to the inquirer and to the *Welding Journal* for publication.

C4. Publication of Interpretations

All official interpretations will appear in the *Welding Journal* and will be posted on the AWS web site.

C5. Telephone Inquiries

Telephone inquiries to AWS Headquarters concerning AWS standards should be limited to questions of a general nature or to matters directly related to the use of the standard. The AWS *Board Policy Manual* requires that all AWS staff members respond to a telephone request for an official interpretation of any AWS standard with the information that such an interpretation can be obtained only through a written request. Headquarters staff cannot provide consulting services. However, the staff can refer a caller to any of those consultants whose names are on file at AWS Headquarters.

C6. AWS Technical Committees

The activities of AWS technical committees regarding interpretations are limited strictly to the interpretation of provisions of standards prepared by the committees or to consideration of revisions to existing provisions on the basis of new data or technology. Neither AWS staff nor the committees are in a position to offer interpretive or consulting services on (1) specific engineering problems, (2) requirements of standards applied to fabrications outside the scope of the document, or (3) points not specifically covered by the standard. In such cases, the inquirer should seek assistance from a competent engineer experienced in the particular field of interest.

