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Numerical welding simulation — Execution and documentation

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National foreword

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Foreword

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The committee responsible for this document is ISO/TC 44, *Welding and allied processes*.

Requests for official interpretations of any aspect of this Technical Specification should be directed to the Secretariat of ISO/TC 44 via your national standards body. A complete listing of these bodies can be found at www.iso.org.

Numerical welding simulation — Execution and documentation

1 Scope

This Technical Specification provides a workflow for the execution, validation, verification and documentation of a numerical welding simulation within the field of computational welding mechanics (CWM). As such, it primarily addresses thermal and mechanical finite element analysis (FEA) of the fusion welding (see ISO/TR 25901:2007, 2.165) of metal parts and fabrications.

CWM is a broad and growing area of engineering analysis.

This Technical Specification covers the following aspects and results of CWM, excluding simulation of the process itself:

- heat flow during the analysis of one or more passes;
- thermal expansion as a result of the heat flow;
- thermal stresses;
- development of inelastic strains;
- effect of temperature on material properties;
- predictions of residual stress distributions;
- predictions of welding distortion.

This Technical Specification refers to the following physical effects, but these are not covered in depth:

- physics of the heat source (e.g. laser or welding arc);
- physics of the melt pool (and key hole for power beam welds);
- creation and retention of non-equilibrium solid phases;
- solution and precipitation of second phase particles;
- effect of microstructure on material properties.

The guidance given by this Technical Specification has not been prepared for use in a specific industry. CWM can be beneficial in design and assessment of a wide range of components. It is anticipated that it will enable industrial bodies or companies to define required levels of CWM for specific applications.

This Technical Specification is independent of the software and implementation, and therefore is not restricted to FEA, or to any particular industry.

It provides a consistent framework for-primary aspects of the commonly adopted methods and goals of CWM (including validation and verification to allow an objective judgment of simulation results).

Through presentation and description of the minimal required aspects of a complete numerical welding simulation, an introduction to computational welding mechanics (CWM) is also provided. (Examples are provided to illustrate the application of this Technical Specification, which can further aid those interested in developing CWM competency).

Clause 4 of this Technical Specification provides more detailed information relating to the generally valid simulation structure and to the corresponding application. Clause 5 refers to corresponding parts of this Technical Specification in which the structure for the respective application cases is put in concrete terms and examples are given. Annex A presents a documentation template to promote the consistency of the reported simulation results.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TR 25901, *Welding and related processes — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/TR 25901 and the following apply.

3.1
boundary conditions
conditions imposed at the spatial boundary of a computational model that describe the interaction between the modelled and unmodelled domains

Note 1 to entry: Complete boundary conditions provide a unique solution to the specific mathematical problem being solved.

3.2
geometric model
description of all geometries analysed within a simulation including the dimensionality of the simulation object

3.3
mathematical model
model comprising the underlying essential mathematical equations including the appropriate initial and boundary conditions

3.4
numerical simulation
simulation performed by adopting approximate mathematical methods generally performed on a computer

3.5
physical model
full array of the physical process to be simulated and boundary and initial conditions relevant to the simulation object as well as adopted simplifications and assumptions

3.6
plausibility check
check of the obtained calculation results in respect of their conformity with basic physical principles

3.7
simulation model
combination of the physical, geometrical and mathematical models and the solution method

3.8
spatial discretization
distribution and type of the geometric units for subdividing the geometric model

3.9
temporal discretization
step size and number of time units for subdividing the duration being modeled

3.10
validation
process of determining the degree to which a model is an accurate representation of the physical problem from the perspective of the intended uses of the model

3.11
validation experiment
experiment designed specifically for validating the simulation results taking account of all relevant data and their uncertainty

3.12
verification
demonstration of the correctness of the simulation model

3.13
calibration
process of adjusting modelling parameter values in the simulation model for the purpose of improving agreement with reliable experimental data

3.14
model
mathematical representation of a physical system or process

3.15
finite element analysis
FEA
numerical method for solving partial differential equations that describes the response of a system to loading

3.16
heat flux
rate at which thermal energy is transferred through a unit area of surface

3.17
power density
amount of thermal power absorbed or generated per unit volume

3.18
prediction
estimation of the response of a physical system using a mathematical model

3.19
computational welding mechanics
CWM
subset of numerical simulation and analysis of welding

4 Description of the problem

4.1 General

Computational welding mechanics is a subset of numerical simulation and analysis of welding that is primarily accomplished through use of the finite element method. Nonlinear thermal and mechanical analyses are performed, which can be sequentially or fully coupled, where the welding power is applied to the computational model in some way, and the resulting transient temperature (and possibly microstructure) fields are then combined with mechanical material properties/models and boundary conditions to predict the stress and strain in the model and its distortion. This description is not intended to be all inclusive or restrictive, but is provided to establish the typical expected use to which this Technical Specification might apply.

This Technical Specification addresses the general CWM problem, which can be defined as a three-dimensional solid element model employing a travelling 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.

This does not preclude use of simplified methods, but rather provides a simulation method benchmark from which simplifications can be judged. The need for simplifications are primarily driven by computational limitations (size and speed), and apply to many industry problems, such as heavy section welds in the pressure vessel or shipbuilding industries. As any simplification of the mathematical model that represents the physical system may increase uncertainty in the simulation results, this shall be counterbalanced with more effort in verification and validation of the model. Note that all computational models require verification and validation, and this subject is addressed in greater detail in Clause 6. The preceding discussion is formalized and expanded upon in the remaining subclauses.

4.2 Simulation object

The first item comprises the exact description of the component or overall structure, respectively, to be investigated (e.g. geometry, service conditions), of the employed base and filler materials, of the welding procedure and parameters, of the applied welding sequence as well as of the restraint conditions. Optionally, a complementary graphical representation or photograph may be attached.

4.3 Simulation objectives

This item concerns the definition of the desired simulation results which ensue from the real task at hand. This is particularly important since many realistic problems still require simplification in order to be analysed with reasonable effort.

Examples include the calculation of welding residual stresses and/or distortions, the assessment of the heat affected zone and its characteristics or the welding procedure net heat input.

In addition, the ultimate aim should be stated to which the desired simulation results are intended to be further applied, such as:

- assessment of the structural integrity of the object under specified service loading conditions, possibly including postulated or known material faults;
- optimization of necessary post weld treatment processes for the relief of welding distortions and/or residual stresses;
- optimization of welding procedures;
- minimization of welding distortion and stresses.

4.4 Physical model

Depending on the objectives defined in 4.3, this item concerns the compilation of the respective appropriate physical effects, boundary conditions and adopted simplifications and assumptions to be simulated. Depending on the desired model complexity, the following exemplary physical effects and influencing variables can be relevant:

- heat transport via heat conduction in the solid;
- convection and radiation at the surface;
- stress versus strain;
- materials changes such as microstructure transformations;
- dissolution or precipitation;

- mechanical behaviour such as elasticity;
- instantaneous or time dependant-plasticity;
- strain hardening and recovery effect;
- thermal expansion;
- transformation induced plasticity.

These factors can be described either by text, graphs, tables, or formulae. The real boundary conditions, most especially initial temperature in the solid, room temperature, and clamping conditions shall be described purposefully.

The simplifications that have turned out to be necessary when defining the simulations goals and that will be adopted in performing the simulation shall be described. The subsequent assumptions shall be justified by verification and validation procedures detailed in Clause 6.

4.5 Mathematical model and solution method

Based on the factors compiled in 4.4, a correspondingly suited mathematical model shall here be defined. To do this, the underlying essential differential equations shall be given or referred to. This definition concern the geometrical model (2D, 3D), supplemented by the mathematical description of the heat source as well as of the initial and boundary conditions. In case of general purpose commercial mechanical analysis software, the selected options of the mathematical solution should be summarized.

Although the typical envisaged solution method is finite element method (FEM), the solution method should always be stated, e.g. analytical method, different or complementary numerical method, or stochastical approach.

4.6 Implementation

The description of the implementation comprises specific details relating to the simulation object according to 4.2 and concerning the spatial discretization, e.g.:

- FE-meshing including the specification of the element types;
- temporal discretization;
- material characteristics;
- initial and boundary conditions.

The result of the implementation is the simulation model.

5 Workflow

5.1 General

The numerical modelling [choice of finite elements (FE), discretization, solver, etc.] is a part of computational solid mechanics specialist's job and not in the scope of this Technical Specification.

The reader is referred to ASME V&V [2] which provides a detailed framework for verification and validation (or "validation and verification") of general computational solid mechanics and also to R6 [3] and AWS A9.5 [4] for a standardized technique for CWM.

Following description of the workflow, recommended methodology for verification and validation (or "validation and verification") is given in the next clause.

5.2 Simplifications and assumptions

5.2.1 General

Simplifications and assumptions are a part of any simulation model, to varying degrees. This clause is intended to address key analysis inputs; those that are either fundamental to the analysis, or that the analysis will be particularly sensitive to.

5.2.2 Material properties

Accuracy of the prediction by CWM relies in part on the accuracy of thermophysical and thermomechanical properties used by the models. Material properties uncertainty can be greatly reduced by state of the art testing; however, even in this case, property determination is not possible over the full temperature range of the welding problem. Therefore, assumptions are inherent to selection of material properties, and shall be thoroughly documented. The typical way of addressing this uncertainty is through a sensitivity analysis to any properties which are estimated or to any properties with significant uncertainty.

NOTE Use of a cutoff temperature is a common approach to significantly reduce the impact of high temperature property uncertainty.

5.2.3 Model scale and scope

One of the primary choices to be made for a CWM model is the model scale and scope. The exact description is in the simulation object, as defined in 4.2. If the exact description is not implemented in the simulation model, then an assumption or simplification has been applied to the problem. The most common simplification with respect to scale and scope in the context of CWM is replacement of a 3D model with a 2D idealization. 3D modelling and analysis is the most rigorous approach for CWM; this is because the welding process is inherently 3D and intensely local for all but the fastest welding speeds or thinnest sections. However, 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 fact, 2D analysis can allow rapid access to often qualitatively meaningful results. 2D models are also useful for heavy section multipass welds to qualitatively investigate the impact of weld sequence changes and major geometric changes. However, the specific quality of the solution and magnitude of the approximation are strongly a function of part size, thickness, and welding inputs. A brief discussion follows for the common analysis assumptions. The choice of 2D (axisymmetric, plane strain, plane stress), 3D (brick, solid), or shell model is determined by the simulation objectives and the characteristics of the analyses.

5.2.4 Analysis coupling

CWM often uses a sequentially-coupled approach, where the mechanical analysis follows the thermal analysis. The sequentially-coupled approach is usually valid because the coupling of thermal, metallurgical, and mechanical effects are mostly one-way in fusion welding. For instance, the mechanical stress and deformation, such as temperature rise by plastic work, are expected to have very little influence on the temperature distribution; nor do they affect most phase transformations. The sequentially-coupled approach is much less demanding computationally than the fully-coupled approach.

In a fully-coupled approach, the governing equations for heat transfer and those for mechanical stress and displacement are solved simultaneously. Though it is fairly rare, there are cases where the fully-coupled approach is required for accurate simulation results. The most notable are when contact conditions may change and substantially impact heat transfer, or when the components to be welded are not rigidly restrained and generated large distortions at the weld location alter the fit-up conditions.

5.3 Process description and parameters

The process description is mandatory to achieve a numerical simulation of welding. The minimal information to gather are the following:

- definition of the welding process;
- average energy per unit length;
- welding speed;
- welding path;
- deposition rate.

5.4 Structure and weld geometries

The dimensions of the component shall be given in order to draw up its FE-mesh. The clamping device, if any, has to be described in the same manner.

5.5 Materials

5.5.1 General

The base materials, chemical composition shall be given as well as the as received material condition. The filler material, if any, has to be described in the same manner.

5.5.2 Thermo-physical material properties

Computations require temperature-dependent thermo-physical property data within the temperature range that occur in the material during the welding operation. As only solid state computations are considered, the convection in the molten zone could be modelled by artificially increase the thermal conductivity above the fusion temperature.

5.5.3 Thermo-mechanical material properties

Computations require temperature-dependent thermo-mechanical properties data within the temperature range that occur in the material during the welding operation.

The materials testing for mechanical behaviour's law identification has to be done as close as possible to the welding conditions (i.e. high heating and cooling rate, accounting for phase transformations, under tensile, and compressive cycles) considering cyclic hardening at relevant strain rate levels.

5.6 Loads and boundary conditions

5.6.1 General

The heat input can be represented by a volumetric or surface heat source. Nearly all kind of welding processes can be simulated using one (or more) of those energy distribution shapes or a combination of them. The shape of the heat source and the input energy can be fitted to experimental data such as the thermocouple temperature measurements or the dimensions of the weld pool and the heat affected zone.

5.6.2 Thermal

The heat transfer analysis rests upon the solution of the classical heat conduction equation with appropriate boundary conditions. The precise description of the phenomena involved in the heat input such as arc are not taken into account in the model as well as the analysis of fluid dynamics in the weld pool. Regarding the thermo-mechanical computation, the fluid flow effect, which leads to homogenize the temperature in the molten area, could simply be taken into account by increasing the thermal conductivity over the fusion temperature.

5.6.3 Mechanical

The mechanical analysis is based on the momentum balance equation where inertial effects are neglected. As the effect of plastic dissipation on heat transfer and the influence of stresses on metallurgical transformations can be neglected, the mechanical analysis can be weakly coupled to the thermal analysis. The mechanical computation is thus achieved in a second stage using the temperatures previously calculated. As no external load is applied during welding, only relevant boundary conditions in relation with clamping device shall be defined for the mechanical computation.

5.7 Results review

The reliability of the results shall be verified and validated as defined in Clause 6.

5.8 Reporting

Reporting of results should be performed as described in Clause 7.

6 Validation and verification

6.1 General

For quality assurance of the simulation results, the following essential measures are at the user's disposal depending on the application case and on the defined simulation goals. Comparisons with experimental results shall be considered with care as uncertainties — both systematic and statistical— are inherent to any measurement technique and device especially if the measure is not direct.

6.2 Verification of the simulation model

For verifying the simulation model, the following options are available:

- tests of consistency between the physical model (4.4), the mathematical model and the solution method;
- confirmation by using different solution methods (numerical and analytical) and comparison with simplified cases (e.g. reduction in dimensionality, rough calculation);
- quantification of the influence of discretization variation (spatial and temporal) on the calculation result;
- proof of the range of validity by parameter study.

6.3 Calibration of the model parameters

Calibration comprises the determination of the variable model parameters (e.g. process parameters, clamping conditions, material characteristics) from the comparison with experimental data, or alternatively with computational results which have not been used for the verification or validation.

Calibration of the thermal model can be accomplished, for example, by using simplified test pieces or smaller parts of local cuts of the simulation object described in 4.2. This implies that the calibration is not generally valid, but relates to a concrete application case.

As the stress-strain behaviour is critical, it could be estimated more accurately by comparison of residual stress computational results with reliable experimental data.

6.4 Plausibility check of the simulation results

A check of the calculation results for plausibility shall be carried out.

6.5 Validation of the simulation results

6.5.1 General

A validation of the simulation results shall be done according to at least one of the following criteria:

- complete or partial comparison between calculation results and data gained from validation experiments, e.g. temperature, weld pool geometry, distortion, residual stresses;
- demonstration that the system performance of the simulation model is in agreement with real conditions, e.g. by sensitivity analysis or parameter study;

For the experimental validation, a choice of experiments, measuring methods, and facilities suited to the simulation object in 4.2 as well as the defined simulation objectives in 4.3 shall be ensured. Selected specific examples follow for validation of residual stress and distortion models.

6.5.2 Validation experiment guidelines

An experiment that is to be used to validate a weld model for particular phenomena of interest should be very carefully designed; see for example ASME V&V [2] for a detailed explanation of general verification and validation principles.

Care shall be taken to ensure the reproducibility of the experiment. The experiment is best designed by first simulating the experiment with the weld model. 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 neither possible nor necessary to test the entire weld structure for the purpose of validating the weld model.

The validation is not necessarily to be performed on the full simulation object.

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 versus similarity of the mock-up to the real structure. See Annex C for a list of good practices to assist in ensuring a quality validation procedure is developed.

7 Reporting/display of results

7.1 General

For traceability, the overall approach shall be documented in the form of a report in accordance with Clause 3 to Clause 5. To do this, all individual items shall be addressed explicitly.

Any non-consideration of the optional measures according to 5.2 shall be justified briefly. For reference, examples of the documentation layout are given in Annex A. In all cases, the documentation template shall at least contain the items given in 7.2 to 7.7.

7.2 Simulation object

- description of the major scope of the project, of the sequential steps, of the simulation, and the principal assumptions;
- expectations of the study (result quality, most important results needed).

7.3 Material properties and input data

- description of all the materials that are used in the welding process (see 5.5) (literature, own data including measurement method), uncertainties, and units of material data.
- description of the material in use, including chemical composition and models used.

Temperature dependent data for both thermophysical and thermomechanical properties should be displayed:

- thermophysical data (thermal conductivity, density, specific heat, enthalpy, thermal expansion coefficient, see 5.5.2);
- thermomechanical data (Young's modulus, Poisson's ratio, strain hardening model parameters, yield stress, plasticity model parameters, see 5.5.3).

7.4 Process parameter

- parameters of the welding process, e.g. welding current, welding voltage, welding efficiency, welding speed, welding position.
- description and parameters of the simulation heat source.

7.5 Meshing

- few images of the part to be simulated and a few significant images of the computational mesh regarding the simulation objectives;
- number of node and elements, mesh size and type/shape functions of the elements.

7.6 Numerical model parameters

- type of transient computation;
- solution method (e.g. static FEA);
- algorithm to reach physical equilibrium (e.g. implicit, iterative);
- values of absolute or relative precisions to reach physical equilibrium;
- values of typical time stepping (time incrementation criteria);
- initial and boundary conditions (see 5.6).

7.7 Analysis of results

Care shall be taken in the evaluation and result display to bring the presentation layout into line with the definition of the simulation objective. Concerning this item, preference shall be given to both graphical and tabular representations with brief text descriptions, also with a view to assuring the simulation results according to the validation and verification.

Annex A
(informative)

Documentation template

The user of this form is allowed to copy this present form prejudice to the property rights of ISO to the entirety of the Technical Specification.

Company name: Division:	**Documentation of welding simulation according to ISO/TS 18166:2016**	Project: Variant/Version: Date: JJJJ-MM-TT Page 1 of x
Cover sheet for brief descriptions		
Simulation object: (optionally, a complementary graphical representation or photograph may be attached.)		
Simulation objectives:		
Physical and mathematical model:		
Solution method and applied software products:		
Summary of the results and conclusions:		
Summary of the measures taken to ensure the quality of the simulation results:		
Assurance of the simulation results	Remarks / Explanatory statements	
Verified [ ] Yes [ ] No		
Calibrated [ ] Yes [ ] No		
Plausibility [ ] Yes [ ] No		
Validated [ ] Yes [ ] No		
Miscellaneous		
Notes (optional):		

Annex B
(informative)

Modelling of heat transfer during welding

B.1 General

A thermal analysis is required to generate metallurgical, residual stress, or distortion predictions. The appropriate choice of heat transfer method is closely tied to the desired final result. There are simple closed form solutions for the temperature field around a moving heat source. These are often adequate for many simple metallurgical calculations. Detailed predictions of the through-thickness residual stress distribution in heavy and irregular sections tend to require more complex methods. The current document does not cover first principle analyses of the molten weld pool (e.g. using computational fluid dynamics), because this is presently too complicated for the engineering applications that are the focus of the procedures. The methods, therefore, use concepts based upon equivalent energy or temperature distributions with heat flow in the solid and molten regions based on conduction alone. This means that models should be calibrated (see Clause 6 for more details).

Basic methods for calibration shall consider the process efficiency and rely on matching measured thermal histories at points near a weld, or a reproduction of the measured spatial weld pool domain, or both.

The weld pool shape and temperature distribution could be predicted by computational fluid dynamics (CFD) models. These aim to predict the weld pool shape and size with consideration of buoyancy, surface tension, and can be coupled with magneto-hydrodynamics.

B.2 Analytical models for prediction of temperature fields

Analytical closed-form solutions offer the possibility of predicting the global transient temperature field orders of magnitudes faster than numerical methods. It is possible, therefore, to automate analytical model parameters so that they agree with experimental reference data. It has been shown that the analytically calculated temperature field for a volume heat source that moves on an arbitrary shaped welding trajectory can provide reasonable accuracy. Conformal mappings techniques enable the transformation of the analytical temperature field from a rectangular bounded domain onto a polygonal bounded domain allowing the temperature field for fillet or overlapping joints. The analytical techniques usually assume that the thermal properties are independent of temperature. The influence of this assumption on the temperature field and the final CWM predictions should be investigated.

Analytical methods can be based on simple point, line, or planar thermal power densities. 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. Typically, the models are calibrated in the spatial region and temperature range that is of greatest importance. These assumptions should be ultimately validated.

Application to finite thickness plates usually involves mirrored “imaginary” auxiliary heat sources that can be difficult to implement in arbitrary, complex shapes.

B.3 Calibration of heat source thermal models

B.3.1 General

Numerical simulations use 2D or 3D models. Proper implementation of these models is often directly tied to other modelling assumptions, such as treatment of material properties and element activation strategies.

For a 2D mechanical analysis it is common to use predicted temperatures from a 2D heat transfer model. A more complex method consists in mapping 3D temperature results on the 2D model.

Calibration procedures (see B.1) for numerical models are described below.

B.3.2 Prescribed temperature model (PTM)

The prescribed temperature model (PTM) uses temperature boundary conditions in the weld pool. The PTM parameters can be repeatedly adjusted until a suitable prediction of the temperature profile is achieved. A simple PTM model could assume a uniform liquidus temperature throughout the weld pool. A more complex PTM method could prescribe a radial temperature profile in the melt pool.

Some more elaborate models have used simplified fluid flow solutions to solve for the solid-liquid boundary and the resulting temperature is applied to the mechanical FEA.

Other models consist in prescribing by block a temperature cycle to the deposited material. This temperature cycle obtained from a prescribed heat input model can be checked to ensure energy balance.

It is assumed that the liquidus boundary (weld pool shape and size) is known. Validation is therefore achieved by reproduction of the known molten boundary in the computational model.

B.3.3 Prescribed heat input model

Heat input to the weld pool can be modelled with either a thermal power density per unit area or volume. One of the most well-known power density models is the double-ellipsoid model of Goldak. The heat input is assumed to have a Gaussian distribution of thermal power density over the weld pool volume.

This and similar models are frequently used for arc welding processes. Other volumes can also be used alone or combined (e.g. cylinder, cone) to generate different weld pool shapes.

The required distribution of thermal power density could be determined from the solution of a PTM analysis.

For 2D models, the heat source is moved across the plane of the model and the heat flow in the direction of welding travel is zero by definition.

Shell element models can be used for thin structures. Here, the flux occurs along the path of the weld. Shell models can be combined with a local 3D model near the arc.

Annex C
(informative)

Validation experiment guidelines

The following should be accomplished.

— For all data acquisition systems, each data item should be stamped with date (year/month/day) and time (hour/minute/second). All clocks in the data acquisition system should be synchronized. Try to start acquiring data well before welding starts and run the data acquisition for a sufficiently long time after welding stops, often at least 24 h.

IMPORTANT — Do not set start time to be zero and simply increment the time.

— It is useful to have one or more video cameras recording the welding scene. Each video frame should be stamped with date and time. It would be particularly valuable if a video camera could provide an image of the transient weld pool (caution should also be used to protect one's eyes from the welding arc). However, even a video showing a view from a distance would provide useful information for validation. A video walk around showing fixtures, tack welds, and fit up at various stages of welding would be very useful for validation. Placing measuring tapes in the scene could provide useful information.

— 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. A pattern of nine strain gauges would be preferred. 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 analyst should know the sampling area. To test the strain gauge behaviour 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 to 200 °C [212 °F to 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 work piece surface and final distorted surface geometry after welding. The surface deformation data are useful in validating the stress and distortion model.

— 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 also suggested to use thermocouples, arranged perpendicular to the welding direction in order to get information about the temperature gradient perpendicular to the weld seam.

— 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.

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

— 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 analyst should 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.

- Hardness maps can be useful data for validating microstructure evolution models.

Annex D
(informative)

Modelling of residual stresses

D.1 General

Welding residual stress analyses typically involve applying the temperature results from the thermal analysis to the computational model defined with mechanical properties and boundary conditions (see 5.2). The coupling between thermal and mechanical behaviour is the thermal expansion, and stress is created by non-uniform temperatures and differential thermal expansion and mechanical properties 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.

More details on the material modelling are given hereafter.

D.2 Material modelling

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. Some work has also used visco-plastic models or combined rate independent plasticity at lower temperatures with visco-plastic models at higher temperatures. These experiences show that the hardening behaviour at lower temperature is important for the residual stresses. The material near the weld is submitted to cyclic loading and choosing isotropic or kinematic hardening or a combination of these two will affect the stresses in this region.

Extreme care needs to be exercised in reviewing the results based on any high temperature material model. Indeed, permanent strains inadvertently created at high temperatures can dominate the solution at cooling. These nonphysical strains are often produced by the element activation scheme for material deposition or by inappropriate material properties estimation at high temperature. For temperatures that exceed the melting point the use of a cut-off temperature is very convenient. With this technique, temperatures that exceed a cut-off value are reset to the cut-off temperature.

The properties at high temperatures are usually unknown. An overly soft weld metal in the model may give numerical problems or nonphysical plastic strains.

An appropriate choice of cut-off temperature is a suitable modelling technique.

The cut-off temperature can also be defined below the melting point to model high temperature annealing effects. Indeed, the very low value of yield strength at high temperatures along with the use of elasto-plastic models may result into artificial hardening and overestimation of the 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 be set to zero above a cut-off temperature.

Care must be taken when considering materials with phase transformation during welding. Specific material models should be used in this case to take into account phase mixture, transformation induced plasticity, or any microstruture evolution leading to a significant change in the mechanical strength of the heat affected zone.

Annex E
(informative)

Distortion prediction

E.1 General

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 permanent strains being built up by the process and is influenced by many factors, such as the following:

- material;
- welding process;
- process parameters;
- joint geometry;
- bead and weld sequence;
- weld direction;
- clamping conditions.

Distortion can negatively affect the dimensional accuracy of the product according to the specified dimensional tolerance, thus compromise its functionality, 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. To avoid this cost, manufacturers usually take steps to mitigate distortion, using clamps, strong backs, reinforcement structures, weld sequencing, or post-weld treatment. All these methods except weld sequencing add additional processing costs and they add or negatively affect residual stresses. Many try to use weld sequencing to minimize distortion but often a structure will have multiple welds. This creates many possibilities 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 and predict distortions.

E.2 Simplified methods

The problem of distortions is inherently three-dimensional and requires modelling of the complete structure and weld sequence. The computation effort in this case can be huge and some alternative simplified methods are possible. These methods are generally known as local-global or multi-scale approach.

They are based on the fact that permanent strains are generated only close to the weld and that these strains are not dependent on what is happening far from the weld. This means that local permanent strains can be computed on a small part of the complete structure and be used subsequently on the complete model for the prediction of the global distortions. For instance, the welding simulation is accurately performed according CWM principles on a small part of the welded component. Appropriate local model results are used as input data for the global model made of three-dimensional brick or shell elements for distortion calculation.

Many similar techniques exist considering or not that far from the weld the material model is linear elastic.

It is possible to upgrade the global model by considering thermal transient effects. Even more computational efforts can be reduced by using estimates of local permanent strains obtained experimentally or by analytical models. To minimize distortion by virtual testing, qualitative results are sufficient and therefore simplified methods become advantageous.

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