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COMPUTATIONAL WELDING MECHANICS

Springer

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Library of Congress Cataloging-in-Publication Data

A C.I.P. Catalogue record for this book is available
from the Library of Congress.

ISBN-10: 0-387-23287-7 e-ISBN 0-387-23288-5 Printed on acid-free paper.
ISBN-13: 978-0387-23287-4

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Printed in the United States of America.

9 8 7 6 5 4 3 2 1 SPIN 11054023

springeronline.com

Preface

The presentation of this book emphasizes an exposition of the computational principles and the application of computational welding mechanics to practice.

The objective in Computational Welding Mechanics is to extend the capability to analyze the evolution of temperature, stress and strain in welded structures together with the evolution of microstructure. Distortion caused by volumetric strains due to thermal expansion and phase transformations are a dominate load in the stress analysis. The microstructure evolution influences the constitutive equations. In particular, as the temperature changes from above the melting point to room temperature, the stress-strain relationship changes from linear viscous, to visco-plastic to rate independent plasticity. In high strength steels, transformation plasticity can have a major affect in reducing the longitudinal residual stress in welds.

In the past twenty years the capability to analyze short single pass welds including the above physics has been developed. The software engineering to develop codes to solve these coupled problems has tended to be near the limit of what users and software developer can manage. The complexity has been too great to develop codes to deal with long multipass welds in complex structures. To deal with this problem, new software engineering methods and strategies have been developed, that are able to automatically create initial conditions, boundary conditions, adaptive mesh generation and manage time stepping. The input is a functional specification of the problem that includes a weld procedure, a weld path and a structure to be welded. The weld procedure contains weld parameters for each weld pass in a weld joint.

By giving designers the capability to predict distortion and residual stress in welds and welded structures, they will be able to create safer, more reliable and lower cost structures.

In the next ten years, we predict that computational weld mechanics will be used routinely in the welding industry. We believe that adequate solutions now exist to solve the problems related to managing the complexity now exist of software and the ease of use of the software.

There are some longer term issues that will require further research. One issue will be obtaining values (preferably functions) for the temperature and history dependent material properties of base metal and weld metal. Another issue will be obtaining sensor data characterizing welds and welded structures. We anticipate that real-time computational weld mechanics will lead to computer controlled welding systems that utilize a model not just of the weld pool but of the structure being welded. We also expect that this will lead to archiving huge amounts of data characterizing the welding process of constructing large structures such as a ship or submarine. Some of these archives will be public and some will be corporate. With such archives, data mining will be used to optimize processes and designs. In all of these endeavors, computational weld mechanics will play an essential role. In that role, the fundamental principles upon which computational weld mechanics is based will not change.

It is our hope that this book will help the reader to learn, understand and apply computational weld mechanics to problems in industry.

John A. Goldak and Mehdi Akhlaghi

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Units

Currently changes are being made in the use of units from the English system to the *SI* system (le System international d'Unites). However, many articles referred to in this book use the English system and many readers of this book are still accustomed to the English system.

Below is a conversion table for units frequently used in this book.

To convert from	to	multiply by
inch *(in.)*	meter *(m)*	2.54×10^{-2}
foot *(ft)*	meter	3.048×10^{-1}
lbm/foot^3	kilogram/meter^3	1.601×10
Btu	joule *(J)*	1.055×10^{3}
Calorie	joule	*4.19*
lbf (pound force)	Newton *(N)*	*4.448*
pound mass *(lbm)*	kilogram *(kg)*	4.535×10^{-1}
Lbf/inch^2 *(psi)*	Newton/meter^2	6.894×10^{3}
kgf/meter^2	Newton/meter^2	*9.806*
Fahrenheit (t_F)	Celcius (t_C)	t_C=(5/9)(t_F -32)

Notations

Efforts were made to use the same notation symbols, as much as possible, to express various quantities throughout the entire book. However, the authors have found that it is almost impossible to use a single, unified system of notation throughout the entire book because:

1. The book covers many different subjects.
2. The book refers to works done by many investigators who have used different notations.

Efforts were made to provide sufficient explanations whenever symbols are used.

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Chapter I

Introduction

1.1 Introduction and Synopsis

Welding as a fabrication technique presents a number of difficult problems to the design and manufacturing community. Nowhere is this more evident than in the aerospace industry with its emphasis on performance and reliability and yet where materials are seldom selected for their weldability.

Developments in calculating the thermal cycle and elastoplastic stress-strain cycle have been slow because of the inherent complexity of the geometry, boundary conditions and the nonlinearity of material properties in welding.

However, the exponential growth in computer performance combined with equally rapid developments in numerical methods and geometric modeling have enabled computational weld mechanics to reach the stage where it can solve an increasing number of problems that interest the industry specially in pipelines, power plants, refineries and pressure vessels, nuclear reactors, building and bridges, automotive, trucks and trains, ships, offshore structures, aerospace structures, micro electronics and many others.

Although the ability to perform such analyses is important, the real justification for computational weld mechanics is that it is becoming cheaper, faster and more accurate to perform computer

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simulations than to do laboratory experiments. Taken to the extreme all relevant decisions would become based on computer simulations. For example since nuclear testing in the atmosphere has been banned, this has actually occurred in nuclear weapons design, a field at least as complex as welding. It is unlikely that computational weld mechanics will eliminate all experiments in welding. Instead, computational weld mechanics is likely to increase the demand for accurate constitutive data, particularly at high temperatures, and to include the effect of changes in microstructure. Also it will not eliminate the need for experiments that simulate or prototype processes and products. However, it will dramatically reduce the number and cost of such experiments and greatly enhance the accuracy and significance of the data obtained for each experiment. In the automotive industry, *CAE* (Computer Aided Engineering) is said to have reduced the number of prototypes required from a dozen to one or two.

In the next few years, digital data collection of not only welding experiments but of production welding will be coupled to computer models. The computer models will use the experimental data to adjust the parameters in the computer model. The experiment and production system will use predictions from the computer model to control the process. The mathematics of this is called a Kalmann filter. In this case, the computer model and experiment are tightly connected. Neither could exist without the other. At this point religious wars between experimentalists and theorists will become meaningless.

Furthermore, models can be examined to provide insight that could never be obtained by experiment. For example, it is well known that work piece distortion caused by welding austenitic stainless steel is some three times greater than that caused by welding carbon steel. By analyzing models in which each property is varied separately, the sensitivity of the distortion to each property can be computed. This would provide the knowledge needed to understand the greater distortion in austenitic steel. Of course, this is not possible experimentally.

In its narrowest sense computational weld mechanics is concerned with the analysis of temperatures, displacements, strains and stresses in welded structures, Figure 1-1.

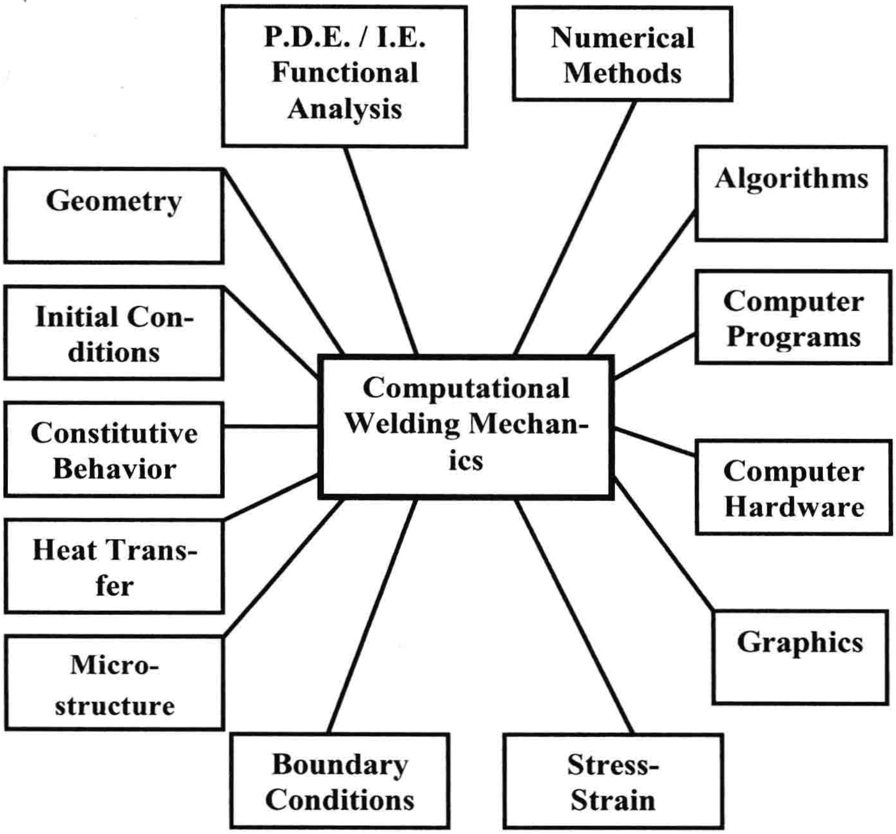

Figure 1.1: Computational welding mechanics draws on the disciplines shown above to compute the temperature, microstructure, stress and strain in welds. (PDE/IE-stands for Partial Differential Equations/ Integral Equations)

In its broadest context, it is an important element of Computer Aided Design *(CAD)* and Computer Aided Manufacturing *(CAM)*. Computer modeling, in general provides the capability of storing vast amounts of data; of organizing and storing relations between data in databases or knowledge bases; and of using these data to compute or predict the behavior of products, processes or systems in the real world. On one hand, it can be viewed as a set of analytical tools for determining the mechanical response of a work piece to a given welding procedure. On the other hand, it can be viewed as a design tool for predicting the quality of a weld and the deformation, Figure1-2.

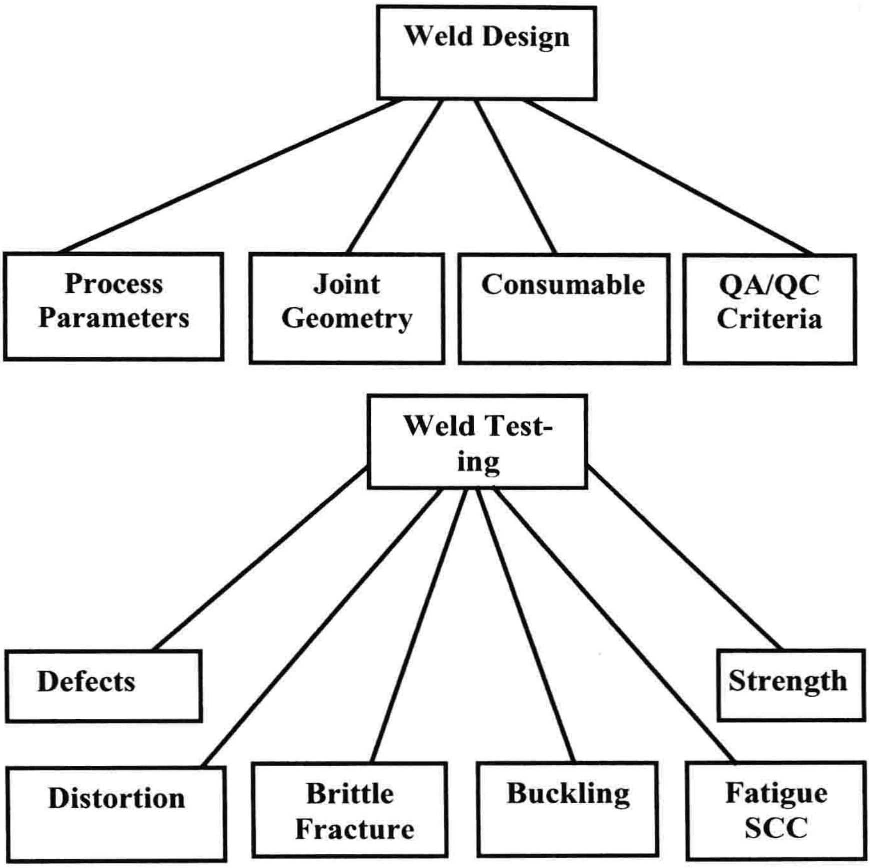

Figure 1-2: The important issues in design and testing of welds are shown schematically. (QA/QC is Quality Assurance, Quality Control and SCC is Stress Corrosion Cracking)

It is necessary at the outset to clearly fix the relationships of computer methods to experimental investigation, Figure 1-3.

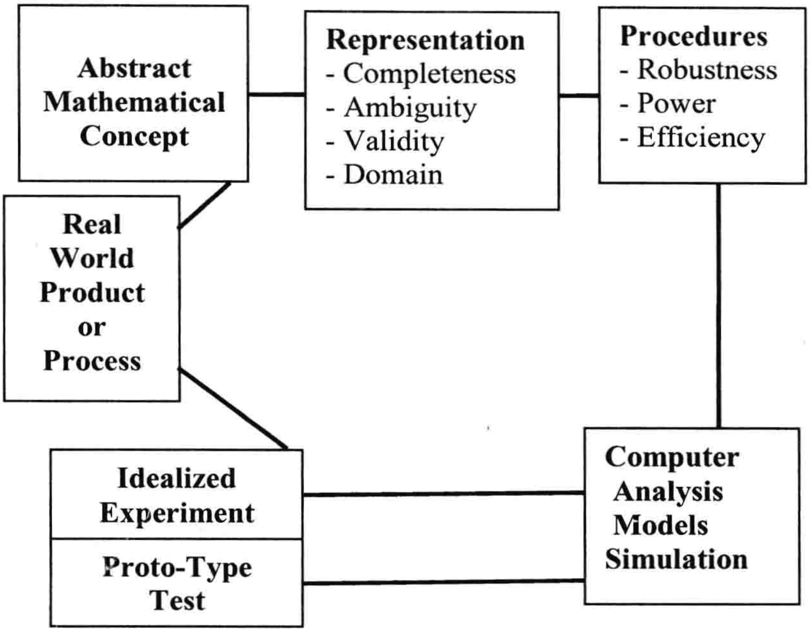

Figure 1-3: The relationships between the real world, experiments, mathematical abstraction and computer analysis.

Experiments tend to fall into two broad categories. Some are based on clearly understood theory where a strong attempt is made to exclude extraneous factors. Measurement of Young's modulus or thermal conductivity of a particular alloy fall into this category. On the other hand, when experiments deal with complex phenomena that do not have a clearly understood theory, a strong attempt is made to include any factor that may be relevant. Developing a narrow gap welding process is an example of this second category.

1.2 Brief History of Computational Welding Mechanics

Historically, arc welding began shortly after electrical power became available in the late *1800s*. Serious scientific studies date from at least the *1930s*. The failure of welded bridges in Europe in the

1930s and the American Liberty ships in World War *II* did much to stimulate research in welding in the *1940s*.

In the *USA*, the greatest attention was focused on developing fracture mechanics and fracture toughness tests. This could be interpreted as a belief that welding was too complex to analyze and therefore they chose an experimental approach that relied heavily on metallurgical and fracture toughness tests. The steady state heat transfer analysis of Rosenthal was an exception [3].

Russia took a different approach. The books of Okerblom [4] and Vinokurov [5] are a rich record of the analysis of welded structures including multi-pass welds and complex structures.

Over time the main techniques for solving heat transfer problems were changing with growing computer capacity. The strategy for analyzing welds and numerical methods (finite difference and finite element analysis) began in the *1960s* with the pioneering work of Hibbitt and Marcal [6], Friedman [7], Westby [2], Masubuchi [8] and Andersson [9]. Marcal [11] made an early summary of experiences from welding simulation. Chihoski sought a theory to explain why welds cracked under certain conditions but not others [51, 52 and 53]. Basically, he imaged that the weld was divided into longitudinal strips and into transverse strips. He then computed the thermal expansion and contraction in each of these strips due to the temperature field of edge and butt welds. He concluded that a small intense biaxial compression stress field exists near the weld pool. Ahead of the compression field there may be a gap or a tensile stress field. Behind the compression field a tensile field or a crack can appear. The startling aspect of Chihoski's theory was that by varying the welding procedure, the position of this compression field could be controlled. To support this theory, Chihoski developed a Moire'fringing technique to measure displacements during edge and butt weld. Chihoski used his theory to understand and solve a number of common problems: cracks and microcracks, forward gapping, upset and part distortion, sudden changes in current demand and unexpected responses to welding gaps. He considered the position and pressure of hold down fingers; the influence of localized heating or cooling; and the effects of gaps. He argued that these parameters could be optimized to obtain crack free welds.

These authors consider Chihoski's papers to be among the most important in computational welding mechanics because he combined experience in production welds with an insight into weld mechanics that enabled him to conceive a theory that rationalized his observations and predicted solutions to his problems.

The reviews by Karlsson [12 and 13], Smith [17], Radaj [18 and 19] and Goldak [1, 14, 15, and 16] include references to simulations performed up to 1992. The research in Japan is reviewed by Ueda [20 and 21] and Yurioka and Koseki [22]. But Finite Element Analysis *(FEA)* methods gained a wide acceptance only over the last decade [10, 23, 24, 25, and 46].

The Moire'fringing technique of Chihoski is today one of the most powerful means of assessing *FEA* of stress and strain in welds (also see Johnson [55] for more on Moire' fringing methods for measuring strain in welds.).

The use of finite difference methods is more a transition between analytical and finite element methods. The main advantage of the finite difference method is that it is rather simple and easily understandable physically [10 and 26].

The finite element method has achieved considerable progress and powerful techniques of solving thermal-mechanical manufacturing process such as welding [1, 27, 28, 29 and 30]. Runnemalm presents in a dissertation thesis [24] the development of methods, methodologies and tools for efficient finite element modeling and simulation of welding. The recently published dissertation of Pilipenko [10] presents the development of an experimental, numerical and analytical approach to the analysis of weldability.

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