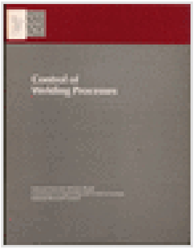


Control of Welding Processes (1987)

Pages
59

Size
8.5 x 10

ISBN
0309320739

Committee on Welding Controls; National Materials Advisory Board; Commission on Engineering and Technical Systems; National Research Council

NATIONAL RESEARCH COUNCIL
COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS

NATIONAL MATERIALS ADVISORY BOARD

The purpose of the National Materials Advisory Board
is the advancement of materials science and engineering in the national interest.

CHAIRMAN

Dr. Bernard H. Kear
State of New Jersey Professor
of Materials Science and
Technology
Director, Center for Materials
Synthesis
College of Engineering
Rutgers University
P.O. Box 909
Piscataway, NJ 08854

PAST CHAIRMAN

Dr. Arden L. Bement, Jr.
Vice President, Technical
Resources
Science and Technology Dept.
TRW, Inc.
1900 Richmond Road
Cleveland, OH 44124

MEMBERS

Dr. Richard C. Alkire
Professor and Head
Department of Chemical Engineering
University of Illinois
1209 West California Street
Urbana, IL 61801

Dr. Norbert S. Baer
Professor, Conservation Center
of the Institute of Fine Arts
New York University
14 East 78th Street
New York, NY 10021

Dr. L. Eric Cross
Director, Materials Research
Laboratory
Evan Pugh Professor of
Electrical Engineering
Pennsylvania State University
University Park, PA 16802

Dr. Frank W. Crossman
Manager, Mechanics and
Materials Engineering
Lockheed Palo Alto Research
Laboratory
3251 Hanover Street
Palo Alto, CA 94304

Dr. Raymond F. Decker
President and
Chief Executive Officer
University Science Partners, Inc.
321 Fisher Bldg.
Detroit, MI 48202

Mr. Edward J. Dulis
President
Crucible Research Center
Crucible Materials Corporation
P.O. Box 88
Pittsburgh, PA 15230

Dr. James Economy
Manager, Organic Polymer
Research
IBM Almaden Research Center
Department K9/80
650 Harry Road
San Jose, CA 95120-6099

Dr. Merton C. Flemings
Professor and Chairman
Department of Materials
Science and Engineering
Massachusetts Institute of
Technology
77 Massachusetts Avenue
Cambridge, MA 02139

Dr. Brian R. T. Frost
Director, Technology Transfer
Center
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Dr. Gordon S. Kino
Professor, Electrical
Engineering and Physics
Stanford University
Stanford, CA 94305

Dr. Alan Lawley
Professor, Materials
Engineering
Drexel University
Department of Materials
Engineering
Philadelphia, PA 19104

Dr. Adolph J. Lena
Executive Vice President
Chief Operating Officer
Carpenter Technology Corp.
P.O. Box 662
Reading, PA 19603

Dr. David L. Morrison
President
IIT Research Institute
10 West 35th Street
Chicago, IL 60616

Dr. Dennis W. Readey
Professor and Chairman,
Ceramic Engineering
Department
Ohio State University
2041 College Road
Columbus, OH 43210

Dr. John P. Riggs
Executive Director,
Technology
Celanese Research Corporation
86 Morris Avenue
Summit, NJ 07901

Dr. William P. Slichter
Executive Director, Research
Materials Science and
Engineering Division
AT&T Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974

Dr. John E. Tilton
Coulter Professor
Department of Mineral
Economics
Colorado School of Mines
Golden, CO 80401

Dr. James C. Williams
Dean, Carnegie Institute of
Technology
Carnegie Mellon University
Schenley Park
Pittsburgh, PA 15213

NMAB STAFF

K. M. Zwilsky, Director
S. M. Barkin, Assoc. Director
Mary W. Brittain, Adm. Officer
2101 Constitution Ave., NW
Washington, DC 20418

12/86

Copyright © National Academy of Sciences. All rights reserved.

CONTROL OF WELDING PROCESSES

Report of the

Committee on Welding Controls

NATIONAL MATERIALS ADVISORY BOARD
Commission on Engineering and Technical Systems
National Research Council (U.S.)

Order from
National Technical
Information Service,
Springfield, Va.
22161
Order No. ADA 172-893

NMAB-421
National Academy Press
1987

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

The report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which established the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

This study by the National Materials Advisory Board was conducted under Contract Number MDA 903-86-K-0220 with the Department of Defense and the National Aeronautics and Space Administration.

This report is for sale by the Defense Technical Information Center, Cameron Station, Alexandria, Virginia 22312.

Printed in the United States of America.

ABSTRACT

Automatic welding processes are being used more and more in manufacturing, and this has led to an increased requirement for close control of the process. The objectives of welding control and the problems involved with such control are addressed. Because welding is such a complicated process, control strategies are needed to close the gap between what is desired by industry and what is practiced. Some of the variables in the process include the base material, joint preparation, controllability of the automated system, consistency of consumables, and welding environment. The importance of understanding the basic processes--arc physics, heat and fluid flow, solidification, and process disturbances, etc.--is emphasized. The state of the art in welding process modeling and the feasibility and need for adaptive control are described. At present, empirically derived models for some processes have been developed, and, if further understanding of the complex interactions can be achieved and verified, systems based on fully integrated computer-aided design and manufacturing and adaptive controls can be achieved. Such a welding process simulation could permit the design engineer to know in advance the interaction of weldment preparation, fixture design, distortion, and mechanical properties and thus do a much better job of optimizing the entire process.

COMMITTEE ON WELDING CONTROLS

Chairman

JOHN G. BOLLINGER, Dean, College of Engineering, University of Wisconsin, Madison

Members

JOHN S. AHEARN, Manager, Materials and Surface Science, Martin Marietta Laboratories, Baltimore, Maryland

JAMES M. CAMERON, Manager, Materials and Welding, Electric Boat Division, General Dynamics, Groton, Connecticut

HOWARD B. CARY, Vice President, Welding Systems, Hobart Brothers Company, Troy, Ohio

WILLIAM J. FARRELL, Senior Vice President, Sciaky Brothers Division, Allegheny International, Chicago, Illinois

DAVID E. HARDT, Professor, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

JOHN F. HINRICHS, Manager, Manufacturing Technology Laboratory, A. O. Smith Company, Milwaukee, Wisconsin

JAMES F. KEY, Manager, Materials Processing Branch, Idaho National Engineering Laboratory, Idaho Falls

MILTON D. RANDALL, Vice President, Research and New Product Development, CRC/Evans Automatic Welding Company, Houston, Texas

RICHARD W. RICHARDSON, Professor, Welding Engineering Labs, Ohio State University, Columbus, Ohio

Liaison Representatives

JEROME PERSH, Staff Specialist, Materials and Structures, Office of Deputy Under Secretary of Defense for R&E (ET), Department of Defense, Washington, D.C.

CHARLES ZANIS, Assistant Director for Platform Technology, Naval Sea Systems Command, Washington, D.C.

CHARLES NULL, Head, Metals Branch, Naval Sea Systems Command, Washington, D.C.

ROBERT A. WEBER, Welding Engineering and Metallurgy, U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, Illinois

NMAB Staff

Joseph R. Lane, Senior Program Officer
Judith Amri, Senior Secretary

CONTENTS

Chapter 1

INTRODUCTION, CONCLUSIONS, AND RECOMMENDATIONS

Welding is today the most commonly used method of joining components in the fabrication of complex structures. If the structure is to perform satisfactorily, the integrity of the welded joints must be as good as the materials being joined. Because weld quality is such an important factor, a National Materials Advisory Board Committee on Welding Controls was asked to identify the variables in welding processes to ascertain where existing control technology must be better understood and improved to ensure the necessary uniformity and reproducibility of structural welds.

When the properties of a metal vary widely due to heat-to-heat variations, a severe penalty is imposed on the design of a structure. Similarly, variability in weld quality will degrade the serviceability of the structure, even though the average quality is high. In traditional practice, a skilled manual welder can compensate for many of these variations and can thereby control weld quality. However, in response to the need for productivity and quality improvement, the trend in manufacturing is away from manual welding and strongly toward automatically controlled welding processes. Thus, in the absence of skilled manual welders, new means for sensing welding process variables must be found, and various forms of control of the automated process must be implemented.

This study examines the nature of variables in automatic welding and the prospects for their closer control. The problem is not merely one of optimizing discrete variables; a systems concept will be necessary if substantial progress is to be made. For that reason, sensing and feedback become important factors in the control of welding processes, and these are emphasized in this study. The bibliography following Chapter 3 provides extensive coverage of developments in the field.

TABLE 1 Scientific Disciplines Encompassed by Welding

Chemistry	Physics, Metallurgy, and Materials Science	Mechanics
Chemical reactions	Physical properties	Mechanical properties
Thermodynamics	Electrical properties	Statics
Kinetics	Plasmas	Dynamics
Electrochemistry	Heat and mass transport	Fracture mechanics
Alloy composition	Fluid flow	Residual stresses
Dilution	Heat flow	Distortion
Slag-metal reactions	Solid and liquid phase diffusion	Restraint
	Crystal (atomic) structure	Structural design, jigs, and fixtures
	Dislocations	
	Vacancies	
	Phase transformations	
	Gas-liquid	
	Liquid-solid	
	Solid-solid	
	Solidification	
	Grain nucleation	
	Grain growth	

SOURCE; National Materials Advisory Board, 1982.

Welding encompasses many scientific disciplines. It involves a complex interplay of solid, liquid, gaseous, and plasma-state phenomena: these are categorized in Table 1. Contributing to the complexity of welding processes is the fact that a large number of these phenomena take place simultaneously in relatively small volumes (0.1 to 10 mm^3), over short distances (1 to 20 mm), and frequently over short time periods (nonequilibrium).

It can be seen that welding is extremely complex, and thus the control problem is severe. Many different welding processes are utilized in industry, each with its own unique set of variables. Not only are the variables numerous, but also models for given processes are incomplete because of limits on present knowledge, although models for at least the more widely practiced processes are in various stages of development.

CONCLUSIONS

The committee finds the following:

1. There is substantial opportunity in transforming welding technology in industry from an experience-based technology to a science-based technology. Fundamental work needs to be done in the

thermophysical and kinetic properties of gases and metal alloys in both the liquid and solid state. Lack of such data is severely limiting advanced analysis. Modeling plays an important role in the basic analyses of the various processes discussed in this report. Models of separate effects, including arc physics, heat and fluid flow, solidification, and solid-state transformations, need to be integrated into fully descriptive process models. Existing two-dimensional models need to be extended to three dimensions to represent most realistic welding conditions.

2. Historic research on basic welding technology has generated data of limited utility in advancing to control-oriented research and development. Fundamental research targeted at generating control-oriented data bases needs to be supported. Such research should provide physical model verification by experimental data, extendable to various base materials, electrical parameters, consumables, gases, and flux materials. A common approach is needed so that data can be transferred to models; this approach should include process identification, model formats, experimental procedures, numerical procedures, and welding system specifications. Model procedures should promote the implementation of "what-if" analyses for welding systems implementation.

3. The application of adaptive controls is in its infancy in the field of welding. Although a few systems are in commercial use, there is widespread agreement that they are limited to special situations and lack generic understanding and applicability. A greater understanding of control strategies and theory is needed as a part of welding research.

4. The development of solid-state technology has opened the door to new control techniques and integrated sensor devices that show promise for higher levels of control of the process.

5. Improved productivity and quality of welded structures will depend on cultural or institutional and procedural changes in the industry as well as on applying technological control theory. Concepts of design for producibility, the application of group technology, and data bases for optimal welding designs need to be developed and widely publicized. It must be recognized that more sophisticated control and reduction of skilled labor in the manufacturing process will require higher levels of design engineering and process planning.

6. Prewelding processing control is important to the total manufacturing system. Although adaptive control can accommodate in-process changes, it should not be considered a means of totally eliminating appropriate engineering practices and procedures, which should always consider preparation of the workpieces as part of the total process. Improved joint design, fixturing, fit-up, etc., can reduce the burden on the control system.

RECOMMENDATIONS

1. Research in welding should not be limited to the traditional metallurgical and mechanical properties of weldments, as has often been the case in the past. Welding controls should be considered a research topic, and output should focus on the results of interdisciplinary team efforts.

2. Generic research should be supported on the principles and procedures for implementing flexible welding work cells. The generic intelligent fixture is a goal of many disciplines in advanced manufacturing systems, and the welding industry is no exception. It may be possible to find new relationships between transduced signals in the fixturing and residual stress and distortion. This area of investigation should include computer-aided tooling design and manufacture.

3. Research should be conducted on interpreting the output of readily available sensors in terms of welding process variables and in terms of the ultimate weld quality and fitness of purpose.

4. New ideas for real-time sensing of weld process variables should be pursued. For example, there is a need for voltage-drop measurements that are independent of contact tube design, for temperature measurements near the weld pool surface, and for reliable information on pool solidification.

5. Sensing and model research should not be pursued in isolation. They must be integrated to achieve desired results in the production system.

6. Welding process control research work is appropriate for funding by both mission-oriented and basic research governmental institutions. Because of the systems nature of welding processes and controls, it is important that there be some national coordination directed toward relating the different research activities in agencies, universities, and centers. Effort should not be channeled to any one group, but rather innovation and creativity in the application of the welding sciences should be encouraged across a broad front, including NSF and other government agencies. A closer tie between the welding research community and academia is needed so that the educational role of welding research application and process technology is transmitted to engineering education.

REFERENCE

National Materials Advisory Board. 1982. Advanced Joining Technology. Report NMAB-387. Washington, D.C.: National Academy Press.

Chapter 2

ANATOMY OF WELDING CONTROLS

WELDING CONTROL OBJECTIVES

The application of controls to welding processes has a basic goal of regulating the operation so as to maintain acceptable quality at least cost. Rapid deposition is the key to economy, while quality can involve mechanical properties, low distortion, and appearance.

In the broadest sense, the subject of welding controls must deal with many prewelding conditions, some of which are institutional and some technical. Prewelding conditions involve such functions as design, procurement, facilities, training, planning, and sequencing, and these must be considered prior to addressing the subject of welding process controls. Postwelding conditions, such as heat treatment effects, physical properties, distortion, residual stresses, and quality, also have to be considered. The institutional problems are related primarily to the segregation or boxing of functions into categories such as design and manufacturing rather than aiming for an integrated smooth-flowing process from design through final manufacture. Technical problems often seem easier to resolve than the institutional problems. Although this report focuses on the technical issues, institutional issues are identified where their influence is significant.

The welding process can be defined as "a joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal" (American Welding Society, 1984). Welding can be classified as a multi-input, multi-output process. That is, there are several variables that can be manipulated to affect the outcome of the process, and there are many variables that can be considered as outputs of the process that has taken place. The variables of ultimate importance are those that relate to the mechanical properties of the finished joint. These are the variables that establish the welding process quality. Unfortunately, these variables are available for inspection only after the process has been completed. No technology exists to directly measure the mechanical properties of a joint during the actual welding process so that the information can be used in direct control of the process itself to guarantee final joint properties. What is possible using currently available technology (to various degrees of success) is to utilize sensed quantities from which the quality of the joining process can be inferred. This is achieved by thoroughly understanding the physical nature of all aspects of the process, establishing sufficient numbers of sensors to acquire information about the process, and then establishing control laws and strategies to effect the desired results. In many welding applications, preprocessing of the materials (i.e., preheating, material control, impurity control, geometry control, etc.) plays a major role in the success of the process implementation. Thus, welding generally involves a number of subprocesses or auxiliary controls (i.e., robot or machine positioning devices, etc.) that are essential to the overall process utilization. The concepts being advanced can be visualized with the aid of Figure 1. Control strategies that are widely used in process control and that are applicable to the welding process involve feedback, feedforward, and adaptive principles.* They can be incorporated in the scheme of Figure 1 in a number of ways but have found limited production use in welding processes because of a lack of understanding of the process or an inability to sense important variables.

The control objective can be viewed as providing regulation of the process to maintain a high-quality weld in the presence of numerous disturbances that are imposed on the process. Control does not necessarily eliminate error, but effective control should improve uniformity and hold errors to within tolerable levels established for acceptable reliable quality. Disturbances that may affect the system can take many forms, depending on the process:

- Changes in base materials, including composition, surface condition, dimensions, and preprocessing history.

- Joint preparation, including location on workpiece, geometry, dimensions, tack geometry, edge condition, fit-up, and back-up.

- Workpiece location, position, clamping, and temperature, and the nature of heat sinks.

- Machine accuracy and controllability in automation systems.

- The nature and consistency of the consumables, including gas composition and flow; electrode composition and geometry; filler material size, composition, surface condition, and geometry; and flux composition and preparation.

---

*In a feedforward system, the major components of load are sensed and used to calculate the value of the manipulated variable required to maintain control at the set point. Feedforward control is one form of closed-loop control. The aim of feedforward control action is to reduce the effect of disturbances on the measured value by reducing the size of the disturbance itself before it enters the process.

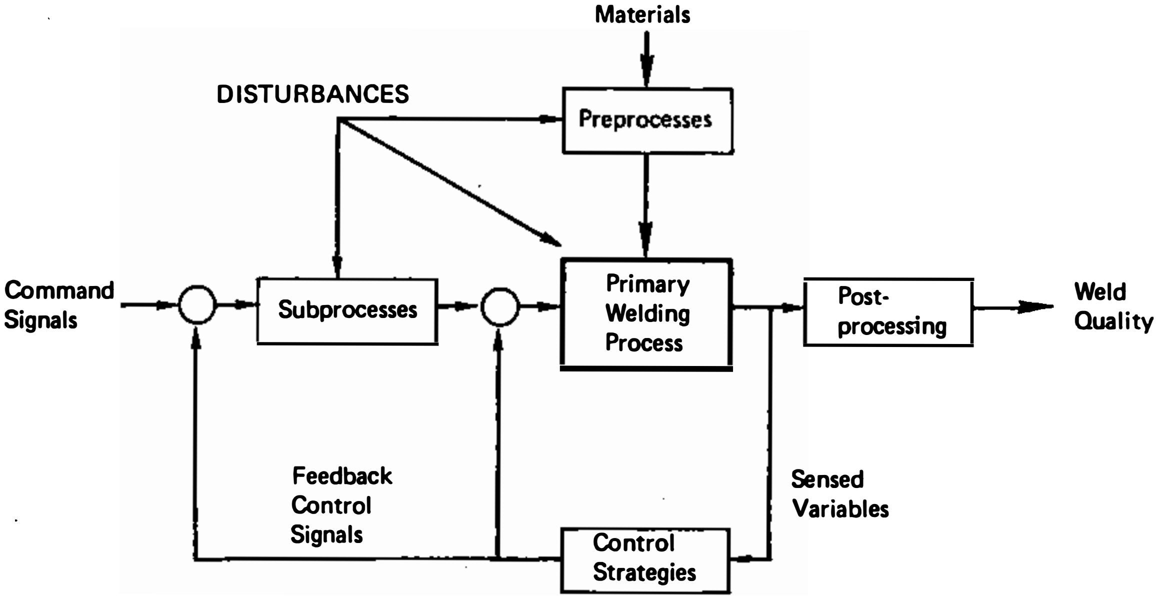


FIGURE 1 Block diagram of the welding control problem.

- Ambient conditions, including temperature, humidity, pressure, and air movement.

The importance of the various disturbances depends on the process and the application, and various levels of control may be necessary to achieve desired results. Understanding process sensitivity to the disturbances is paramount. The underlying target of applying higher levels of control in welding is to better regulate the process to achieve the quality objective. Two broad categories of control can aid in achieving this objective. First, the development of new sensing devices can provide better and new feedback signals that more reliably or accurately describe the process result. These can aid in more effective implementation of classical feedback control concepts as well as in the addition of new control loops in numerous places in the overall control scheme. Second, the utilization of advanced control strategies, including a range of adaptive control principles, optimal control philosophies, nonlinear control techniques, and programmed logical decision systems that test against alternatives, can provide a higher level of control intelligence. However, to utilize any of these effectively requires depth of understanding of the process and mathematical models of the process with which to work.

The performance of any control system is potentially degraded by the presence of dead-time or transportation lag, the time that it takes to make, assess, and transmit information about an output variable. In the case of weld quality, ultrasonic inspection is widely used to detect flaws in a joint. This inspection technique is generally a postprocessed signal, and considerable time elapses before the information gathered can be utilized for control of the process. At best, the information can be useful on a part-to-part basis, as it is too late to alter the welding process on the part being inspected. However, with dedicated hardware, ultrasonic testing can and is being used in a real-time mode to measure penetration for adaptive control. Because the welding process involves liquid material and solidification processes, the dynamics of the process variables cover a wide range of time perspectives. Parts of the process are slow, taking minutes to establish the final results (i.e., the solidification and cooling in the process). Other aspects of the control are fast, with millisecond responses, such as the bandwidths associated with machinery position control, voltage control, and wire feed control systems in the welding equipment.

Examples of implementation of the philosophies advanced are appearing from the laboratory and are finding their way into industry for some welding processes. This report presents areas for research that can capitalize on opportunities, particularly in military systems.

FAULTS AFFECTING QUALITY AND PRODUCTIVITY

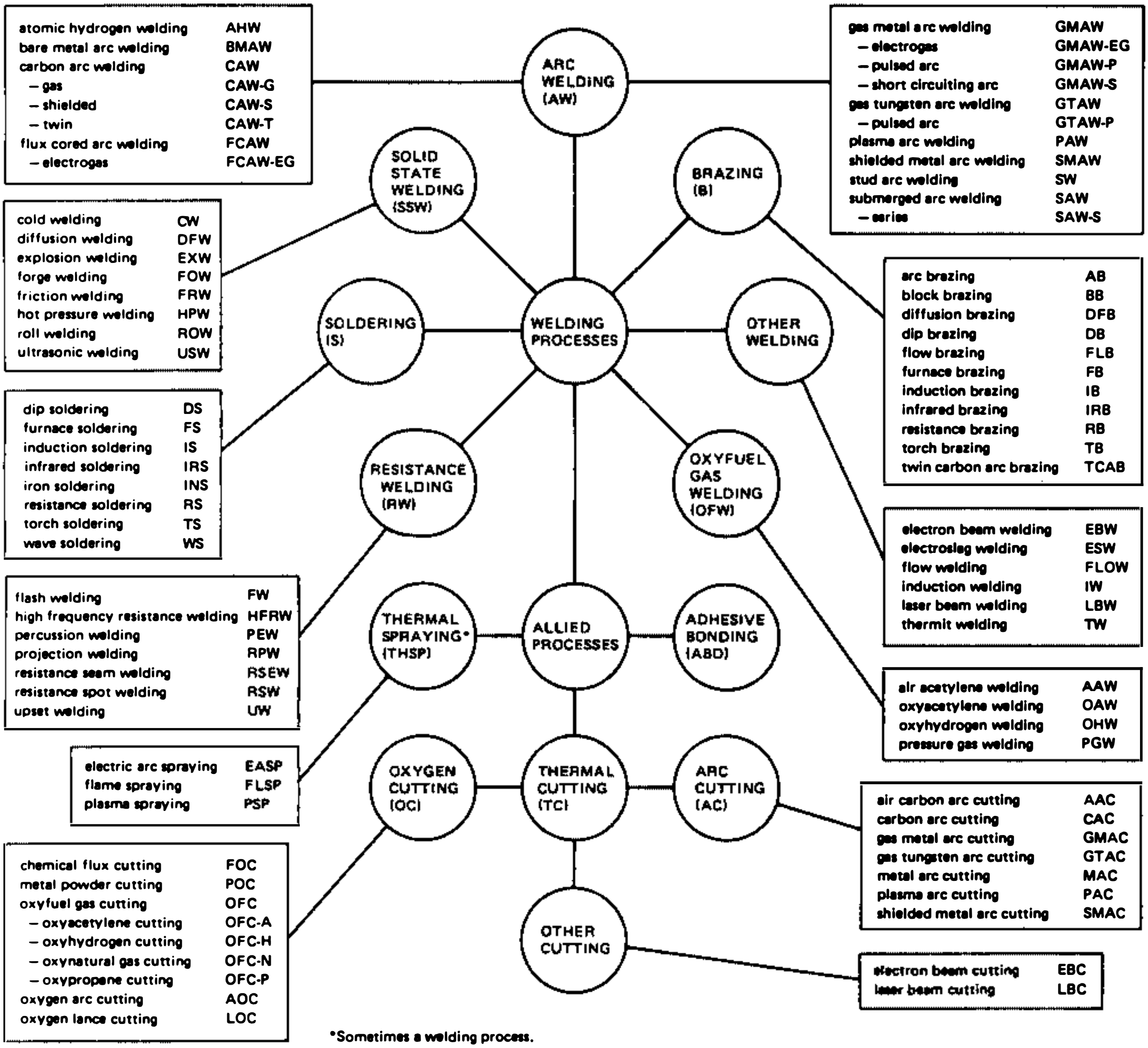
Imperfections in welded joints affect the ultimate fitness for purpose of the joints and thus directly determine quality. If repair or reworking is required to assure quality, or if scrap results, then they directly affect productivity. The reduction of weld imperfections through the use of real-time control is a long-term objective. However, practices, procedures, and a wide range of institutional requirements are all important factors and in some instances predominate.

Imperfections can have their origin in metallurgical, geometrical, process, and procedural causes. For example, metallurgically caused imperfections include hot cracks, cold or delayed cracks, microfissures, microstructure alteration of heat-affected zone (HAZ), or weld metal and HAZ segregation. Geometrical causes include poor fit-up, mismatch, undercut and cavity, overlap, excessive reinforcement, concavity and convexity, and the nature of the weld dressing. Faults in the weld process and procedures can result in a lack of fusion, incomplete penetration, slag inclusions, porosity, burn-through, entrapped weld spatter, insert ring lack of fusion, backing ring lack of penetration, tungsten inclusions in gas-tungsten-arc welds, copper inclusions, oxide films, and surface irregularities. A goal of research in the welding field should be to identify these defects that are caused by faults and to relate them to disturbances so that they can be controlled, thus the greatest potential for increases in quality and productivity. Additional work is needed to better define what is actually allowable in a structure (i.e., number and size of defects) to better define fitness for purpose.

WELDING FABRICATION SYSTEMS CONCEPTS

The American Welding Society has categorized welding processes and standardized nomenclatures as shown in Figure 2. There is indeed a great variety in the nature and the application of the various welding processes. These primary processes constitute the joining action that occurs at the point where actual welding takes place to form specific weld bonds. Actual primary processes are varied in nature, as noted in Figure 2, but they have three physical similarities in common: They are composed of subprocesses involving the application of energy, the formation of a bond, and the thermal and mechanical relaxation of the affected materials. The phenomena that take place during welding are interactive in that the final result depends on the way in which each elemental subprocess affects the other. The most common welding process is fusion welding, which includes arc welding, resistance welding, gas welding, electron beam welding, laser welding, and others.

Figure 3 shows how the primary welding processes relate to a welding manufacturing system. The figure constitutes a more detailed depiction of the interactions outlined in Figure 1. It should be readily apparent that obtaining quality and productivity in welded elements is an institutional as well as a technical problem. Automation of the process requires tooling and equipment, formalized procedures, and reliable processing of materials in preparation for welding. Feedback control, adaptive control, and other control techniques can reduce the sensitivity of the actual welding process to deviations in any of the contributing elements. However, none of these developments in technology will alleviate the requirements for approaching a welding problem as a fabrication system in which all of the technology is properly and reliably applied and in which all of the organizational elements have been appropriately addressed.



*Sometimes a welding process.

Figure 2 Welding and allied processes (American Welding Society, 1984).

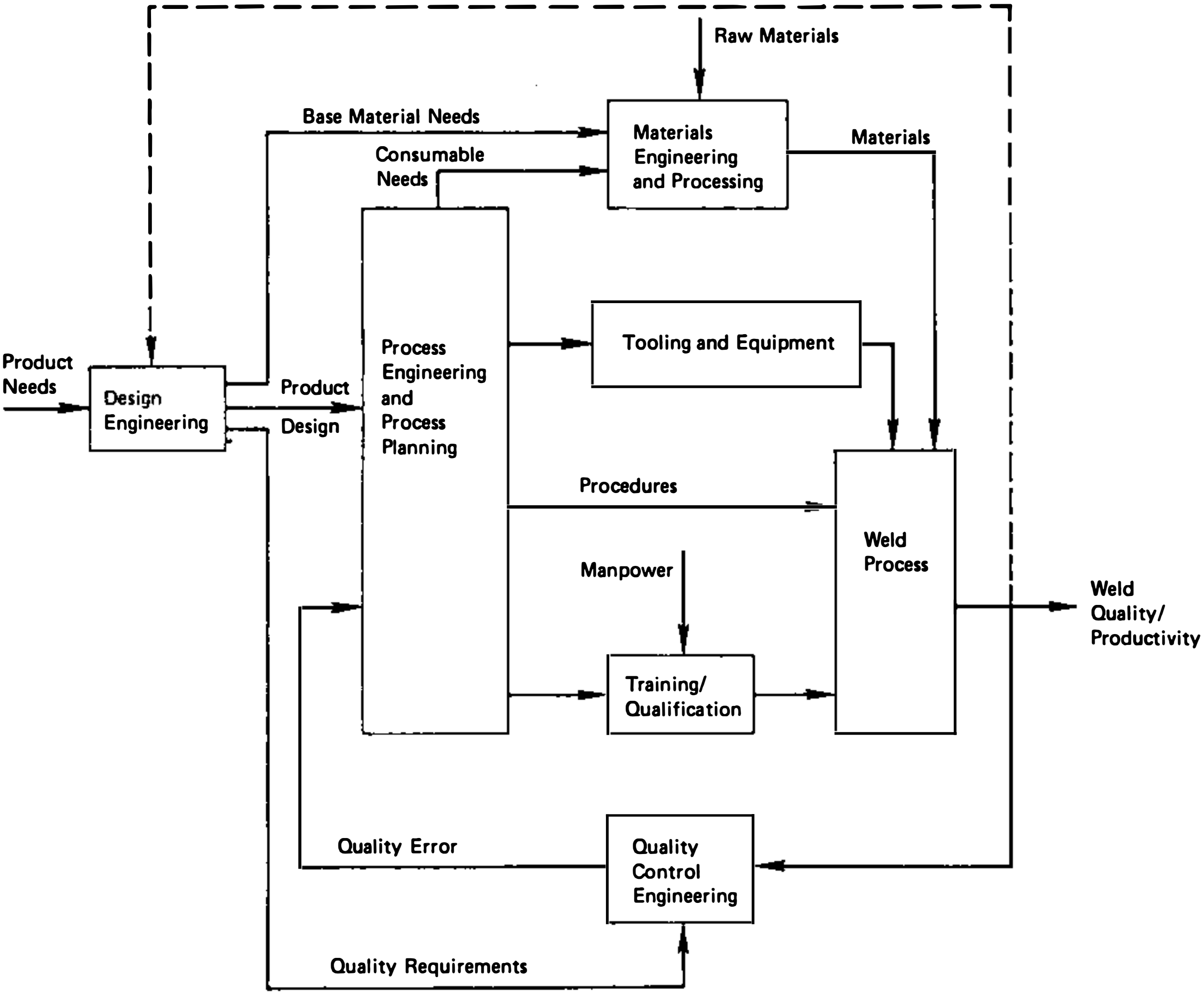


FIGURE 3 Welding manufacturing system.

AUTOMATION MATRIX

The levels to which process automation has been applied to welding machine and process equipment, and the forecast application, are shown in Table 2. The welding application system has been divided into elements that include the heat source, filler source, travel rate, manipulation, position control, guidance of the deposition process, fusion zone, and final weld quality. The level of process automation is described as either manual, semiautomatic, machine, automatic, or adaptive. Note that the control of the fusion zone in a welding process is controlled automatically only in an adaptive control mode. At this point in time the resistance welding process and the electron beam welding process have been the most advanced in terms of the application of controls and defect detection. It is not visualized for the immediate future that even adaptive control can automate the final quality as measured by the actual joint mechanical properties. To achieve this level will require further sensor technology development and perhaps integration into a knowledge-based system. Automation through the adaptive control level in any of the widely used processes can significantly reduce welding sensitivity to disturbances.

TABLE 2 Automation Matrix: Level of Control and Mechanization

	Level of Process Automation				
Elements Controlled	Manual	Semi-Automatic	Machine	Automatic	Adaptive Control
Heat source	Person	Machine	Machine	Machine	Machine
Filler source	Person	Machine	Machine	Machine	Machine
Travel rate	Person	Person	Machine	Machine	Machine
Position	Person	Person	Machine	Machine	Machine
Guidance	Person	Person	Person	Machine	Machine
Fusion zone	Person	Person	Person	Person	Machine
Quality	Person	Person	Person	Person	Person

Time frame for application of automation in arc processes:

|——1985——————————————|

|————————1990————————|

|——————————————2000——|

Electron beam 65 percent mechanized by 1985

Note: Based on definitions in Standard Welding Terms and Definitions, American Welding Society, 1984.

REFERENCE

American Welding Society. 1984. Standard Welding Terms and Definitions. Miami, Florida: American Welding Society, Inc.

Chapter 3

WELDING CONTROL PROBLEMS, CHALLENGES, AND OPPORTUNITIES

The Department of Defense, particularly the Navy and the Army, uses welding (primarily arc welding) as a preferred fabrication method for joining a wide variety of materials for various combat and noncombat vehicles. It is estimated that the Navy will spend more than $1 billion for welding HY-80/100 steels in the next 10 years. At present, welding is highly labor-intensive and costly because low productivity, high quality-assurance (QA) cost, and relatively high (5 percent) rejection rates require expensive reworking (at 5 times the cost of initial fabrication). Weld control research is necessary for reducing costs through better productivity, quality, and repeatability and the ability to rely on statistical quality control to reduce the man-hours required. In addition, demographic factors, such as employing personnel in the harmful work area (near the welding arc), the decreasing birth rate and available manpower pool, and the fact that fewer people desire to be welders, has decreased the number of welding personnel. A major shipbuilder reportedly loses 50 percent of its qualified welders each year. These personnel must be replaced, with associated training expense. This trend in personnel dictates that welding operations be less labor-intensive and highly automated. Finally, high-performance materials such as HY-100 and HY-130 steel, armor steels, rapid solidification processed (RSP) alloys, metal matrix composites (MMC), and perhaps ceramics will require much closer control of the welding process than was required in the past, and perhaps closer control than can be expected from a manual welder.

Increased joint reliability is critical in the development of present and future systems in the Army inventory. Current military thrusts in metal joining are in the areas of weldability studies, joining process developments, and the development of adaptive controls for welding and thermal cutting processes. Continued development of these areas will be necessary for new materials such as aluminum and steel armors, metal matrix composites, rapidly solidified aluminum alloys, lightweight aluminum-lithium alloys, and ceramic-metal combinations to be used in the manufacture of defense material.

Metal joining technology in the Air Force is directed at application of the existing welding and joining technology to the repair and fabrication of advanced engine materials and electronic components. Included is the development of automated facilities for repair of shrouded turbine blades. Improved confidence in the quality and reliability of welded construction could extend the application of welding in aircraft structures.

In shipbuilding, there are two major areas for improved weld productivity: the use of work cells, and the utilization of adaptive welding systems for hull and structures welding. Both areas require a minimum of man-machine intervention, and both areas require some degree of adaptive control. They also require significant attention to many preprocess functions in order to accurately define an effective process control system.

The work cell concept for flexible manufacturing of parts for assembly into hulls requires the application of group technology, the standardization of parts, intensive production planning, and sequencing of material flow. The welding controls and processes must be flexible to handle parts of various geometries. The welding controls must also be adaptive in the sense that they must find and follow the joint, must change process parameters as a function of joint variation, and must locate and position beads in multiple-pass welds.

In the fabrication and erection of hulls and structures, a fully adaptive welding system is required. This system should have a means of locating the joint as well as the guidance of the arc along the joint. It also should be able to adapt to irregularities within the joint. Compared to optical methods, it seems that the present through-the-arc control systems offer the advantage of requiring fewer pieces of ancillary equipment, such as lenses, lights, and cameras, and also permit submerged arc welding. The advent of integrated circuit optical sensors presents new opportunities that could be the basis for important future research. However, the through-the-arc systems need additional development, including better understanding of the transfer function within the arc (i.e., the volt-ampere relationship between the arc and joint sidewalls) and the characteristic of the arc-over-the-liquid metal. It is believed that, by establishing these and other transfer functions, control algorithms could be developed for an effective shipyard-type adaptive control system.

UNDERSTANDING THE BASIC PROCESSES

A special group of the arc welding processes consists of those wherein weld metal crosses the arc. This group includes shielded metal arc welding, gas-metal-arc welding, flux cored arc welding, and submerged arc welding. A second category includes arc welding processes where the weld metal does not cross the arc. The arc is used as a heat source to melt the filler metal and the base metal. These processes are gas-tungsten-arc welding, plasma arc welding, and cutting. Another group of processes includes the specialized arc processes such as stud welding and electrogas welding. Electroslag welding is not an arc welding process but may be included since it utilizes the same basic equipment that is used for several other arc welding processes. The processes where the metal crosses the arc are all similar and are controlled in a similar manner. The processes where the metal does not cross the arc are all similar, but the control systems are different from those of the first group.

All of the arc welding processes can be analyzed with respect to the "method of applying." This relates to the level of mechanization and control. Several of the arc welding processes have, to date, only been applied as a manual process, whereas others have been applied as semiautomatic, machine, automatic, and various levels of advanced control.

Gas-Tungsten-Arc Welding

Gas-tungsten-arc (GTA) welding is probably the most amenable to control of the various arc welding processes. As a result, state-of-the-art control of GTA welding tends to lead other arc welding processes, even though there are many parameters requiring independent control.

There are several reasons why GTA welding is more suited to control, whether manual or automatic. The arc operates from a nonconsumable tungsten electrode, which produces a much more uniform and stable heat source than consumable electrode arcs. Filler wire is added separately to the GTA process and is thus independent, in terms of rate, position, and orientation, from the arc. The process behaves in a similar manner over a wide range of heat, power, or energy inputs (from a few tens of watts to tens of kilowatts). The GTA process does not produce significant spatter, smoke, or fume and thus presents a relatively clean environment. The uniformity and cleanliness of the heat source make it preferred for the welding of most advanced materials, which are adversely affected by even slight contamination during welding. Because of the nature of the GTA process, it finds application in precision and high-quality welding applications. In these applications, more attention is routinely paid to joint preparation, part cleaning, maintenance of equipment, the following of weld procedures, and postwelding inspection. For these reasons, GTA welding often finds application in aerospace, electronic, nuclear, and other "high-technology" areas. Technology and the cost of higher levels of control are often more acceptable in these industries. On the other hand, GTA welding does not find application in many of the more traditional areas of welding because metal deposition rates are quite low compared to consumable electrode welding.

There are difficulties with the manual and automatic control of GTA welding. There is often a greater level of skill, dexterity, and manual control associated with precision GTA welding. A part of this may be identified with the frequent need for full-penetration welds to adhere to stringent standards. Welds are often small, and part and weld geometries may be more complex. Also, quality requirements may be extremely high, and the volume of welding very low. A chronic problem with automatic control of GTA welding is the common use of radio frequency (RF) for arc starting and/or stabilization, which produces severe interference with sophisticated electronic control circuits and systems. This has been a particular problem relative to the application of robots to GTA welding.

The control of GTA welding, as for the control of any process, involves the recognition and control of the variables of the process. In manually controlled welding, control is related to the training, skill, and experience of the welder, combined with the accumulation of procedures and practices. The recognition and control of the variables is often very qualitative and intuitive. Automatic control requires a much more quantitative identification of the process variables and their interrelationships. In this regard, it is useful to consider the welding process in a more formal representation, including a discussion of the process and its inputs and outputs.

The primary process in GTA fusion welding is the action that occurs in and around the point of welding (the weld pool). It does not include any of the process equipment, which can be identified with surrounding subprocesses. The primary process does include the electrode tip, the arc, the filler wire tip, and the affected base metal.

It is possible to consider inputs and outputs of the primary process. This is useful for a more systematic consideration of methods of control. Inputs may be divided into main and disturbing inputs. Outputs may be divided into intermediate and final outputs. The final outputs are those variables that are ultimately to be controlled. Main inputs are those variables that can be adjusted by the process intelligence, in real time, to affect the final outputs. Tables 3 through 6 summarize variables in the several categories. They also include indications of the need for, methods of, types of, and viability of suitable controls.

State-of-the-art GTA process control primarily resides in the accurate, repeatable, and precise control of main inputs. Welding power source controls, and associated control of peripheral equipment, are the most advanced of any arc welding processes. Also, significant advances have occurred in the development of real-time, process feedback controls (so-called adaptive welding controls); however, on the whole, the practical use of such controls has been limited.

Power sources for GTA welding have typically been the most accurate, precise, and electronically advanced of all types of arc welding power sources; they are also typically the most expensive. Modern GTA power sources are highly constant current, with electronic feedback controls on the weld current or pulsed arc sources. Earlier GTA power sources utilized magnetic amplifier controls. Modern technology power sources utilize semiconductor-controlled rectifier and transistor-type controls. Switching transistor-type power sources at present offer the highest level of controllability and speed.

GTA power sources also provide the best capability for sequential control and programming of the process main inputs. This includes control

TABLE 3 Main Inputs (inputs controllable at time and point of welding)

- Heat source
  - Current
  - Arc length
- Motion
  - Weld travel speed
  - Travel speed oscillation
  - Cross-seam oscillation rate, amplitude, and dwell
  - Filler wire feed rate
  - Filler wire feed oscillation rate and amplitude
- Torch position and orientation
  - Torch position relative to joint (transverse)
  - Torch angle relative to travel
  - Work angle relative to torch
- Filler wire position and orientation
  - Filler wire angle relative to work plane
  - Filler wire angle relative to travel
  - Filler wire height above work
  - Filler wire entry position to arc/weld pool

TABLE 4 Disturbing Inputs (inputs not at present controllable and subject to variation at time and point of welding)

- Heat source
  - Electrode type and composition
  - Electrode tip geometry
  - Current (sometimes)
  - Current waveform variations*
  - Pulsed waveform parameters*
  - Shielding gas
  - Magnetic fields
- Gas shielding (torch and back-up)
  - Torch gas mixture
  - Torch gas flow rate
  - Torch gas contamination
  - Torch gas flow (uniformity/turbulence)
  - Same as above for back-up gas
  - Back-up gas coverage, distribution, and uniformity
- Filler material
  - Wire diameter
  - Wire composition (major)
  - Wire composition (minor)
  - Wire surface condition (contamination)
  - Wire position and orientation relative to arc and weld pool
- Workpiece
  - Workpiece position and orientation
  - Tack locations and size
  - Workpiece temperature
  - Welding current flow and distribution
  - Thermal distortion
- Fixturing and tooling
  - Clamping positions
  - Clamping force
  - Thermal contact
  - Electrical contact
  - Back-up
  - Fixture temperature
- Base material
  - Composition (major)
  - Composition (minor)
  - Processing history
  - Mechanical and physical properties
  - Dimensions
  - Surface condition and preparation
- Joint preparation
  - Joint location relative to workpiece
  - Joint geometry and dimensions
  - Joint surface condition
  - Tack geometry
  - Back-up
  - Joint position
- Environmental
  - Air temperature
  - Air pressure
  - Humidity
  - Air movement
  - Time of day

*Depends on process.

TABLE 5 Final Outputs (ultimate measurable results of the solidified weld)*

- Weld location relative to joint
- Weld geometry
  - Weld bead width
  - Weld bead depth
  - Weld bead area
  - Weld bead cross-sectional shape
  - Weld bead surface reinforcement
  - Penetration
  - Underbead size
  - HAZ size
- Mechanical and metallurgical properties
  - Tensile strength
  - Ductility
  - Hardness
  - Toughness
  - Metallurgical structure
  - Residual stress
- Surface condition
  - Oxidation
  - Slag coverage
  - Weld bead texture
- Gross defects
  - Porosity
  - Inclusions
  - Lack of fusion
  - Lack of penetration
  - Cracks
  - Voids

---

*In the laboratory, one can measure distortion now with moiré interferometry, with the possibility of determining residual stress.

TABLE 6 Intermediate Outputs (outputs that can be observed or measured in real time as the process proceeds)

Power

- Current
- Voltage

Spacial (relative)

- Position and orientation of electrode relative to workpiece
- Point of heating relative to joint
- Heating and melting distribution relative to heat source and joint
- Motion of weld pool
- Filler wire location and orientation relative to arc and melt (weld pool)
- Filler wire transfer location

Geometry

- Weld pool size and shape
- Weld pool surface convexity or concavity
- Penetration (from backside)*
- Filler drop size

Thermal

- Temperature distribution around weld
- Heating and cooling rates
- Solidification rates

Emission

- Light
- Sound
- Chemical
- Spatter

---

*Top side measurements can be made with ultrasonics.

of gas pre- and post-purge, arc starting and stopping sequences, upslope and downslope of welding current, programmable variation of weld current during welding, and coordination of wire feeding. Much of this capability has been developed for the particular application to automatic GTA pipe welding. Such open-loop sequential controls can be used very effectively in pipe welding because of the highly repeatable conditions that prevail. These systems still require continuous manual monitoring for real-time adjustment (i.e., feedback) control of main inputs. Monitoring is primarily of disturbing inputs associated with the location and shape of the weld pool.

GTA power sources have pioneered the concept of pulsed welding. In pulsed welding, the weld current is pulsed to a high level from a low level. Rates of pulsing are usually in the range of 1 to 10 times per second. Wire feeding and weld travel may also be synchronized with current pulsing. Pulsing provides another "dimension" of process main inputs (that of temporal variation). The primary advantages of pulsed GTA welding are debatable; however, it is claimed to provide better penetration and more controllable solidification characteristics. The former can be related to the high current pulse; the latter to the transient, pulse-to-pulse solidification mechanism (the idea of overlapping spot welds).

One of the most successful process feedback controls in welding is the automatic voltage control (AVC). These controls consist of sensing the intermediate process output of voltage for the purpose of controlling the length of the welding arc. Arc length needs to be controlled to maintain constant power input and distribution and arc stability. Such controls are found on most mechanized and robotic GTA welding systems.

Manual controls are still extensively relied on in GTA welding to maintain the desired weld position and geometry. Control is via observation of intermediate outputs relating to pool position and size.

The automatic controls that have been pursued for the most part are joint trackers and penetration controls (full-penetration, primarily). Increased impetus for such controls has resulted from the desire to apply robots to GTA applications. The application of robots to GTA welding is particularly troublesome because of the dimensional precision required and the need to control penetration. Generic approaches do not exist for either control at the moment, although much development work is in progress. The use of vision technologies is at present the most active area of investigation. Such systems must be developed before fully automated GTA welding will become a reality.

Gas-Metal-Arc Welding

The gas-metal-arc (GMA) welding process belongs to a larger class of processes known as consumable electrode welding. An uncoated, gas-shielded, continuous wire is fed into the arc. A shielding gas protects the arc and weld pool from the atmosphere. The nature in which the wire melts and transfers to the weld pool is an important characteristic of the process.

There are three commonly accepted, distinct modes of metal transfer in GMA welding. These are referred to as short-circuiting transfer, globular transfer, and spray transfer. In addition, a fourth transfer mode, denoted "drop spray" or sometimes "streaming spray," is mentioned in the welding literature.

GMA welding used for heavy weldments in steel 1/4 in. and thicker has different constraints compared to high-production GMA welding of items in the transportation, automotive, and appliance industries, for example. In GMA welding of parts for the automotive industry, which is usually in steel ranging from 0.04 to 0.16 in. thick, welding speeds are generally well above 50 in. per minute in order to achieve the necessary high production rates. In the past, quality levels on such weldments have addressed fitness-for-service aspects only. Recently, however, in addition to fitness for service, the esthetics of the weld deposit, such as no spatter or burn-through, have also been called for on the product. Because mass-produced parts for automotive use are made by metal stamping and forming, these formed parts are similar but never exactly the same. Thus parts can have a variety of differences that cause changes in the weld joint fit-up. Gaps and other forming distortions can and do affect the ultimate quality of the product.

Welding controls should be researched and designed to adaptively accommodate the manufacturing nuances associated with stamped and formed high-volume parts. Synergic pulse arc welding power supplies for GMA welding are becoming more readily available. It appears that synergic pulse arc welding provides a means by which one can tailor the exact amount of energy and filler metal required to make a proper high-quality weld. A real-time seam-tracking device that also provides welding parameter adjustments for weld joint characteristics and dimensions is required. Combining the synergic GMAW process with the real-time seam tracker describes a primitive adaptive control system for production welding.

If and when a basic adaptive control system is developed, it should be further enhanced by information that predicts part distortions caused by the heat of the welding process and clamping fixtures. Stock thicknesses, part shape, and material properties appropriately modeled could, in combination with an adaptively controlled synergic pulsed GMA welding system, be used to predict and control weld locations, sequences, width, and length.

In addition to the control elements to achieve individual welds, one needs to have real-time monitoring of all parameters and equipment operating characteristics. Such a control system should continuously monitor all functions of the welding cell and process. The reporting system should only report exceptions to expected preprogrammed values and/or predictions that preventive maintenance needs to be performed on a specific device or apparatus. Diagnostic measures for the welding cell and process are also required. Once the adaptive control philosophy and maintenance assessment procedures have been developed for a complete welding cell, a strategy needs to be developed to interrelate multiple cells.

Considerable advancement has been made in recent years in GMA welding control systems that can track the weld joint and control the welding parameters as required to adjust for changing joint configurations. Basically, three types of systems have been developed: (1) tactile sensing guidance systems that provide geometrical control and flexible programming, (2) vision systems that view the weld joint just in advance of the arc or look down directly on the weld pool and make modifications to the welding system to accommodate the change, and (3) through-the-arc systems that use changes in arc length during oscillation across the joint as they affect arc voltages and/or current to modify the system parameters.

Cell systems have been developed and reduced to practice industrially over the past 11 years. One system compares the amperage change as the arc shortens approaching the joint sidewall on each side of the weld joint as the arc oscillates across the joint. The system translates the oscillator pivot point left or right to balance the left and right current changes.

An alternative system uses through-the-arc sensing as a means of deriving weld pool surface topography as well as arc positioning information (used to fine-tune a base-line robot program) from the voltage and current relationships that exist during the welding process. As an arc is moved laterally across a welding joint, changes in the impedance of the plasma column occur as the arc length is varied in relationship to the electrical contact tip. This impedance change is reflected in the voltage and current waveforms that are produced as a result of the welding arc. This makes it possible to generate an equivalent model of the welding pool by monitoring the voltage and current waveforms produced by the welding arc in relation to the linear position in the welding joint. As the arc is displaced into a sidewall, the impedance will be decreased, resulting in an increase in the instantaneous welding current and a decrease in the instantaneous welding voltage. The current will show an immediate increase as the welding arc moves into the sidewall, and the welding voltage will decrease at the same point. By evaluating the change in both voltage and current as a function of time and position, it is possible to determine actual sidewall excursions.

If the change in voltage and current are multiplied together, the result is a relationship that reflects power. If the power relationship is integrated with respect to distance and lateral velocity, a signal can be derived to detect positional changes that have occurred during the lateral oscillation of the welding arc, thus providing a means of determining actual sidewall locations.

TABLE 7 Status of Research in GTA and GMA Welding Process Characterization

Topic	Theoretical or Modeling Status
GTA Welding Arc Properties (Neutral sheath)	
Temperature distribution	First-principle finite-difference model including forced shield gas flow
Electrical conductivity	First-principle modeling of conductivity using electron collision cross sections for single- and two-component plasmas
Thermal conductivity	First-principle Chapman-Enskog modeling of thermal conductivity using electron collision cross sections for single- and two-component plasmas
Viscosity	First-principle modeling of viscosity of one- and two-component mixtures
Gas density	First-principle modeling of pressure using ideal gas considerations
GTA Welding Plasma Characteristics (electrically conducting core)	
Temperature distribution	First-principal finite-difference modeling including forced shield flow
Electric field distribution	Approximated using either finite element or finite difference methods; only 2-dimensional calculations
Axial and radial current distribution	Approximated using electric field calculated values, plasma conductivity, and temperature profiles; most model results for single-gas constituents; calculations restricted to 2 dimensions
Axial and radial gas flow velocities	Finite element and finite difference computations that solve mass, momentum, and energy equations; most codes are 2-dimensional
Magnetic fields	Direct calculations using magnetic permability and arc current
Pressure	Assumed constant in existing calculations
GTA Welding Heat Input Distribution to Work Piece	
Stationary arc-copper	Semi-quantitative at best
Moving heat source-molten pool	No current models
GTA Welding Pool Surface Geometry	Vortex theory (MIT), thermal expansion, arc force (plasma jet); all quantitative

Experimental Status or Model Verification	Needs
Measurement based on single Ar I line compared with continuum	Temperature measurements near or at electrode surfaces; model needs refinement to include more realistic boundary conditions
Probe measurements have yielded some verification near anode for single-component plasmas	Electron collision cross sections for a wide range of atoms, single- and multiple charged ions
No known verification	Same as electrical conductivity
No known verification	Same as electrical conductivity
Holographic interferometric and Schlieren measurements have determined density contours	Improved analytical methods for interpretation of holographic interferometry and Schlieren data; better correlation between measurement methods
Two-line method using Ar I and II	Temperature near or at electrode surfaces; model needs refinement to include more realistic boundary conditions
None to date; estimates have been made using probes	3-dimensional calculations required for moving heat source
Predicted values have not been extensively compared to actual arc currents; some early probe measurements; a limited amount of hydrogen H beta line with measurements	Extensive comparison with experimentally determined distributions; developments of 3-dimensional calculations
Laser-Doppler velocimeter and interferometric measurements of flow velocity and flow dynamics	Development of 3-dimensional and turbulent flow models
No known verification	None
None	None
Heat input distribution has been measured for a wide range of variables for a straight-polarity arc to a copper anode	Well developed, quantitative model
No known experimental data	Both experimental data and quantitative work
No known verification	Both experimental data and quantitative models

TABLE 7 Status of Research in GTA and GMA Welding Process Characterization

Topic	Theoretical or Modeling Status
GTA Welding Base Metal Heat Flow and Fluid Flow	
Weld pool shape and base metal isotherms via heat flow	Finite element and finite difference models exist for GTA welding
Fluid flow in weld pool	Simple 2-dimensional numerical models exist for GTA welding
Weld pool surface	2-dimensional finite-element method model vaporization taking into account for GTA welding
GTA and GMA Welding Bead and HAZ Microstructure and Macrostructure	Simple analytical model exists
GTA and GMA Welding Process Control	
Penetration control model	Simplified analytical and numerical models exist for GTA welding, none for GMA welding
Penetration control sensing	Several potential techniques exist using optical, ultrasonic, infrared filter radiometry, and voltage sensing
Seam tracking and joint location	(See experimental status)
GTA and GMA Welding In-Process Inspection	Limited ability to detect weld pool and bead geometry and defects exists using ultrasonic technology and signal processing

Note: A complete physical understanding of GMA welding arcs, either theoretical or experimental, has not been developed. Notable exceptions to this are several wire melting models that have partial experimental confirmation. A critical need is development of the heat input distribution, including the filler metal component, to the workpiece.

(continued)

Experimental Status or Model Verification	Needs
Nominal agreement between models and experimental at low welding speeds; poor agreement at high welding speeds	3-dimensional moving heat source finite-element method model incorporating vaporization, condensation, radiation, convection, conduction, surface oxidation, plasma jet end cover gas shear forces, Lorentz, buoyency, surface tension forces, and solidification segregation
Limited or no verification of models	
No known experimental verification	Thermophysical properties data base
Limited development	Adequate data base of material thermophysical and kinetic properties; structure development model needs to be integrated with heat flow-fluid flow model; correlation with mechanical properties needed
Process characterization is well developed; limited or no demonstration of control capability	Demonstration of process control model in real time for both GTA and GMA welding
Demonstrated for limited conditions and geometries	Torch-side, noncontact direct or indirect sensing of penetration and/or sidewall fusion in GTA and GMA welding
Several techniques exist for tracking weld torch with respect to the weld joint	Technique for tracking weld pool with respect to weld joint end previous fill passes; long-range technique for tracking joint location
Ability to identify weld bead defects and weld pool and bead geometry has been demonstrated under laboratory conditions	Extensive signal processing and transducer signal coupling development

This adaptive-like feedback-controlled welding system uses the increase in power-product profiles as the arc approaches the sidewall to control the maximum excursion of the welding arc into the sidewall. The system integrates the power-product relationship from a point beyond weld centerline until the integrator reaches a predetermined integration value. Upon reaching this value, the integrator stops the oscillator, computes the current distance from the opposite sidewall, and determines the actual welding width. By dividing the welding width in half, the centerline position is determined. By knowing the width of the welding joint and the changes that occur in this width during the welding operation, the control can then perform adaptive modifications to the welding procedures.

One of the important factors governing mechanical properties of deposited weld metal is the actual heat input applied during welding. It is important to maintain a heat input range to ensure proper metallurgical properties. A control system has been developed that monitors both voltage, current, and travel speed to calculate the actual heat input. To maintain a desired heat input, the system must control the contact tube-to-work distance, travel speed, welding voltage, and wire feed rates.

Another important feature to be considered during welding is the fill height. Fill height is a function of joint width, wire feed velocity, recovery efficiency, and travel speed. The weld control system should maintain a constant fill height relationship as the welding joint varies in width.

By using an adaptive-feedback control welding system such as through-the-arc sensing, it may be possible to obtain more consistent metallurgical properties in some applications. It is also feasible to obtain proper sidewall fusion for varying joint openings and to maintain proper fill-height relationships for each successive pass. Under the proper conditions, this technology has proved to be a major step forward in providing adaptive control. However, as with the GTA welding process, much research needs to be done to extend applications and to provide more basic understanding of the processes.

Table 7 summarizes the status of research and needs associated with GTA and GMA welding processes as observed by the committee.

Submerged-Arc Welding

The submerged-arc process is a consumable-electrode welding process that utilizes a granular mineral type of flux to cover the arc and liquid metal. The flux protects the arc from the environment, visually obscures the arc, and performs certain metallurgical functions. The flux is usually fed to the arc zone from hoppers or from pressurized units. The rate of flow must be coordinated with the arc travel speed to ensure a proper, uniform flux burden over the weld pool.

The fluxes are formulated to react with the liquid metal, providing such reactions as deoxidation, alloying, and bead shape control. The flux also contains constituents to help in initiating and stabilizing the arc and to permit welding at very high currents--either AC or DC or combinations of AC and DC arcs.

Other than the utilization of fluxes, the submerged-arc process is similar to other automatic consumable electrode welding processes. It uses AC or DC or both AC and DC power supplies, filler material feeding equipment, and process control systems. Power supplies may be either single or multiple AC transformers or special tapped transformers for multiple electrode operations; DC power supplies, both constant-current and constant potential, can be used, either singly, in multiples, or in combination with AC transformers.

Filler metals used may be in the form of wire or strip or combinations of the two. Filler metal feeding can be a constant-feed-rate system, usually containing an internal feedback circuit to regulate the feed speed around a preset value. The constant-feed system is usually used with constant-potential power supplies and small-diameter wires. However, for larger diameter wires and strip, the most common system is one utilizing constant-current power supplies and a voltage-regulated feed system.

The process control units perform such functions as initiating primary power, starting and regulating filler metal feed, the starting and control of arc travel, and the control of flux feeding.

Postweld cleaning is performed by vacuum removal of the fused and unfused flux and then separating and reusing the unfused flux. Some applications permit the automatic recycling of the flux, whereas others use manual means for recycling.

Submerged-arc welding finds wide use in heavy fabrication industries such as shipbuilding, pressure vessels, pipeline manufacture, and earth-moving equipment. The attractiveness is in the economics, since the process is commonly used at currents in excess of 1000 amperes per wire and in application of three or four electrodes. Under these conditions weld metal deposition rates of 30 to 100 pounds per hour can be achieved.

At present, there is no known case of fully adaptive control systems (beyond seam-tracking) having been applied to the submerged arc process. The major factors that affect the process are these:

- Stability of primary power
- Transient response of the power supply
- Control of arc length (voltage)
- Stability of the travel speed
- Contact tip-to-work distance
- Flux burden over the melt
- Consistency of flux mesh size

- Electrode spacing in multiple-arc operations
- Joint, wire, and flux cleanliness
- Joint fit-up consistency
- Bead placement in multiple-pass welds
- Wire and flux chemistry variations
- Wire surface condition and straightness

Plasma Welding

Energy sources for plasma welding are generally the same as those used for GMA and GTA welding. Therefore, the same advantages and disadvantages of the magnetic, semiconductor-controlled rectifier, transistor, and inverter-type supplies apply to plasma. Plasma does have the ability to control wire feed rates independent of the energy source.

There are two ways of operating a plasma torch: keyhole mode (plasma keyhole welding, or PKW) and fill mode. In PKW, control of the gas flow and pressure is critical because the keyhole geometry is rather sensitive to these parameters. Likewise, the PKW process is sensitive to changes in joint geometry because of changes in keyhole. Thus, accurately prepared weld joints are required for acceptable weld performance. Geometry and position are important because, as the mass of molten metal is increased in attempts to weld thicker sections, gravity tends to pull the molten metal out of the weld zone, thus providing an upper limit on material thickness using state-of-the-art torches. Thicker sections will be feasible if the plasma could be confined to a narrow beam such as is achieved in electron beam welding.

If thick sections (greater than 1 in.) are to be welded using plasma, then a grooved joint geometry must be used for the first pass, followed by fill-mode passes. Having to resort to fill passes can substantially reduce the economic benefits of the plasma process.

Regarding sensors for adaptive control, at present there are none that are used with the plasma process. The problem here is that the parameters (such as current, speed, gas pressure, and flow rate mismatch) that affect the plasma keyhole, for example, are not understood theoretically but are handled by experimental iteration (many tests). There is no underlying understanding to use as a basis to control the welding operation. A key element in understanding is modeling of keyhole metal flow.

There has been considerable research activity in plasma welding over the past 15 years. However, most of this work was aimed at developing the plasma process itself and not at developing adaptive weld controls. From the point of view of research needs, the most pressing areas would appear to be (1) improved understanding of the weld process itself, (2) identification and development of sensors that can be used to control the welding operation, and (3) improved design of a plasma torch to allow narrow but deep welds to be fabricated.

High-Energy-Beam Processes and Resistance Welding

The two high-energy-beam welding processes (electron beam and laser), in common with resistance welding, provide low-loss, quasi-adiabatic melting when the input parameters are properly adjusted. This one circumstance, however, is the only obvious characteristic shared by both resistance and high-energy-beam welding processes.

Resistance Welding

Resistance welding, patented by Elihu Thompson in 1877, gained wide utilization for joining sheet-metal components in such diverse industries as aerospace, household appliances, and automobile and truck manufacture. The attractiveness of the process is that it is rapid, and it continues to be the least expensive method for joining sheet metal components.

The assurance that every weld meets a predetermined quality standard has been a continuing problem. Prior to World War II, this had been dealt with by the use of skilled machine operators and/or over-welding. Statistical quality control measures were introduced during the war to compensate for the loss of experienced technicians. All these methods, with varying emphasis, continue to be employed today.

Resistance welding is a dynamic process. There are two main inputs--welding current and electrode force. The latter is converted to pressure (a compressive load) through the medium of the contact area of the water-cooled copper alloy electrodes against an incremental portion of the outer surfaces of the workpiece. For welding in conformance to military specifications, the contacting face of each electrode is machined to a spherical radius. Although electrode face geometry may be considered a main input, the fact is that the original geometry gradually changes in an unpredictable fashion as the high-speed repetitive spot-welding operation proceeds in the manufacturing environment. Electrode face geometry, therefore, becomes one of the many manufacturing variables (disturbing inputs) that must be compensated for by adaptive control.

To produce a high-quality spot weld, a localized finite volume of the workpiece that is clamped between the electrodes must be very rapidly heated so that the temperature at the common interface of this local volume quickly reaches the melting temperature. For example, when spot welding two thicknesses of 0.036-in.-thick René 41 alloy, melting temperature is achieved in three cycles, or 0.05 second. This represents a rate of temperature rise at the common interface of approximately 50,000°F per second!

During this 0.05 second of extremely rapid heating, the local volume through which the welding current flows is always in the solid state. Thus, all the energy dissipated by the current flow is converted to heat. A relatively small fraction of the heat so generated is lost by conduction into the water-cooled electrodes and into the surrounding mass of the workpiece. The energy input must be fast enough so that only relatively negligible losses occur while the temperature rises. This is the critical portion of the process. If a temperature equilibrium is allowed to occur at even 2400°F (René 41 alloy has a melting temperature of 2500°F), melting temperature will never be reached, even if the welding current were sustained for hours. The result would be a "stick" or "dud" weld, with little or no useful mechanical strength.

If it were possible to examine both surfaces at the common interface of the clamped volume at the instant that the current has been flowing for 0.05 second, there would be clear evidence that the welding current is flowing through a circular cross section. Near the periphery (and often in the exact center) of this outlined circle, there would be very localized randomly distributed sites where tiny spots of melting had begun. If, at the same time, one could examine the opposing surfaces in contact with the electrodes, it would be apparent that the diameter of the electrode indentation is very nearly equal to the diameter of the area carrying the welding current at the common interface.

As the process proceeds beyond 0.05 second, a significant portion of the energy fed into the local volume provides the heat of fusion, causing the tiny sites of localized melting to grow, merge, and finally form the characteristic spot weld nugget. Again, the energy input must be sufficiently high for nugget growth to be sustained until the required diameter and penetration are obtained.

In the example given, if the rate of energy input that existed at the 0.05-second mark is sustained, the nugget will continue to grow. At 0.2 second, the nugget will be on the order of 0.190 in. in diameter and 0.043 in. in thickness. At this point, the welding current should be terminated, the liquid nugget allowed to solidify, the hot solid compacted to eliminate shrinkage voids, and the cooling rate controlled if necessary.

In 1951, the first quantity that could be measured throughout the progress of a single spot weld was identified and demonstrated (Roberts, 1955). In the words of the originator, "The total quantity of heat developed in a workpiece during the formation of a spot weld is a function of the work resistance. A knowledge of the variations of this parameter during the formation of the weld is therefore of interest and importance."

The parameter in question was termed "instantaneous resistance," which was defined as the ratio of the instantaneous value of the applied voltage to the current passing through a purely resistive conductor at the same instant in time.

This original work recognized the difficulty in measuring the voltage developed across the "load of the welder" (the voltage drop across the upper and lower electrodes, which includes the weld current path through the workpiece plus the electrode-workpiece contact resistances). This difficulty was ingeniously circumvented in a manner suitable for fundamental investigation, and curves showing the instantaneous resistance variation with time while spot-welding aluminum, 18-8 stainless steel, and low-carbon steel were presented.

Each material investigated exhibited a significantly different shape of the curve of instantaneous resistance versus time. It was concluded that the resistance of a workpiece was not constant during the formation of a weld, and its variation modulates the welding current waveform to a degree dependent on the electrical characteristics of both the workpiece and the welding machine.

Subsequent investigators have verified the characteristic changes in instantaneous resistance due to the passage of the welding current for a variety of engineering materials. Figure 4 shows the variation in instantaneous resistance with time for spot welds in four different materials. The curve for a high-temperature alloy, such as Inco 718, Hastalloy X, or René 41, would be similar to that shown for stainless steel but shifted upward because the instantaneous resistance values are higher.

The relationship between instantaneous resistance and many disturbing inputs has been investigated under controlled conditions. For the process variables examined, it was considered that only a change in either electrode force, edge distance, or electrode tip diameter is likely to cause a significant alteration in the slope of the instantaneous resistance curve for a given material. Finally, methods to automatically measure instantaneous resistance in the manufacturing environment were developed.

A second measurable quantity carrying information concerning real-time resistance spot-welding process performance was identified and demonstrated during 1954 (Farrell, 1954). The discovery of this parameter arose from the observation that the reciprocating upper electrode of a well-designed spot welder would move upward, against the clamping force, during each welding cycle. It was reasoned that this upward movement was caused initially by thermal expansion as the limited volume of metal clamped between the electrodes was driven to melting temperature early in the welding cycle, and then by the volumetric expansion due to the change in state while the local melting occurred. A sensitive device to continuously measure the upper electrode movement during the welding cycle was designed, built, and tested, and the hypothesis was confirmed.

The expansion parameter is a particularly sensitive measure of temperature rise because of the physical conditions that prevail from the initiation of current flow until the onset of melting. The welding current heats a finite cylindrical element of an infinitely larger mass. The cross-sectional area of this finite element carrying the welding current at any instant until the onset of melting is approximately equal to the electrical contact area; its length is equal to the total thickness of the pile-up. The heating rate of this cylindrical element is extremely rapid. In the example given, a two-thickness ply of 0.036 + 0.036-in. high-temperature alloy will be driven from room temperature to a peak of 2500^{o}F at the common interface in three cycles, or 0.05 second.

When the military specification edge distance is respected, the stiffness of the material in the plane of the sheets is extremely high. If the welding machine is properly designed, so that friction, excessive

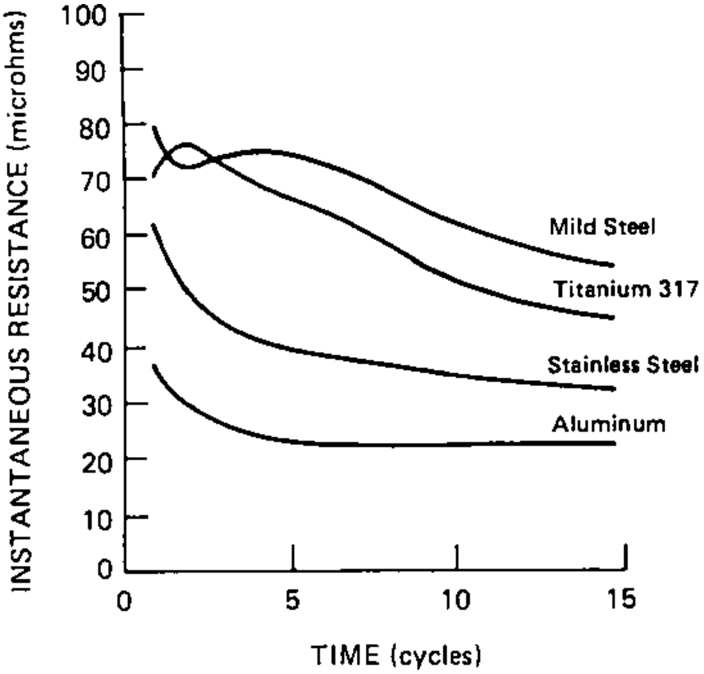


FIGURE 4 Variations in instantaneous resistance with time for various materials (Towey and Andrews, 1968).

inertial mass of the reciprocating member, and resistance to motion by the current-carrying shunts are not significant quantities in total, nearly the entire volumetric thermal expansion will occur along the axis of the cylinder and therefore will increment the reciprocating electrode upward, providing a sensitive and convenient transducer for measuring average temperature rise (average temperature because the extremely rapid heating rate causes relatively steep temperature gradients to exist both radially and axially).

The expansion measurement, given a suitably designed resistance welding machine, is therefore a function of temperature rise until melting begins and of weld nugget diameter during the latter portion of the welding cycle. The negative expansion after the weld is completed is a measure of weld nugget solidification, compaction, and cooling rate. By means of the latter condition, these phenomena may be matched to the metallurgical and thermal characteristics of the alloy being welded.

However, if the weld is placed too close to the edge of one or both of the sheets, the narrow edge ligament will yield when temperature rise weakens it enough so that thermal expansion in the horizontal direction requires less work than would be required to move the reciprocating electrode upward against the constant welding force. Under these circumstances, the expansion parameter is not a meaningful transducer of temperature rise. In addition, the expansion parameter is affected by changes in the value of the electrode force during the welding current flow period.

Investigators have found that the rate of change and/or the peak value of either of these measurable parameters can give useful information concerning the dynamic performance of the process. Consequently, various organizations have packaged systems incorporating measurement and classification of one of these parameters as a quality-monitoring device. Later, more ambitious systems, utilizing feedback and real-time adjustment of the welding current based on one or the other measurement, were marketed. Unfortunately, none of these relatively simple control systems was able to cope successfully with all the manufacturing variables encountered in the production environment. Therefore, human surveillance, destructive and nondestructive testing, and statistical quality control methods continue to be relied on by manufacturers who must meet military specifications or equivalent quality standards.

Recently, impelled by a management decision to automate the fabrication of sheet-metal assemblies for jet engines, one manufacturer constructed an analytical model of the resistance spot-welding process. The model was formulated to simultaneously investigate mechanical, electrical, and thermal parameters and their interaction. This model both unified and extended much of the previous analytical work, which first appeared as early as 1958. Building on the fundamental knowledge gained from the model, an industrial group developed a closed-loop adaptive control termed "SWAC" (spot-welding adaptive control). Interestingly enough, this system utilizes both the instantaneous resistance and the expansion measurements.

Spot-roll, spot, seam, and projection welding constitute the group of resistance welding processes in which the required heat at the joints to be welded is generated by the resistance offered through the workparts to the relatively short time flow of low-voltage, high-density electric current (American Welding Society, 1958). The process is extremely rapid. As a consequence, it has proved difficult to measure the significant parameters so as to define a control strategy. Simple controls are not adequate to cope with problems such as material or surface variations.

Electron and Laser Beam Welding

The possibility of welding in a vacuum by means of a beam of energetic electrons was first demonstrated in 1956 by Stohr at the Commissariat à l'Energie Atomique. At that time, the technology of the electron beam energy source already possessed a solid foundation. The pioneering work of Child on electron emission was accomplished in 1911 and of Langmuir on electron beam formation in 1913. At the time of Stohr's achievement, the electron beam was already being used for melting metals where high purity was required. Consequently, reliable precisely controlled welding equipment evolved rapidly as the equipment designers learned from the practice of the process.

In contrast, laser welding technology did not have the advantage of extensive development of the fundamental apparatus prior to its application as a welding energy source. It was 1960 before Maiman achieved the first operating laser--a low-power ruby rod type excited by a helical flash lamp. The first industrial CO_2 laser was built in 1966.

Since it was clear that the laser beam can also be concentrated to produce a high-energy-density heat source, it was ultimately placed in competition with electron beam welding. The perceived advantage of the laser was its potential for producing high depth-to-width-ratio welds in atmosphere, as opposed to the vacuum environment required by the electron beam process. By necessity, the major effort has been directed toward the development of increasingly more powerful energy sources, with a relatively low level of process technology maturation as a result.

The major welding applications for multikilowatt laser welding are found in the automotive industry. Here, the flexibility and ability of the beam to travel through atmosphere without significant dispersion simplifies automation and results in high productivity. Many applications are identified where complex geometries are reduced to simple-to-manufacture components that are joined together without distortion by the narrow laser weld. Very frequently, the total welded area is orders of magnitude larger than required to carry the maximum imposed service load. Eliminating the pumpdown time required for electron beam welding results in increased throughput and comparable or lower capital costs for applications requiring up to about 5 kW of laser power.

For full-penetration welding up to a thickness of perhaps 0.200 in., there is a close similarity in electron beam and laser welding.

For high-quality welding, electron beam welding has an edge for some applications because of the beneficial metallurgical effects of the vacuum environment. However, the application of gas environments has narrowed the gap.

For many difficult-to-weld materials and tapered or variable-section-thickness joints, the ability to focus and deflect the electron beam in various patterns by the application of electromagnetic fields and the rapid rate at which beam power can be changed by bias control represent unique advantages for electron beam welding, given the present state of the art.

There is a considerable body of experience with deep-penetration welding utilizing the electron beam. This experience has shown, for example, that the shape of the weld transverse cross section is a critical parameter when developing a procedure to produce a defect-free weld in a given alloy. If the cross section has essentially parallel sides, the probability is high that weld metal voids or solidification cracking are not present. On the other hand, if the weld is wide at the top, necks down at some lower level, widens and then narrows again at the root (like an upside-down Coca-Cola bottle), shrinkage voids and/or solidification cracking can be expected. A simpler geometry--wide top tapering to a narrow stem toward the root (shaped like a wine glass without its base)--is prone to solidification cracking and root porosity, especially when welding many of the more complex alloys.

Electron beam designers have learned to reduce the beam divergence to a minimum when designing electron guns for heavy section welding. Process engineers have learned to place the focal plane of the electron beam below the midplane of the work thickness in order to obtain favorable weld geometry. These techniques, often in combination with beam oscillation, allow the development of procedures to produce deep-penetrating welds in plate thicknesses up to at least 5 in. without internal defects.

Electron beam and laser energy sources can both generate sufficiently high power density to produce deep penetrating welds in the keyhole mode. Nevertheless, there are significant differenes in welding capability for the two systems. These differences are the result of several circumstances. First, electron beam welding is conducted in a vacuum. The plasma generated by the interaction of the energetic electrons in the beam and the metal vapors produced by the beam tunneling through the thickness of the workpiece expand so rapidly in the vacuum environment that they do not interfere with the transmission of energy from the incident beam to the workpiece. On the other hand, laser welding is practiced in the atmosphere The plasma plume is relatively localized and thus absorbs energy from the incident beam, reducing the fraction transferred to the work. Progress is being made in methods to effectively disburse the plasma and thus reduce the severity of this problem, but still more effective methods need to be developed.

The second circumstance is related to the physical nature of the photon beam, as compared with the electron beam, and to the maturity of apparatus development. Electron beams for welding are accelerated by potential gradients between 60 and 150 kV At 60 kV, the electrons in the beam exhibit an equivalent wavelength of 4.86×10^{-4} µm, whereas the CO_2 laser produces a beam of 10.6 µm. Thus, electron beams achieve the specific power necessary for deep penetration welding with small aperture angles, while relatively large angles are required for the beam produced by the high-power cross-flow CO_2 laser.

The relatively large convergence angle of the laser beam introduces difficulties in developing procedures that produce essentially straight-sided welds free of defects in heavier thicknesses. The focal plane of currently available high-power lasers must be positioned on or very close to the surface of the workpiece in order to attain deep penetration welding. Therefore, weld cross-sectional geometry is strongly influenced by the beam convergence angle, which in turn determines the nature of the multiple reflections within the cavity. As a consequence, increasing welding speed becomes the principal means for improving weld geometry. It appears that, if the advantages of laser welding are to be extended to weldments of increasing thickness, the brightness of the source must be improved.

Finally, the spatial distribution of power in the beam produced by high-power lasers of current technology is not radially symmetrical. Such asymmetry is not acceptable in contour welding.

Thus, if the experience in applying electron beams for welding is relevant, the welding range of the laser will be extended by the introduction of devices producing a beam of shorter wavelength. The high-power "EXIMER" laser currently under development is an indication of what the future may hold in store.

Electron beam and laser welding offer numerous challenges for future research. Increasing the tolerance to fit-up, understanding metallurgical implications, and optimizing the utilization of energy are examples. The interaction of these high-energy-density beams with the metal of the workpiece produces free electrons, positive and negative ions, plasma, photons, and x-rays. Furthermore, some fraction of the incident beam passes completely through the cavity produced during deep penetration welding. It has already been shown that the penetration achieved in electron beam welding can be controlled by measuring the through current and maintaining it at a constant value by feedback control. It is probable that the particles and/or radiation produced by the beam-workpiece interaction carry information that can be exploited to achieve completely adaptive control.

SENSORS FOR IMPORTANT PROCESS VARIABLES

In reviewing the various welding processes, it becomes clear that sensing important process variables is a key ingredient to future progress in welding controls development. The following are some areas for investigation:

1. Smart integrated instrumentation that integrates sensor outputs and the process model into conventional sensing devices to provide direct output of welding process variables.

2. Low-cost process versions of infrared sensors, including emissivity information.

3. A means of measuring the voltage drop across the arc voltage directly, independent of contact tube design, which would provide an independent measure of true arc voltage.

4. Real-time nondestructive testing to provide timely information for quality control. This would be particularly useful for multi-pass welding.

5. Real-time sensors for sensing pool geometry and for guidance. Research should include ultrasonic, optical, eddy current, infrared, x-ray, and acoustic emission methods.

6. Ultrasonic sensor research, including geometry, guidance, phase changes and boundaries, residual stress, and cooling rates. There are fundamental problems to be solved, such as the effects of temperature, signal processing, sound propagation path, and sorting.

7. High-energy-beam process sensors to track formation and explosion of plasma in atmosphere for lasers and in vacuum for electron beam processes and to measure beam power spatial distribution and aperature angle.

8. Sensors for centerline defects, for fit-up, and for gap control.

9. The measurement and tracking geometry of square butt joints.

Weld bead morphology, location, and microstructure must be controlled within prescribed limits for satisfactory welds. Although still in development, sensors and controls exist for seam tracking, i.e., weld bead location control. There are no real-time systems that will sense and control weld bead morphology. However, basic research has shown that ultrasonic transducers have strong potential for sensing bead shape as well as defects. Direct sensing and control of microstructure are probably far in the future. However, indirect control should be possible if models of solidification dependence on alloy chemistry and energy input are well understood.

PROCESS MODELING

To properly understand the process of welding, all of the diverse physical processes involved must be analyzed and quantified. This then allows prediction of welding outcome from process inputs, evaluation of the effect of weldment design changes, and process innovation. Such analysis must, therefore, consider the plasma physics, pool fluid dynamics and electromechanics, system heat transfer, and metallurgical effects of welding. Welding research for the past 80 years has addressed many of these issues, and modern numerical techniques are allowing specific solutions to be reached. However, the problems of uncertain material properties and boundary conditions, and the simplifications necessary because of the complex geometries involved, have kept such models removed from the role of precise process outcome prediction (i.e., open-loop control).

However, with the limited goal of real-time closed-loop control of the welding process, a more restricted and simplified modeling paradigm can be followed. In this methodology, here referred to as "control modeling," the basic assumption is that closed-loop process regulation will be the context of the model application. This being the case, the requirements of the model shift from strict physical fidelity at a microscopic level to macroscopic accuracy over the range of interest. While this sounds like the definition of a classical engineering empirical model, there are some important differences.

Since all existing control theory requires a linear, lumped parameter description of the process to be controlled, there is an immediate restriction on the form of mathematical description of the process. However, the physics of welding is fundamentally a nonlinear, distributed parameter system, so the modeling dichotomy is clear. At least two choices exist: (1) ignore the physics and construct a linear input-output relationship for the process that correctly predicts the outcome of certain experiments (i.e., the strictly empirical approach) or (2) construct a linear lumped parameter model based on a simplified physical description of the process that also correctly predicts the outcome of a process. The important distinction here is that the latter approach can be extrapolated to a wider range of operation and even to diverse processes with a predictable result. This is because the physical basis for the model provides the basic causality or input-output relationships for the process.

This grounding in the basic physical mechanism can be achieved in several different ways. A classical engineering analysis approach is the most straightforward and often leads to a complex but comprehensive description of the process. But this area of welding has so far proved too difficult and complex for such a complete model. However, the technique mentioned can be used even if several parts of the complete model are lacking in detail but are understood in general. For example, if the effect of current pulsing is known to increase the circulation in the weld pool, thereby influencing the heat transfer and in turn the weld penetration, but the exact mechanism is unknown, this information is still sufficient to construct a control model of the process.

In modeling the welding process it is important to recognize that, for a given process and alloy system, it is necessary to experimentally sort out relationships between processes and materials that will guide model development. Also, process models should be developed that can be solved for either process parameters (process control) or for weld properties (computer-aided design). Models must be confirmed experimentally and the experiment-model cycle iterated as necessary. In addition, changes in welding processes and alloy systems having different melting and solidification characteristics will require new or revised models.

When control of welding processes is considered, it soon becomes evident that the control system must respond to conditions that are determined by the myriad processes that precede the actual welding step. Taken to its source, all of these processes respond to the demands of the basic weldment design. This suggests that, while the influence of real-time sensing and computer control of the process is being studied, the impact of a fully integrated design and manufacturing system for welding should also be studied. Such a system for welding has the objective of presenting the maximum amount of accurate manufacturing information to a designer so that explicit, well-founded design decisions can be made. The fact that the actual process of welding will be automated allows the modeling and design simulation of this step to be more accurate than if the models had to capture the individual skills of accomplished welders. However, it does require that the manipulation hardware necessitated by automation be accounted for in the design. This concept was exemplified earlier in Figures 1 and 3.

Following the typical mold of computer-aided manufacturing, the system that is envisioned would work from the geometry data base provided by the designer and then apply a series of analyses to assess the quality of the design and the manufacturability of the parts. However, because of the complex interaction of the various stages of weldment preparation and the sensitivity of the mechanics of the final part to the way in which it is processed, a fully integrated design and manufacturing system for welding must do much more in the way of analysis and simulation than the typical CAD/CAM system for machined parts.

For example, in the weldment preparation it is necessary to specify a geometry for the edge to be welded. In addition to various machined configurations (i.e., square butt, "V" or "J" grooves), which can be rather easily quantified, there is the class of weldments that use flame-cut edges. Here the effectiveness of the design is coupled to the attainable quality of the basic edge preparation method. If the design system can assess the ultimate quality of the weld when given a specified preparation method, the designer can then more accurately judge the design options.

Coupled to joint preparation geometry is the total joint geometry or fit-up that is also a strong function of the shape of the basic components. If it is a basically flat part, then it is the flatness of the stock material and the quality of the fixturing that is of importance to fit-up. Anticipated thickness variations can also be critical for assessing the ultimate part quality. If the weldment components are to be formed before welding, then it is likewise necessary to know how well they will be formed and what type of fixturing will be necessary.

The fixturing, which is typically designed at the time of manufacture, should also be integrated into the design package. (This is an excellent example of where a designer can extend his or her influence into the manufacturing realm, thereby avoiding costly upstream errors.) By providing the analytical tools in a design context, the fixturing can be specified to provide appropriate joint stability, heat sinking, and torch manipulation with appropriate clearance. Clearly, if the fixturing cannot be designed, it is an indication that the part itself may need redesign. Here the real power of the CAD/CAM system becomes evident, since such a discovery can be easily accommodated at the design phase. On the other hand, if the need for redesign is not uncovered until the part is in manufacturing, the cost of redesign can be staggering.

All of this manufacturing information to be presented to the designer can be thought of as welding process simulation. This would be a comprehensive simulation in that it would include all of the coupled effects involved in the process: weldment preparation, fixture design, thermal analysis (e.g., for distortion analysis), and finally a mechanical and metallurgical analysis of the simulated welded part to assess expected tensile strength, toughness, and fatigue strength. By including all of these considerations in a simulation, the designer becomes aware of all of the ramifications of design choices and can truly optimize the design.

However, the fidelity of manufacturing simulations, particularly those for welding, will always be less than perfect. Thus it would be necessary to provide a means for updating the analytical sections of the system and the associated data bases by feeding back information from the actual manufacturing processes. This is quite often the best way to provide information as to expected quality or process-property effects. It also keeps the designer in contact with reality.

The development of such a system will require a strong analytical effort in process physics. The real goal is to accurately capture the physical processes in welding in a form that will be useful to a designer. This actually charts a road somewhat between the analytical needs for basic process understanding and models for process control. Since the simulations are used to present accurate information about existing situations, they need not have the ability to allow study of process variations, but they must capture the unknown effects of unique combinations of design options. Clearly the basis for simulations will be in the fundamental studies of welding and allied processes, but the successful researchers will be those who can correctly assess the needs of the simulation and the efficiency of its implementation versus the dependence on complete, intricate physical detail.

There is also a significant indirect benefit of such a comprehensive system that goes well beyond those stated here. If a single person (the "designer") can have rapid access to complete welding design and manufacturing information, and it is presented in the form of simulated part manufacturing and testing, then the educational value alone makes such a system worthwhile. The excessive fragmentation of engineering effort and the resulting lack of experience in most engineers is an area where computer-based analysis and simulation must have its most significant impact. By placing all of the consequences of a design choice before the individual making those choices, and by incorporating actual manufacturing data in the system, the experience and insight of the designer will rapidly accumulate.

In regard to welding process control, the impact of a CAD/CAM system for welding is great. In the simplest case, the welding process will be easier to execute and the need to accommodate uncertainties will be reduced because of superior, comprehensive weldment and weld processing design. In addition, the critical areas of a particular weld can be identified and called to the attention of the control system so that disturbances can be "previewed." The information from the sensors used in the control systems and the control actions taken to maintain a good weld can also be the primary source of updating information to a CAD/CAM system, and this, too, may affect how the control system is constructed.

REFERENCES

American Welding Society. 1958. Welding Handbook, Fourth Edition. A. L. Phillips, ed. Miami, Florida: American Welding Society.

Farrell, W. J. 1954. A Proposed New Method for the Control of the Electric Resistance Welding Process. Internal document of Sciaky Brothers, Inc., Chicago, Illinois (August 19).

Roberts, W. L. 1955. Resistance Variations During Spot Welding. Welding Journal, Research Supplement (November).

Towey, M., and D. R. Andrews. 1968. Instantaneous resistance during spot weld formation as a parameter for an automatic control system. Welding and Metal Fabrication (October).

BIBLIOGRAPHY

Apps, R. L., and J. Ma. 1982. MIG transfer discovery of importance to industry. Welding and Metal Fabrication, Vol. 50, No. 7, pp. 307-16.

Balchin, N. A. 1970. Programmed Metal-Arc Welding--A Practical Approach to Automation. Pp. 106-10 in Advances in Welding Processes. The Welding Institute.

Blackmon, D. R., and F. W. Kearney. 1983. A real time approach to quality control in welding. Welding Journal, Vol. 62, No. 8, pp. 37-9.

Bollinger, J. G., and P. W. Ramsey. 1979. Computer controlled self-programming welding machine. Welding Journal, Vol. 58, No. 5, pp. 15-21.

Bollinger, J. G., and H. L. Harrison. 1971. Automated welding using spacial seam tracing. Welding Journal, Vol. 50, No. 11, pp. 787-95.

Cary, H. B. 1979. Modern Welding Technology, pp. 31-33. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

Chin, B. A., N. H. Madsen, and J. S. Goodling. 1983. Infrared thermography for sensing the arc welding process. Welding Journal, Vol. 62, No. 9, pp. 227s-34s.

Cook, G. E., et al. 1982. Analyzing Arc Welding Signals With a Microcomputer. Pp. 1282-88 in the October 4-8, 1982 Conference of the IEEE Industry Applications Society.

Cook, G. E. 1980. Feedback and Adaptive Control of Process Variables in Arc Welding. Pp. 32.1-32.9 in Developments in Mechanized, Automated and Robotic Arc Welding. The Welding Institute.

Eagar, T. W. 1980. Automated Welding--Research Needs. Pp. 487-96. in Papers Presented at the August 3-8, 1980, AIME Symposium.

Essers, W. G., and R. Walter. Heat transfer and penetration mechanisms with GMA and plasma-GMA welding. Welding Journal, Vol. 60, No. 2, pp. 37s-42s.

Essers, W. G., and R. Walter. 1979. Some Aspects of the Penetration Mechanisms in Metal-Inert-Gas (MIG) Welding. Pp. 289-300 in Arc Physics and Weld Pool Behavior. The Welding Institute.

Glickstein, S. S. 1979. Arc Modelling for Welding Analysis. Pp. 1-16 in Arc Physics and Weld Pool Behavior. The Welding Institute.

Goldberg, F., and R. Karlen. 1980. Inductive Seam-Tracking and Height-Sensing Systems for Arc Welding Methods and Thermal Cutting. Pp. 24.1-24.7 in Developments in Mechanized, Automated and Robotic Arc Welding. The Welding Institute.

Halmoy, E. 1979. Wire Melting Rate, Droplet Temperature, and Effective Anode Melting Potential. Pp. 49-57 in Arc Physics and Weld Pool Behavior. The Welding Institute.

Heitmayer, U., and K. Weman. 1980. Opportunities in Adaptive Control of Welding Robots by the Effective Use of Sensors. Pp. 42.1-42.9 in Developments in Mechanized, Automated and Robotic Welding. The Welding Institute.

Hunter, J. J. 1980. On-Line Control of the Arc Welding Process. Pp. 37.1-37.12 in Developments in Mechanized, Automated and Robotic Arc Welding. The Welding Institute.

Hunter, J. J. 1978. Automation of arc welding. The Industrial Robot, Vol. 5, No. 1, pp. 27-31.

Inoue, K. 1980. Simple Binary Image Processor and Its Application to Automatic Welding. Paper FA7-3 presented at the August 13-15 IEEE 1980 Joint Automatic Control Conference, Vol. II.

King, F. J. 1978. Seam Tracking Systems with the Arc As Sensor. Pp. 193-202 in Advances in Welding Process. The Welding Institute.

Kuhne, A. H., B. Frassek, and G. Starke. 1984. Components for the automated GMAW process. Welding Journal, Vol. 63, No. 1, pp. 31-34.

Lesnewich, A. 1958. Control of melting rate and metal transfer in gas-shielded metal arc welding, Part 1--control of electrode melting rate. Welding Journal, Vol. 37, No. 8, pp. 343s-53s.

Morris, G. J., and R. L. Apps. 1977. Programmed control of MIG welding parameters. Welding and Metal Fabrication, Vol. 45, No. 8, pp. 487-93.

Miller, K. J. 1980. Robot Arc Welding at Caterpillar Tractor Company. Pp. 39.1-39.9 in Developments in Mechanized, Automated and Robotic Welding. The Welding Institute.

Mishler, H. W., and R. E. Monroe. 1974. An optical sensor for adaptive control of the welding arc. Welding in the World, Vol. 12, No. 7, pp. 183-94.

Masaki, I., et al. 1980. Welding Robot With Visual Seam Tracking: Unika-80A. Pp. 12.1-12.8 in Developments in Mechanized, Automated and Robotic Welding. The Welding Institute.

Needham, J. C., C. J. Cooksey, and C. R. Milner. 1960. Metal transfer in inert gas shielded arc welding. British Welding Journal, Vol. 7, pp. 101-14.

Nied, H. A. 1984. The Finite Element Modeling of the Resistance Spot Welding Process. Pp. 123s-132s in Welding Research Supplement. Miami, Florida: American Welding Society.

Renwick, R. J., and R. W. Richardson. 1983. Experimental investigation of GTA weld pool oscillations. Welding Journal, Vol. 62, No. 2, pp. 29s-35s.

Spynu, G. A. 1980. Problems of Development and Application of Industrial Robots for Arc Welding. Pp. 20.1-20.8 in Developments in Mechanized, Automated and Robotic Welding. The Welding Institute.

Solomon, H. D., and L. P. Harris. 1983. Minor Element Effects on Gas Tungsten Arc (GTA) Weld Penetration. Pp. 161-163 in Production Research and Technology. Warren, Michigan: Society of Automotive Engineers.

Weinschenk, H. E., and M. Schellhase. 1979. Statistical Analysis of Arcing Voltage in the CO_2 Welding Process. Pp. 241-49 in Arc Physics and Weld Pool Behavior. The Welding Institute.

Waszink, J. H., and L. H. J. Graat. 1983. Experimental determination of the forces acting on a drop of weld metal. Welding Journal, Vol. 62, No. 4, pp. 108s-16s.

Waszink, J. H., and G. J. P. M. Van den Heuvel. 1982. Heat generation and heat flow in the filler metal in GMA welding. Welding Journal, Vol. 61, No. 8, pp. 269s-82s.

Waszink, J. H., and G. J. P. M. Van den Heuvel. 1979. Measurements and Calculations of the Wire Extension in Arc Welding. Pp. 227-39 in Arc Physics and Weld Pool Behavior. The Welding Institute.

Wright, R. R. 1980. Welding Automation in Action. Pp. 13.1-13.8 in Developments in Mechanized, Automated and Robotic Welding. The Welding Institute.

Yokoshima, N., and H. Takagi. 1980. On-Line Adaptive Control of Narrow Gap CO_2 Welding With Industrial Television Camera. Paper FA7-F presented at the the August 13-15 IEEE 1980 Joint Automatic Control Conference, Vol. II.

Zacksenhouse, M., and D. E. Hardt. 1983. Weld pool impedance identification for size measurement and control. Journal of Dynamic Systems, Measurement, and Control, Vol. 105, pp. 179-84.

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

JOHN S. AHEARN is Manager of the Materials and Surface Science Department at Martin Marietta Laboratories. He received his B.S. degree from St. Lawrence University and M.S. and Ph.D. degrees in physics from the University of Virginia. His research has focused on solid-state physics and the weldability of discontinuous reinforced metal matrix composites.

JOHN G. BOLLINGER, the committee chairman, is Dean of the College of Engineering and Bascom Professor at the University of Wisconsin, Madison. His principal interest is in computer control of machines and processes and computer-integrated manufacturing systems. He was a Fulbright Research Fellow in Germany and later in the United Kingdom. He is a member of the National Academy of Engineering and serves on several corporate boards.

JAMES M. CAMERON's expertise is in welding. Starting as a welder, he developed gas metal arc automatic welding equipment at Westinghouse Electric Company and welding processes at ACF Industries before moving to Electric Boat Division of General Dynamics Corporation, where he is now employed. A graduate of the University of Buffalo, he is a member of the American Welding Society, having served two terms as director. He also is a representative to the English Welding Institute and a member of the Curriculum Advisory Committee of the Wentworth Institute.

HOWARD B. CARY is a graduate of Ohio State University. He supervised welding at Fisher Tank Division during World War II and at Marion Power Shovel Company. During 1946-48 he engaged in welding research at Battelle Memorial Institute. At present he is Vice President, Welding Systems, at Hobart Brothers Company Technical Center.

WILLIAM J. FARRELL has been with Sciaky Brothers, Inc., for 40 years, where he is now Senior Vice President. His previous experience was with Consolidated Edison and Grumman Aircraft. His principal expertise is in high-energy beam and resistance welding processes.

DAVID E. HARDT is a professor in the Mechanical Engineering Department at Massachusetts Institute of Technology, doing research in the application of system dynamics and control of batch manufacturing processes. He is a Ph.D. graduate in mechanical engineering from MIT and is a member of the American Society of Mechanical Engineers and the Institute of Electrical and Electronics Engineers.

JOHN F. HINRICHS is currently manager of the Manufacturing Technology Lab at A. O. Smith Automotive Products Company. He has a BSME in mechanical engineering from Marquette University and a MSME in metallurgical engineering from the University of Wisconsin. He is a registered professional engineer in Wisconsin and a certified manufacturing engineer. He is a member of the American Welding Society, the American Society for Mechanical Engineers, the American Society of Metals, and the Robotics International Society of Manufacturing Engineers.

JAMES F. KEY received his degrees in mechanical engineering from the University of Texas, Austin. After varied experience in industry and academia, he joined the Idaho National Engineering Laboratory where he is now Manager of the Materials Processing Branch. He assists in technical papers review for the American Welding Society.

MILTON D. RANDALL is a graduate of the University of Texas, Austin, and recent past president of the American Welding Society. He is currently Vice President for Research and New Product Development at CRC/Evans Automatic Welding Company.

RICHARD W. RICHARDSON was educated at the University of Kansas and the University of Colorado, followed by 2 years as National Research Council Postdoctoral Fellow at the NASA Lewis Research Center. At present he is a member of the Robotics Coordinating Committee, and Associate Professor in the Department of Welding Engineering at Ohio State University. Active in the American Welding Society he is on the Welding Research Council Automation Committee, a reviewer for the Journal, and a member of the Institute of Electrical and Electronics Engineers and the Society of Manufacturing Engineers.