ARTICLE

Current Issues and Problems in Welding Science

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Losses of life and property due to catastrophic failure of structures are often traced to defective welds. However, major advances have taken place in welding science and technology in the last few decades. With the development of new methodologies at the crossroad of basic and applied sciences, the promise of science-based tailoring of composition, structure, and properties of the weldments may be fulfilled. This will require resolution of several contemporary issues and problems concerning the structure and properties of the weldments as well as intelligent control and automation of the welding processes.

In the last 20 years, the growth of modern welding science and technology has been phenomenal. Worldwide, welding is a multibillion-dollar fabrication technology used extensively in the construction of buildings and bridges and in the automotive, aircraft, aerospace, energy, shipbuilding, and electronic industries. Perhaps because welding is a construction technique, it is viewed by many as a primitive science. Nothing could be further from the truth. In the last several decades, welding has evolved as an interdisciplinary activity requiring synthesis of knowledge from various disciplines and incorporating the most advanced tools of various basic and applied sciences. Scientists from diverse disciplines such as arc and plasma physics, thermodynamics, high-temperature chemistry, materials science, transport phenomena, mathematical modeling, computer science, robotics, economics, and a variety of engineering fields including mechanical, chemical, and electrical engineering are currently making new contributions.

The practice of welding dates from prehistoric times, when people soldered with copper-gold and lead-tin alloys (*1*). The development of modern welding technology began in the latter half of the 19th century (Fig. 1) when electrical energy became readily available (*2*). Various welding processes have been defined based on the type of heat source. In the last few decades, the development of new, high-intensity heat sources such as electron beams and lasers has facilitated welding of high melting point metals and alloys and has provided further impetus for the growth of welding. In a broad sense, welding includes the formation of metallurgical bonds in welded, brazed, and soldered joints and excludes joints made by mechanical means or with adhesives. In brazing and soldering, used extensively in electronic packaging and for joining small areas, the bonding takes place by the melting and solidification of the brazing or the soldering alloy. No fusion of the parts takes place. This article focuses on conventional fusion welds in which the joining involves melting and solidification of the parts.

Depending on the thickness of the metal and the method used, welding may involve single or multiple passes of the heat source on the joint with or without the addition of a filler metal. The welded joints vary in length from small spots in automotive and electronic industries to tens of meters for shipbuilding and aerospace applications. Parts range in thickness from a fraction of a millimeter to tens of centimeters. The time necessary for welding ranges from a fraction of a second to several days. The post-weld cooling rates vary from less than 100°C to several million degrees Celsius per second. The flexibility of the length scales, time scales, temperature gradients, and cooling rates and the uniqueness and complexity of the physicochemical phenomena involved in welding, especially the presence of an electrically conducting gas plasma in many welding processes, often preclude meaningful and straightforward application of knowledge of other materials-processing operations to understand welding.

The interaction of the material and the heat source leads to rapid heating, melting, and vigorous circulation of the molten metal driven by buoyancy, surface tension, and, when electric current is used, electromagnetic forces. The resulting heat transfer and the thermal cycle determine the structure and properties of the weld metal (*3*). For repetitious welding tasks, the relative motion between the pieces being welded and the heat source is predetermined, programmed into a computer, and achieved with the help of a suitable robot often capable of multi-axial motion. During welding, the location and the size of the weld pool and other important parameters are followed by an appropriate tracking system, often based on infrared or optical emissions to obtain precise welding. Because of a high-intensity heat source, an electrically conducting gas plasma forms near the weld pool. The light emission from the plasma is a useful tool in monitoring metal vapor emissions from the weld pool (*4*) and is therefore important for health and environmental safety. In addition, the optical data have been used to estimate the energy reaching the workpiece in laser welding (*5*) and to estimate the electrical conductivity of the arc in gas-tungsten arc welding (*6*).

This article examines significant recent advances in welding science. In the last few decades, major progress has been made in (i) understanding physical processes, (ii) understanding structural evolution and the correlation between microstructure and properties of the welds, and (iii) intelligent control and automation of welding. However, technological advances and continuing interdisciplinary research on welding have brought new issues and problems to the surface. A substantive discussion of the issues, problems, and their eventual resolution, apart from contributing improved understanding and control of welding pro-

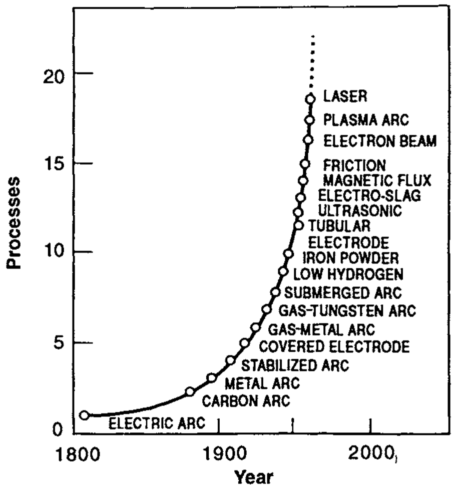

Fig. 1. Growth of welding processes since electrical energy became readily available [reprinted from (*2*) with permission, © 1963 American Welding Society]. The processes are defined based on the source of energy.

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cesses and welded materials, is also important for several other materials-processing operations, especially those requiring application of high energy density heat sources. The significant progress made in welding science suggests that welding processes based on science may be designed to tailor the composition, structure, and properties of the welded materials in a practical way. However, substantive issues and problems must be addressed and new methodologies must be developed before the dream becomes a reality.

Physical Processes

There are several regions of interest in the welding process (Fig. 2). In the weld pool, the metal undergoes vigorous recirculatory motion driven by buoyancy, electromagnetic, and surface tension forces. Buoyancy effects originate from the spatial variation of the liquid metal density mainly because of temperature variations and, to a lesser extent, from differences in local composition. Since large variations in temperature are present in the weld pool, the corresponding density gradients produce convective flows. Electromagnetic effects result from the interaction between the divergent current path in the weld pool and the magnetic field it generates. The effect is important when a large electric current passes through the weld pool. The spatial variation of the surface tension owing to temperature and composition gradients at the weld pool surface often provides the main driving force for the convective flow, known as the Marangoni flow. Depending on the interplay between the various driving forces, the convective flow can be a simple recirculation or a complex pattern with several convective cells operating (Fig. 3) (*7*). Fluid flow and heat transfer are important in determining the size and shape of the weld pool and the weld macro- and microstructures (*8, 9*).

The heat conduction models (*8*), traditionally used for the prediction of the weld pool geometry, the temperature fields, the cooling rates, and the simple features of the solidification structure, are being increasingly replaced by more accurate models that account for convective heat transfer (*9*). Indeed, the modeling of heat transfer, fluid flow, and mass transfer has already provided detailed insight into the welding processes that could not have been obtained otherwise. Currently, there are at least two main difficulties in using mathematical modeling to solve welding problems. First, because the welding processes are highly complex, a fully comprehensive model of weld pool heat transfer and fluid flow requires extensive calculations. Consequently, one has to consider the level of simplification that can be tolerated for a particular application. Three versus two dimensions, a transient versus a steady state, a flat weld pool surface versus a free deformable surface, and a laminar structure of flow in the weld pool versus a turbulent flow using turbulence models of different degrees of sophistication must be considered in designing simulations. While it is expedient to weigh heavily in favor of a particular set of simplifications because of the availability of existing software packages or other computational conveniences, the consequences of such choices vary depending on the goals of the simulation effort. Mathematical modeling is a powerful tool to understand the development of weld pool geometry and other welding parameters. However, in view of the complexities of the welding processes, attempts to understand them through simulation must involve well-designed and concomitant experimental work to validate the models.

A more fundamental limitation is imposed by the lack of necessary thermophysical data. Our existing database of high-temperature materials properties was developed to a large extent to understand the manufacturing and subsequent processing or use of metals and alloys. Unlike welding, these operations seldom involve temperatures much above the melting point of metals. Furthermore, in most processing operations the environment does not contain plasma. In contrast, in many welding operations the peak temperature in the weld pool can reach close to the boiling point of the metal and a plasma plume surrounds the weld metal (*10*). Plasma lowers the interfacial tension of pure metals. However, the temperature coefficient of surface tension is not significantly affected (*11*). Thermophysical data for such high-temperature systems are scarce, especially for systems containing plasma. Thus, in addition to the difficulty in developing a rigorous simulation of the highly complex welding process, the lack of appropriate thermophysical data often impedes an in-depth understanding of this process.

Variable depth of penetration during the welding of different batches of a commercial material with composition within a given prescribed range has received considerable attention. Previous work has shown that knowledge of the interfacial phenomena in welding (*12*) is the key to understanding and controlling weld penetration. Oftentimes, the penetration depth is determined by the concentration of the surface active elements in the commercial alloy (*13*). These elements can affect the temperature coefficient of surface tension and the result-

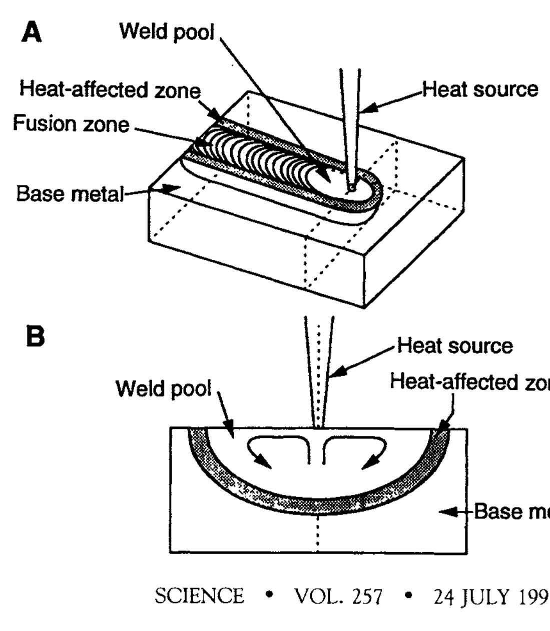

Fig. 2. Schematic diagram showing interaction between the heat source and the base metal. (**A**) Three distinct regions in the weldment: the fusion zone, the heat-affected zone, and the base metal. (**B**) The recirculatory motion within the weld pool.

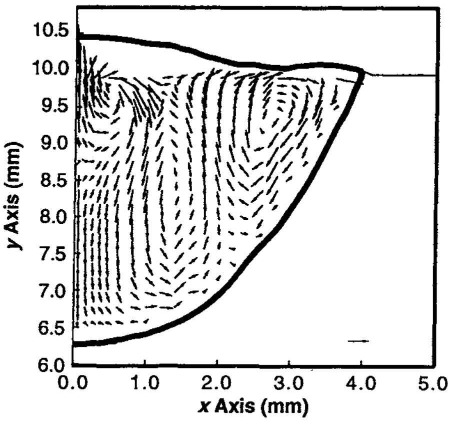

Fig. 3. Calculated fluid-flow pattern in a stationary arc weld [reprinted from (*7*) with permission, © 1991 The Minerals, Metals and Materials Society and ASM International]. The results show computed flow pattern in a stainless steel weld pool 25 s after the initiation of the arc. The flow is driven by buoyancy, surface tension, and electromagnetic forces. Several vortices are shown. Scale velocity vector in lower right, 0.1 m/s.

ing direction of fluid flow in the weld pool (*14*). The convective heat transfer, in turn, affects the weld penetration. Appropriate thermophysical data would be of significant value in the reliable prediction of weld penetration.

In submerged arc welding, an important function of the welding flux is to protect the weld metal from exposure to oxygen, nitrogen, and moisture in the environment. Traditionally, in systems involving a molten metal and an ionic melt such as the welding flux, the feasibility of a chemical reaction is determined by a straightforward application of thermodynamics. Although the thermodynamic calculations do not provide any information about the reaction rates, many reactions take place rapidly at temperatures commonly encountered in welding. Under such conditions, the equilibrium calculations can point to trends in weld metal composition changes (*15*). However, the reaction times are short in welding systems. The kinetic factors are important in determining how fast the thermodynamic equilibrium is approached (*16*). Beside reactions between the weld metal and the flux, electrochemical reactions can contribute to the changes in the composition of the weld metal (*17*). Because the voltages used in the welding process are sufficiently high for the flux to decompose electrochemically, electrolysis of reducible compounds in the flux can add elements to the weld pool. Although the importance of the welding consumables in general and the welding flux in particular is now well recognized, scientific understanding of their roles is still evolving.

The dissolution of hydrogen, oxygen, and nitrogen in the weld metal affects weldment properties. The gases may dissolve interstitially in the weld metal, whereupon they escape to form pinholes or bubbles or combine with elements in the alloy to form inclusions. In the welding of steels, hydrogen induces cracking, nitrogen increases the yield strength and the tensile strength but reduces the ductility, and oxygen promotes inclusion formation. When a metal is exposed to a pure diatomic gas such as hydrogen, the concentration of the species in the metal is proportional to the square root of its partial pressure at any given temperature (*18*). However, near the weld pool surface, beside common diatomic molecules, excited molecules, atoms, and ions are also present in the gas plasma. As a result, the interstitial concentrations in the weld metal are significantly higher than those calculated (*19*). Physical modeling of nitrogen partition between isothermal drops of pure metals and nitrogen plasma showed that the formation of excited neutral atoms and ions from various inelastic electron impact reactions in the gas phase is the main cause of enhanced nitrogen solubility (*20*). A general principle for understanding the partition of hydrogen, oxygen, and nitrogen between the weld pool and its environment remains to be developed.

The weld pool surface temperatures are normally much higher than the melting points of the weld metals. Consequently, pronounced vaporization of alloying elements takes place, especially when high energy density heat sources are used (*21*). Such losses often change the composition of the weld metal, affect weld properties, and are a serious problem in the welding of many important engineering alloys (*22*). The weld metal composition change depends on the vaporization flux and the surface-to-volume ratio of the weld pool, the latter often being the dominant factor. Although the rate of vaporization increases with laser power, the composition change is most pronounced at low powers because of the small size and, consequently, high surface-to-volume ratio of the weld pool (*23*). Currently, there is no comprehensive theoretical model to predict, from fundamental principles, laser- or electron beam–induced metal vaporization rates and the resulting weld pool composition changes. A comprehensive theoretical model would allow calculation of acceptable limits of operating parameters and would be useful for weld metal composition control.

Weldment Structure and Properties

The weldment is divided into three distinct regions (Fig. 2): the fusion zone (FZ), which undergoes melting and solidification, the heat-affected zone, adjacent to the FZ that often experiences solid-state phase changes but no melting, and the unaffected base material. The integrity of welded joints depends on the weldment microstructure and properties. Rapid heating, cooling, and local structural changes cause significant spatial variations in the composition, microstructure, and residual stress (*24, 25*) in the fusion and heat-affected zones. Recent developments in microstructural characterization techniques such as analytical electron microscopy and scanning tunneling microscopy have made it possible to characterize microstructures on scales as fine as a few nanometers. To clarify experimental data obtained under welding conditions, simulation techniques such as differential thermal analysis, thermomechanical simulation, and welding of single crystals have been successfully used to understand microstructural development (*24, 26*). Because of the spatial variation of weld properties, fine-scale evaluation of properties is often desirable. Recent techniques such as mechanical property microprobe, indentation creep testing, and miniature impact specimen testing (*24*) have made it possible to test welds either by performing tests on small areas or by miniaturizing test specimens. Thermal neutrons, which can penetrate 50 mm into steel, have recently been used (*27*) to characterize residual stresses in weldments, and neutron scattering analysis can characterize stresses in materials on a millimeter scale.

Because the FZ undergoes a liquid-to-solid transformation, the size and shape of grains, the distribution of inclusions, and defects such as porosity and hot cracks are controlled by its solidification behavior. Temperature gradient, growth rate, undercooling, and alloy constitution are important factors in determining the FZ microstructure. Depending on the welding process, the weld metal cooling rates may range from 10° to 10^7°C per second. Solidification microstructures in welds, which are often difficult to interpret, are commonly analyzed with the help of classical theories of nucleation and growth (*3, 28*). Furthermore, recent advances in rapid solidification theories are also being extended to understand the development of microstructures in welds (*3, 28, 29*). Increased use of high-energy beams such as electron and laser beams have helped make observations of nonequilibrium microstructures under rapid cooling conditions common. Unlike the case in solidification of castings or ingots, weld pool solidification occurs without a nucleation barrier, and so no undercooling of the liquid is required for the nucleation of a solid. Solidification occurs spontaneously by epitaxial growth on the partially melted grains. Innoculents and other grain-refining techniques are useful in welding in much the same way as they are in casting practices.

The development of microstructural features during growth of the solid in the FZ is controlled by the shape of the solid-liquid interface. The stability of this interface is mostly determined by neighboring conditions. Depending on the interface shape, growth of the solid will occur in planar, cellular, or dendritic modes. Sometimes all these distinct microstructural features of growth can be observed in a weld. The dendritic growth of the solid with its multiple branches has been observed during welding of a single-crystal nickel-base superalloy (Fig. 4). Theories have been developed for interface stability under the conditions of slow cooling, assuming equilibrium at the interface. In recent years, necessary modifications have also been made to these theories to accommodate nonequilibrium conditions prevalent during rapid solidification (*29, 30*). However, their application to weld pool solidification remains to be developed.

During solidification, extensive solute redistribution occurs resulting in segregation that can drastically affect weldability, microstructure, and properties. The potential for the weld to crack as the FZ cools, a phenomenon known as hot cracking, is often attributed to elemental segregation during welding. It is only recently that some attention has been paid to this important aspect of weld pool solidification (*31*). In evaluating solute redistribution under dendritic growth conditions, the dendrite tip temperature is important. The tip's temperature and composition are strong functions of its radius, growth rate, and thermal gradient. Since the weld dendritic structures are typically fine because of high growth rates, the contribution to the total undercooling owing to the curvature effect is significant. The FZ grain structure controls the hot-cracking tendency and properties of welds. Because solidification proceeds spontaneously by epitaxial growth of the partially melted grains in the base metal, the FZ grain structure is mainly determined by the base metal grain structure and the welding conditions (*3, 32, 33*).

During weld pool solidification, the grains often grow along a crystallographic direction. For cubic metals, the preferred growth directions are <100>. Conditions for growth are optimum when a preferred direction coincides with the heat flow direction. Therefore, among randomly oriented grains in the polycrystalline cubic base metals, the grains having <100> crystallographic axes most closely aligned with the heat flow direction are favored for growth. However, the development of the FZ grain structure in welds is complicated because of the competing growth of grains with various orientations in the three-dimensional FZ. Various fundamental issues related to the microstructural development of the FZ such as the mechanism of grain growth, role of weld pool shape on the grain or dendrite selection process, grain multiplication or transition, and predictive capabilities of the grain growth remain to be addressed. Recent advances in this area include theoretical and experimental analysis of the dendrite growth selection process (*34*) and transitions in the grain structure (*35*). Use of Fe-15Ni-15Cr (an iron alloy containing 15% by weight nickel and 15% by weight chromium) single crystals to investigate the details of the microstructural development has been useful. The analytical model based on modern solidification theories provides for a three-dimensional relation between the travel speed, solidification velocity, and dendrite growth velocity to predict the microstructural features in the FZ. Furthermore, from the experimental observations of the dendritic arrangements, a three-dimensional reconstruction of the weld pool (Fig. 5) provides a detailed insight into the microstructural development.

The heat-affected zone (HAZ) poses a significant challenge to the characterization and understanding of microstructure-property relations. Depending on the thermal cycles and temperature gradients that result from welding, phase transformations and grain growth occur, and microstructural and composition gradients and residual stresses develop, in the HAZ (*36*). Significant opportunities still exist for microstructural modeling within the HAZ and for achieving predictability of structure-property correlations in welds.

The fracture behavior of weldments is influenced by the microstructural and stress gradients. However, to date the development of the theory and application of fracture mechanics has been directed toward homogeneous materials like the base metal. A critical need exists to develop a fundamental understanding of the role of microstructure and composition gradients in the fracture behavior of the weldments. Finally, important issues such as the design of better weld metal alloys (*37*), assessment of radiation damage in welds, corrosion behavior, and welding and weldability of advanced materials remain to be addressed.

Sensing, Control, and Automation

A skilled manual welder uses his sensory perceptions such as touch, sight, and hearing to evaluate the process and take the necessary corrective measures. Success de-

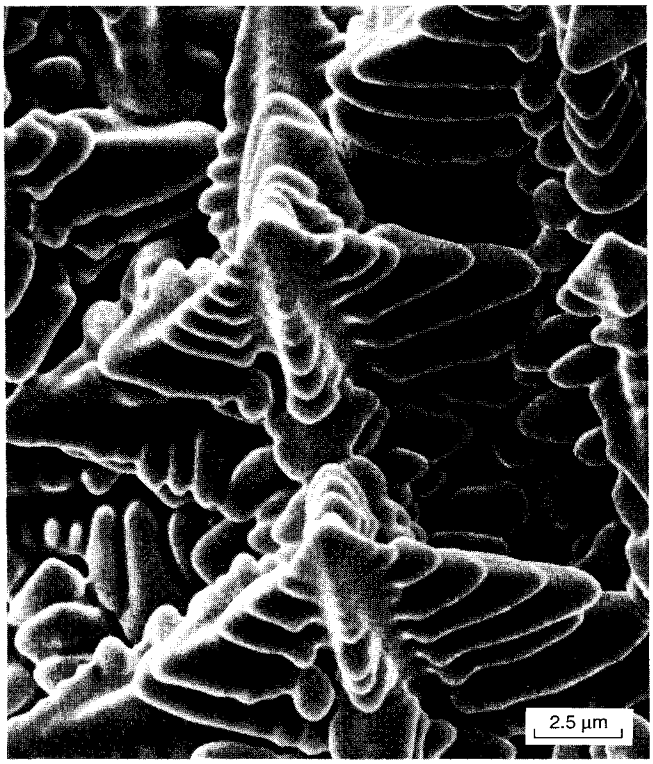

Fig. 4. A scanning electron micrograph showing the development of dendrites in a nickel-base superalloy single-crystal weld. The micrograph was taken on a hot-cracked surface formed during electron-beam welding of the alloy. The primary, secondary, and tertiary dendrite arms and growth perturbations on the arms are clearly discernible.

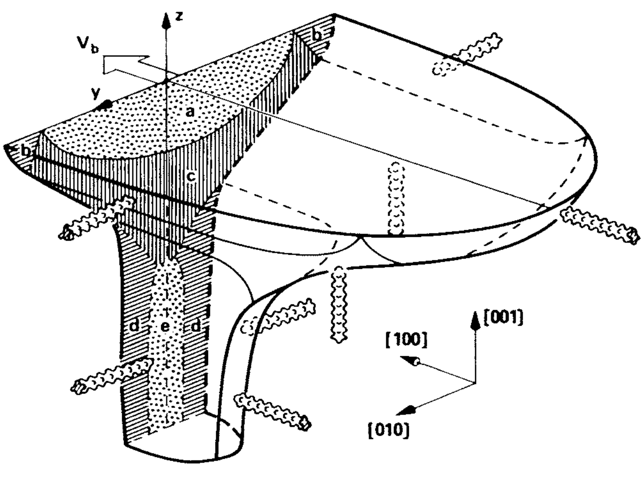

Fig. 5. A three-dimensional schematic diagram of a weld pool. Letters a and e, b and d, and c correspond to three regions with distinct microstructural features. Bead-like structures emerging from the weld pool represent dendrites. The weld pool shape was constructed using several two-dimensional transverse optical micrographs of Fe-15% Ni-15% Cr single-crystal welds. V_b represents the velocity of the heat source. Velocity in the [100] weld direction, 3 mm/s.

pends on his intuition and skills, and the procedure is labor-intensive and frequently unreliable. As a result, manual welding operations are being progressively replaced by automated systems to achieve increased productivity and quality. Recent automations have been carried out with robots that are not equipped with appropriate sensors. Defect-free welds could not be made in these operations owing to lack of adaptive controls (*38*).

The ultimate goal of adaptive control in welding is to regulate the process to make welds of desired quality and performance and to achieve high productivity. The implementation of adaptive control in welding would involve sensing and control of the heat source position, weld pool temperature, weld penetration, defect formation, and, ultimately, control of microstructure and properties. Achievement of effective automation in welding by integration of the various elements of adaptive control would involve solution of a problem with many highly coupled and nonlinear variables. The trend is to use an emerging research tool known as intelligent control. This approach enables the user to choose a desirable end factor such as property, defect control, or productivity instead of process parameters such as current, voltage, or speed to provide for appropriate control of the process. Important elements of intelligent control include sensing, control theory and design, process modeling, and artificial intelligence. Currently, only limited efforts are under way to advance various aspects of intelligent control. These include the development of a connectionist fuzzy-logic system for welding control (*39*), independent control of electrode melting (*40*), and multi-output process dynamics (*41*). Significant progress needs to be made in each facet of intelligent control to improve the quality and productivity of weldments.

An important element in the intelligent control loop is process modeling. Process modeling calculations in real time could provide the necessary bridge for coupling the process parameters with the desirable properties of the weld. Most of the comprehensive process models require extensive computer time and cannot be used for real-time applications. However, the large models are needed to "calibrate" computationally simpler models that can be used in real time.

Advances are being made in the development of sensors for real-time control in welding. The types of sensors currently being developed use optical, infrared, acoustic, and ultrasonic radiations. Optical sensing systems (*42*) allow viewing of the puddle area and sometimes of the solidification substructure formed on the pool surface (*43*). Light emission during welding also provides information about the type of excited and ionized species and about the electron density and energy in the plasma plume above the weld pool. Although emission spectroscopy has been used as a noncontact on-line tool for the analysis of important data and for the determination of important welding parameters, its use as an on-line sensor in welding has been limited to laboratories. Recent investigations of infrared detection have demonstrated the potential of this type of sensing for seam tracking, control of weld geometry, and reduction of discontinuities (*44*).

Outlook

Welding has evolved in the last few decades from almost an empirical art to an activity combining the advanced tools of various basic and applied sciences. Significant progress is being made in understanding the existing processes and welded materials and in using the results to advance automation and process control. However, several key problems and issues remain to be addressed. The main difficulties in the comprehensive modeling and analysis of the welding processes are inadequate understanding of the plasma-metal interaction during welding and the scarcity of appropriate thermophysical data at temperatures much higher than the melting points of weld metals. In view of the complexities of the welding processes, the model predictions must be tested by well-designed experimental work. Reliable science-based correlations between the microstructure and properties of welds as well as models to predict such relations are important for the development of the field. Appropriate methodologies for intelligent process control of composition, structure, and properties of welds are necessary. Integration of a fundamental understanding of the welding processes and a knowledge of the evolution of microstructure and properties remains a major challenge in the pursuit of intelligent process control to produce defect-free, structurally sound, and reliable welds.

Apart from serving as a basis for sound welding of important existing materials, the improved scientific infrastructure will soon meet the need for welding a new class of engineered and other advanced materials that are now evolving. In recent years, the progress in research has been accompanied by an equally impressive advance in education and a growing recognition of the importance of the field by governmental funding agencies. As current scientific problems and issues are addressed, there will be progress toward a science-based control of composition, structure, and properties. Achievement of such a goal, an important milestone in the advancement of welding technology, is well in reach of the welding community within the next two decades.

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RESEARCH ARTICLE

Three-Dimensional Structure of an Angiotensin II–Fab Complex at 3 Å: Hormone Recognition by an Anti-Idiotypic Antibody

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The elucidation of bioactive conformations of small peptide hormones remains an elusive goal to structural chemists because of the inherent flexibility of these molecules. Angiotensin II (AII), the major effector of the renin-angiotensin system, is an octapeptide hormone for which no clear structural models exist. Peptide hormones such as AII share the property that they bind to their receptors with high affinities, in spite of the fact that they must overcome an extremely large conformational entropy barrier to bind in one conformation. A "surrogate system" that consists of a high-affinity monoclonal antibody (MAb) and AII has been used to study a bound conformation of AII. The crystallographic structure of the complex reveals a structure of AII that is compatible with predicted bioactive conformations of AII derived from structure-activity studies and theoretical calculations. In the complex, the deeply bound hormone is folded into a compact structure in which two turns bring the amino and carboxyl termini close together. The antibody of this complex (MAb 131) has the unusual property that it was not generated against AII, but rather against an anti-idiotypic antibody reactive with a MAb to AII, which renders this antibody an anti–anti-idiotypic antibody. The high affinity for AII of the original MAb to AII was passed on to MAb 131 through a structural determinant on the anti-idiotypic antibody. Strikingly, the conformation of AII in this complex is highly similar to complementarity determining region loops of antibodies, possibly indicating that a true molecular mimic of bound AII was present on the anti-idiotypic antibody against which MAb 131 was elicited.

Angiotensin II (AII) is the primary active component of the renin-angiotensin system and plays a central role in the regulation of blood pressure. The hormone, an octapeptide of sequence Asp-Arg-Val-Tyr-Ile-His-Pro-Phe, participates in a number of physiological functions associated with the regulation of blood pressure. Receptors for AII have been identified in blood vessels, heart, liver, adrenal gland, and pituitary gland, where they mediate vasoconstriction, ionotropic effects, glycogenolysis, secretion of aldosterone, and release of prolactin, respectively (*1*). Direct effects of AII on the central nervous system have also been described (*2*).

The renin-angiotensin system has been the target of extensive drug design efforts for control of hypertension. Inhibitors of angiotensin-converting enzyme—mechanism-based inhibitors of the cleavage of the inactive pro-decapeptide angiotensin I (AI) to AII—are some of the most successful antihypertensive drugs (*3*). Yet, the most effective inhibitor of AII action would be a molecule that directly prevents the binding of AII to its receptor. Unfortunately, success in designing molecules that act as AII receptor antagonists has been hindered by the lack of direct structural information concerning the bioactive conformation of AII.

Angiotensin II has been the subject of extensive study to determine its solution conformation or conformations; however, its extreme flexibility has hindered attempts at determining its structure by either spectroscopic or crystallographic methods (*4*).

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