ADVANCES IN WELDING SCIENCE AND TECHNOLOGY

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Over the years, welding has been more of an art than a science, but in the last few decades major advances have taken place in welding science and technology. With the development of new methodologies at the crossroads of basic and applied sciences, enormous opportunities and potential exist to develop a science-based design of composition, structure, and properties of welds with intelligent control and automation of the welding processes. 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 applied sciences. A series of international conferences[1-3] and other publications[4-5] have covered the issues, current trends and directions in welding science and technology. In the last few decades, major progress has been made in (i) understanding physical processes in welding, (ii) characterization of microstructure and properties, and (iii) intelligent control and automation of welding. This paper describes some ofthese developments.

Physical Processes

During welding, as the heat source interacts with the metal, melting, solidification, and various solid state transformations occur and these processes influence the structure and properties of the welded product. In the weld pool, liquid metal undergoes vigorous circulation. In recent years, significant progress has been made in understanding how the various physical processes in the weld pool influence the development of the weld pool, the macro and microstructures of the welded region, and residual stress. Since the early efforts of heat transfer calculations,[6-7] significant advances have been made in the calculation of weld pool heat transfer and geometry. The fluid flow and heat transfer affect the size and shape of the weld pool, the cooling rate, and the kinetics and the extent of various solid state transformation reactions.[8-14] The weld pool geometry influences dendrite and grain growth selection processes.[14-17] Mathematical modeling is now commonly used to simulate the development of weld pool geometry and cooling rate by considering both conduction and convection heat transfer phenomena. In many instances, convection plays a critical role in determining the weld penetration, shape and size. Convection in the weld pool is driven by surface tension, buoyancy, and, when electric current is used, electromagnetic forces. A critical variable that controls the weld penetration is the nature and amount of surface active element in the alloy. Although mathematical modeling is a powerful tool for understanding the physical processes in welding, attempts to understand these processes through numerical simulation must involve concomitant, well-designed experimental work to validate these models.

During welding, partitioning of gases between the weld pool and its surroundings significantly affects the weld metal composition, microstructure, and properties. In addition, vaporization of alloying elements, and transport of elements into and away from the weld pool greatly influence the microstructure, composition, and properties of weld metal. Gases such as hydrogen, nitrogen and oxygen may dissolve in the weld metal to form porosity and inclusions that may affect weldment properties. Oxygen and nitrogen contents as high as 0.7 and 0.2 wt%, respectively, have been obtained in the weld metal during arc welding.[18] These concentration levels were far greater than those in the base and filler metals. With very high power density heat sources such as lasers and electron beams, the temperature can exceed the boiling point.[19-21] Consequently, pronounced vaporization of alloying elements takes place. Such loss of elements from the weld pool often results in a change in the composition of the weld metal and is a serious problem in the welding of many important engineering alloys.[22-27] Figure 1 shows the change in the manganese concentration during laser welding of various grades of high manganese steels.[24] Efforts to develop a fundamental understanding of the various gas species that are present and vaporization of elements are just beginning.

The physical processes like heat transfer, fluid flow, vaporization of alloying elements and dissolution of gases also control other physical processes that occur in the liquid weld metal during weld cooling. For example, the dissolved oxygen in low alloy steel reacts with the dissolved deoxidizing elements like aluminum, titanium, silicon and manganese to form non-metallic oxide inclusions in liquid steel. These inclusions are trapped within the solid during solidification. These trapped inclusions may stimulate the formation of an acicular ferrite microstructure during solid state phase transformations.[28-30] Hence, substantial research has been done in the past and is being performed currently to modify the inclusion characteristics to obtain the optimum weld metal properties. Recently, fundamental theories of ladle steel deoxidization reactions have been extended to inclusion formation in steel weld metal.[31] This work indicates that the inclusion characteristics are quite sensitive to the oxygen content, the deoxidizing element concentrations, the presence of pre-existing inclusions, and the reaction temperature. A complete understanding of inclusion formation and spatial distribution of these inclusions in steel welds is of importance in estimating the effect of inclusions on solidification and solid state phase transformations.

The development of the microstructure in the fusion zone (FZ) also known as weld metal, depends on the solidification behavior of the weld pool. In general, solidification microstructures that are observed in welds are often quite complicated and difficult to interpret. Significant progress is yet to be made in characterizing and understanding the development of microstructures in the FZ. Attempts have been made to interpret these microstructures by considering classical ideas of nucleation theory as well as growth behavior that are used for conventional solidification process. Recent advances in rapid solidification theories are also being extended to understand the development of microstructures in welds.[14-17,32-48] With the increased use of high energy beam processes, such as electron and laser beams for welding, observations of non-equilibrium microstructures under rapid cooling conditions are becoming very common. Such observations have been well documented for austenitic stainless steel welds.[44-48] Figure 2. shows a fully austenitic stainless steel weld microstructure in a laser weld, which would normally contain a duplex austenitic plus ferrite microstructure.

The development of the microstructural features during growth of the solid in the FZ is controlled by the shape of the solid/liquid interface. The nature and stability of the solid/liquid interface is mostly determined by the thermal and constitutional conditions that exist in the immediate vicinity of the interface. Depending on these conditions growth of the solid will occur by planar growth, or cellular of dendritic modes. Sometimes in a weld, all of these distinct microstructural features of growth can be observed. The dendritic growth of the solid, with its multiple branches, during welding of a nickel-base superalloy single-crystal is shown in Fig 3. Solidification theories have been developed for interface stability under the conditions of equilibrium at the interface,[36-37] and these theories can be extended to welds. In recent years, necessary modifications have also been made to these theories to accommodate extreme non-equilibrium conditions prevalent during rapid solidification.[38,49-54] These may be extended to weld pool solidification.

Another significant aspect of the weld pool is the solute redistribution. It is only recently that some attention is being given to this important aspect of weld pool solidification.[33,55] In evaluating solute redistribution under dendritic growth conditions, the dendrite tip temperature is extremely important.[14] The tip temperature and composition are strong functions of tip radius, growth rate, thermal gradient, and other factors in welds. Since the structures are finer because of higher growth rates, the contribution to the total undercooling due to the dendrite tip curvature effect is very significant. The effect of increased undercooling at the dendrite tips would be to increase the dendrite tip or core composition (for $K<1$) and reduce microsegregation.[14]

One of the critical microstructural feature that controls hot-cracking tendency and properties of welds is the FZ grain structure. Crystallographic effects and welding conditions have been found to influence significantly the development of grain structure.[14,56] Often, the grains during weld pool solidification tend to grow along a crystallographic direction i.e., the easy growth direction.[14,56-57] For cubic metals, the easy growth directions are <100>. Conditions for growth are optimum when one of the easy growth directions coincides with the heat flow direction. Therefore, during welding, among the randomly oriented grains in the polycrystalline base metal, those grains that have one of their <100> crystallographic axes most closely aligned with the heat flow direction will be favored. A number of fundamental issues related to the microstructural development of the FZ, such as details of the mechanism of grain growth selection process, role of weld pool shape on the grain or dendrite selection process, grain multiplication or transition, and finally, related predictive capabilities, are currently being addressed using theoretical and experimental analyses.[15-17,32,58] An extremely powerful experimental technique that utilizes macroscopic single crystals of Fe-15Ni-15Cr to investigate the details of the microstructural development has been used.[15-17,32] The analytical model based on modern solidification theories provides a relationship between travel speed, solidification velocity and dendrite growth velocity to predict three-dimensional microstructural features in the FZ. Furthermore, from the experimental observations of the dendritic arrangements, a three-dimensional reconstruction of the weld pool is possible (Fig. 4). Finally, significant progress on the beneficial effects of having a fine-equiaxed grain structure in the FZ center is being made.[58]

During welding, extensive solid state phase transformations occur in both the FZ and the heat affected zone (HAZ). The nature of these transformations depends on the heating and cooling rates and also the maximum temperature reached at any given location during the weld thermal cycle,. 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.[59-62] Characterization and modeling of these transformations and the resulting microstructures in weldments remains a great challenge. Because of the extensive thermal gradients and non-uniform thermal exposure, both the FZ and the HAZ often exhibit significant compositional, microstructural, and property gradients. Such gradients are unique to welded structures. In addition, generation of thermal stresses during welding can drastically affect the kinetics of solid-state transformations in both the FZ and HAZ. Significant advances have been made in recent years in modeling the solid-state phase transformations in weldments.[63-68] Models have been developed based on physical metallurgy principles.

Microstructural Characterization and Properties

In both the FZ and HAZ of a weldment, gradients in composition microstructure and stresses exist because of heating, cooling, steep thermal gradients, and partitioning of elements during welding. The origin of microstructural and stress gradients and their influence on the structural integrity of weldments is an unexplored field. This is in part due to the lack of understanding of the formation of these gradients and their complex interactions and the unavailability of characterization tools to probe these gradients on both macroscopic and microscopic scales. However, recently developed experimental techniques, particularly microstructural characterization, mechanical properties measurement, and simulation are ideally suited for examination and characterization of welds with microstructural and composition gradients.[69-70] It is now possible to characterize microstructures on scales as fine as a few nanometers or less. An example of atomic scale chemical analysis of elemental segregation in a stainless steel weld by the atom probe field ion microscopy technique is shown in Fig. 5.[71] Techniques, including analytical electron microscopy, Auger electron spectroscopy, scanning electron microscopy, secondary ion mass spectroscopy, and atom probe field ion microscopy, can be effectively used to unravel the complexities of the weld microstructures.[69]

Welding Control and Automation

As welding technology matures, there will be a steady decline in manual welding operations. For increased productivity, future welding operations will require automated welding systems with effective adaptive control.[72] One of the critical elements of adaptive control is sensors. In making a manual weld, a master welder uses his sensory perceptions such as touching, seeing, and hearing to evaluate the process and make the necessary adjustments for corrective measures, if required. Advances are being made in the development of sensors for welding. The types of sensors currently being developed include optical, arc, infrared, acoustic and ultrasonics. Another critical element in the adaptive control loop is process modeling. Process modeling computations in real time could provide the necessary bridge for coupling the process parameters with the desirable properties of the weld. The ultimate goal of adaptive control in welding is to regulate the process to make welds with desired quality, performance, and productivity. The current trend is to use an emerging research tool known as intelligent control. This will enable one 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 underway to advance various aspects of intelligence control. These include development of a connectionist fuzzy logic system for welding control,[73] independent control of electrode melting,[74] and multi-output process dynamics.[75] Significant problems are yet to be solved in all these facets of intelligent control to improve quality and productivity of weldments.

Summary

This paper summarizes some of the recent developments in welding science. A fundamental understanding of the various aspects of this critical technology is still evolving. Enormous opportunities and potential exist to develop a science-based tailoring of composition, structure and properties of welds through intelligent control automation of the welding process to improve weldment quality and productivity.

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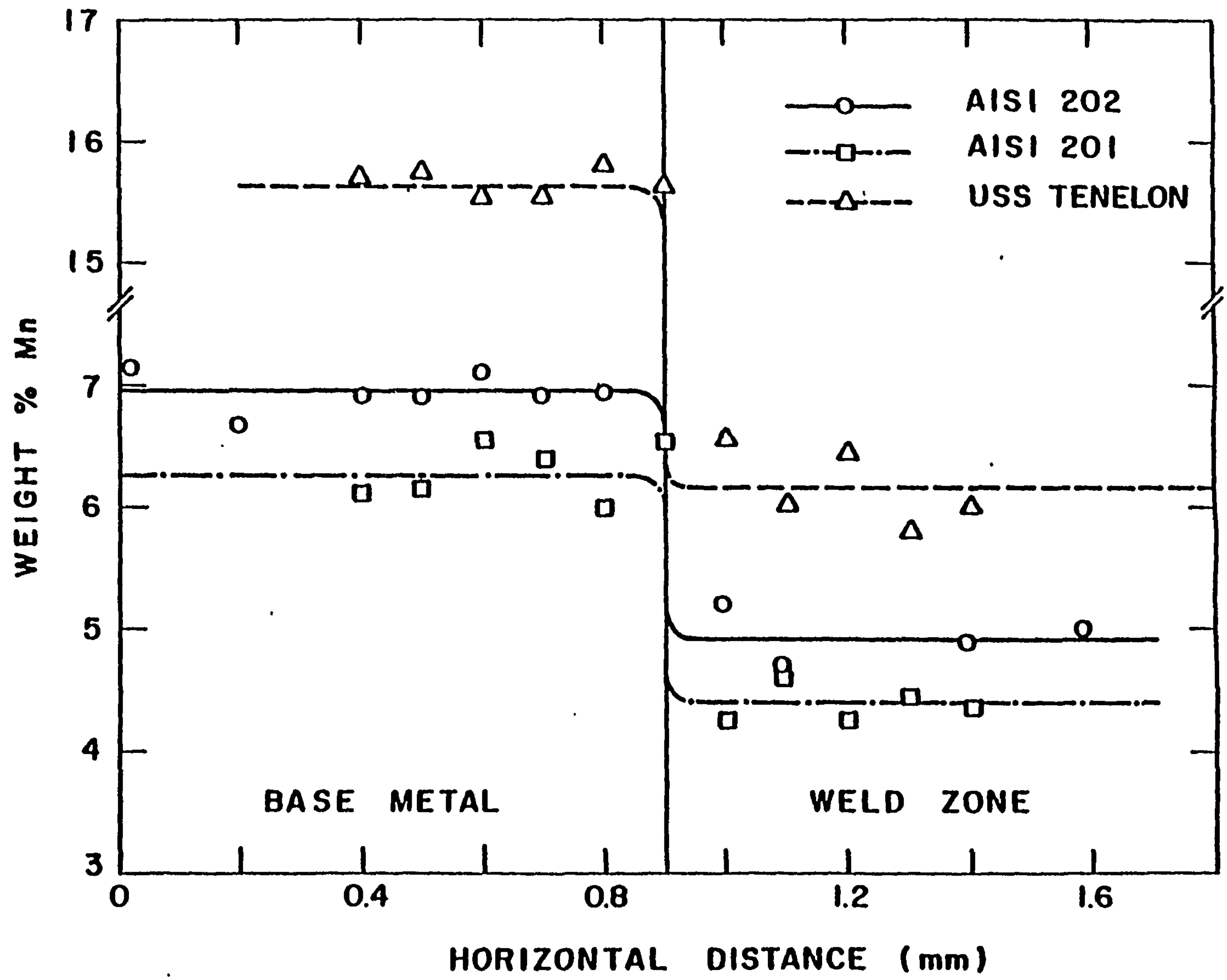

Fig. 1 Concentration of manganese versus distance in the base metal and in the weld zone for continuous wave carbon dioxide laser welding. Laser power: 560 watts; welding speed: $3.5x10^{-3}$ m/s; shielding gas flow rate: 10^{-4} m^3/s; and sample thickness: $7x10^{-4}$m.

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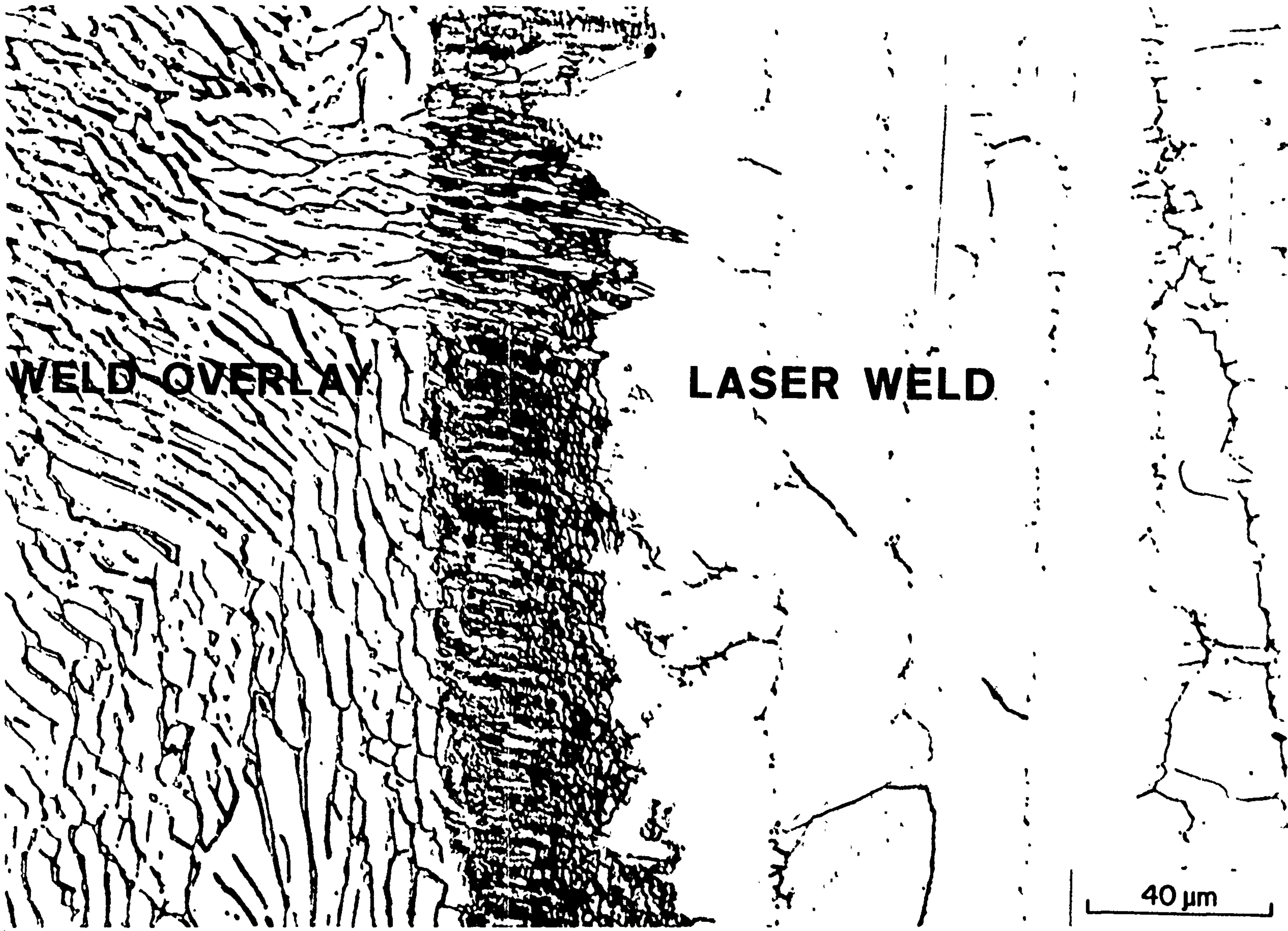

Fig. 2. Duplex (austenite plus ferrite) structure in conventional weld overlay and fully austenitic structure in laser weld region of type 308 stainless steel.

Fig. 3 Scanning electron micrograph showing the development of dendrites in a nickel-based superalloy single-crystal weld.

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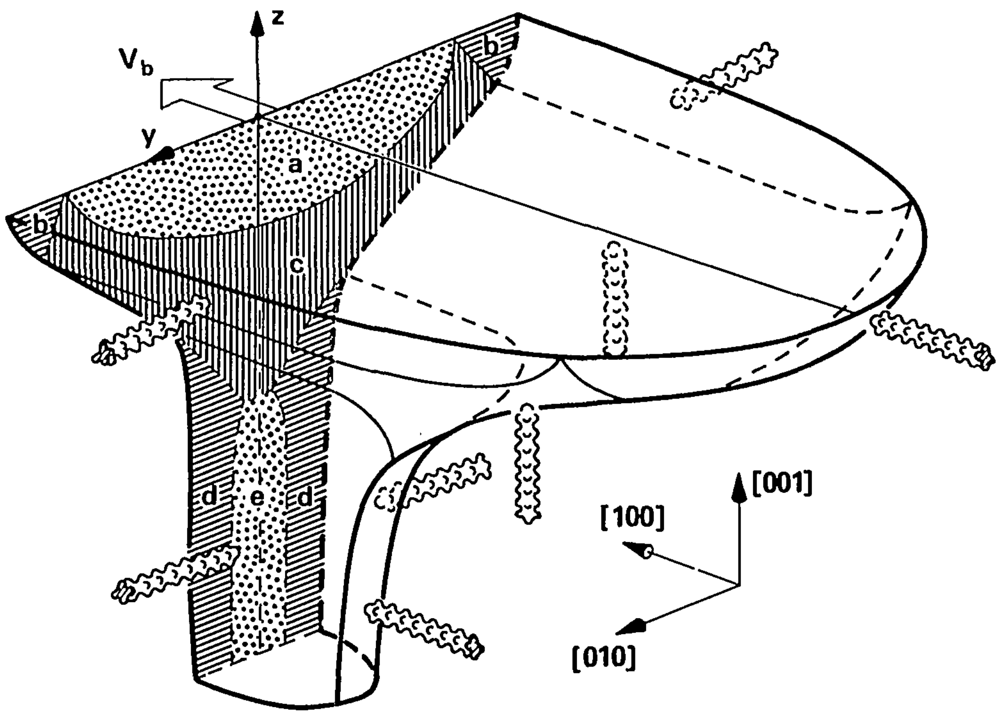

[100] WELD 3 mm/s

Fig. 4 Reconstructed three-dimensional diagram of a weld pool showing the development of weld microstructural features.

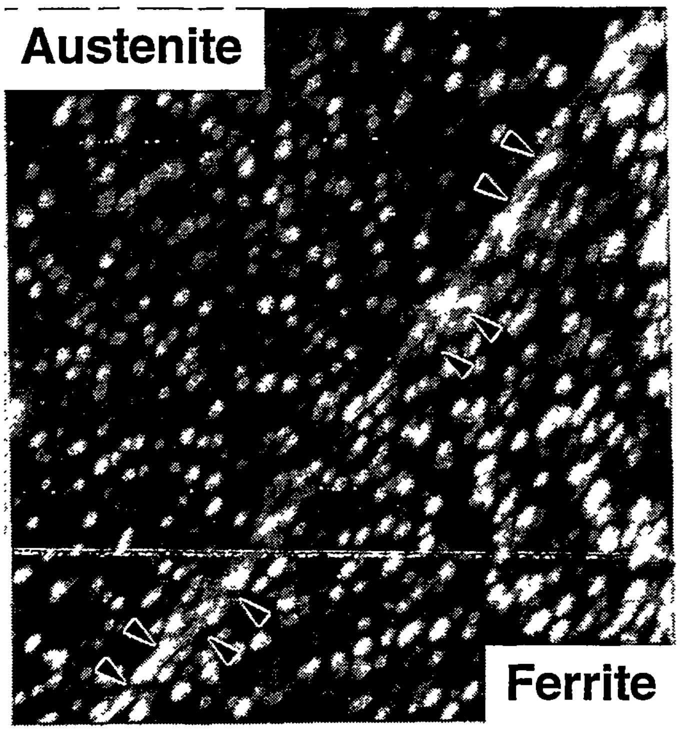

Fig. 5 Field ion image of austenite-ferrite interface in a stainless steel weld in the as-welded state. The difference in the contrast suggests elemental segregation. The atom probe composition profile showed that boron was segregating to the austenite-ferrite interface.