CONF-9410296--1

ADVANCES IN WELDING SCIENCE - A PERSPECTIVE

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ABSTRACT

The ultimate goal of welding technology is to improve the joint integrity and increase productivity. 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 tailoring of composition, structure, and properties of welds with intelligent control and automation of the welding processes.

1. INTRODUCTION

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. Defects in welds, or poor performance of welds, can lead to catastrophic failures with costly consequences, including loss of property and life. Perhaps because welding is a construction technique, it is viewed by many as a primitive science. 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. A series of international conferences[1-3] and other publications[4-5] have all covered the issues, current trends and directions in the 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 of these developments.

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2. PHYSICAL PROCESSES

During welding, as the heat source interacts with the metal, melting, solidification, and various solid state transformation occur and these transformations influence the structure and properties of the welded product. In the weld pool, metal undergoes vigorous circulation. In non-autogenous welding, where filler metals are used, additional physical processes add to the complexity of the weld pool phenomena. 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.[6-12] The weld pool geometry influences dendrite and grain growth selection processes.[12-15] The distribution of nitrogen, oxygen and hydrogen 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.

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 stresses. Much of the recent research on the weld pool phenomena has attempted to gain an understanding of fluid flow and heat transfer in the weld pool. Significant progress has also been made in understanding both weld pool solidification behavior and solid state transformations in the weld metal and the heat affected zone and measurement of residual stresses. It should be noted that a fundamental understanding of some of these topics is still evolving.

2.1 WELD POOL SHAPE AND PENETRATION

Since the early efforts of heat transfer calculations,[16-17] significant advances have been made in the calculation of weld pool heat transfer and geometry. Mathematical modeling is now commonly used to simulate the development of weld pool geometry and cooling rate. Most of these models now address coupled conduction and convection heat transfer problems to predict weld pool geometry and cooling rate. 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. Recent work has shown that consideration of a temperature coefficient of surface tension that is dependent on temperature and composition is important for the calculation of fluid flow in the weld pool and its shape.[18-20] In actuality, depending on the interplay between various driving forces mentioned above, the convective flow can be simple, or more complex with a number of convective cells,[18-20] as shown in Fig. 1. For simplicity, most of the earlier models have addressed stationary arc welds with a flat weld pool surface. In recent years, the models have been refined to incorporate realistic weld pool conditions such as free deformable weld pool surfaces and moving heat sources.[21-24]

Mathematical modeling is a powerful tool for understanding the heat transfer, fluid flow and development of weld pool geometry. However, in view of the complexities of the welding process, attempts to understand them through numerical simulation must involve concomitant, well-designed experimental work to validate the models.

2.2 VAPORIZATION OF ELEMENTS FROM WELD POOL SURFACE

During the interaction of the heat source with the metal, the weld pool surface temperatures are much higher than the liquidus temperature of the weld metal. When very high power density heat sources such as lasers and electron beams are used, the temperature can even exceed the boiling point.[25-27] 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.[28-34] Figure 2 shows the change in the manganese concentration during laser welding of various grades of high manganese steels.[30]

DebRoy et al.[29,32-33] have developed a comprehensive model to understand the vaporization of elements and the composition change of the weld metal. Their procedure allows for the calculation of both the evaporation and the condensation fluxes based on the application of conservation of mass, momentum and energy equations to both the liquid and the vapor phases. The model predictions were compared with experimental results for laser welding of titanium, pure iron and stainless steel. The experimental data and the model predictions are consistent with one another.

2.3 SOLUTION OF GASES IN WELD METAL

During welding, hydrogen, nitrogen and oxygen may dissolve in the weld metal to form porosity and inclusions that may affect weldment properties. During laser welding, the concentrations of hydrogen, nitrogen and oxygen in the weld metal are affected by the interaction between the weld pool and the surrounding gas shield environment. Oxygen and nitrogen contents as high as 0.7 and 0.2 wt%, respectively, have been obtained in the weld metal during arc welding.[34] These concentration levels were far greater than those in the base and filler metals.

In a diatomic gas environment, the equilibrium concentration of a species such as hydrogen in a metal is given by the Sieverts' law, which states that the concentration is proportional to the square root of the partial pressure at any given temperature.[35] However, in most welding processes, the weld metal is exposed to a plasma environment. The gas phase contains neutral atoms, ions, excited molecules and atoms, and electrons. Under these conditions, the concentrations of these species in the metal are significantly higher than those calculated from the Sieverts' Law.[36-38] The transformation of ordinary molecular species to excited neutral atoms or ions in the gas phase leads to enhanced solution of the species in the metal. Gedeon and Eagar,[37] in their study of hydrogen dissolution, clearly indicated the prominent effect of atomic hydrogen gas in determining the hydrogen concentration in the weld metal. Efforts to develop a fundamental understanding of the partition of species such as hydrogen, nitrogen and oxygen between the weld pool and its environment are just beginning.

2.4 WELD METAL INCLUSION FORMATION

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 stimulate the formation of acicular ferrite microstructure during solid state phase transformations.[39-41] Hence, substantial amounts of research had been done in the past and are 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.[42] This work indicates that the inclusion characteristics are quite sensitive to the oxygen content, the deoxidizing element concentrations, the presence of pre-formed inclusions, and the reaction temperature. The inclusion formation depends strongly on the concentration of dissolved oxygen and deoxidizing elements, and on the weld cooling rate. 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 transformation.

2.4 WELD SOLIDIFICATION

Development of the microstructure in the fusion zone (FZ), also known as weld metal, depends on the solidification behavior of the weld pool. Since the properties and performance of the FZ depend on the solidification behavior and the microstructural characteristics, understanding weld-pool solidification behavior is critical. Efforts are underway to use both analytical and numerical models to understand better the solidification behavior of the FZ.[12-15,43-46] Most of our current knowledge of weld pool solidification is derived from an extrapolation of the knowledge and models for freezing of castings, ingots and crystals at lower thermal gradients and growth rates.[12] The same parameters that are important in determining microstructures in castings, such as growth rate (R_s), temperature gradient (G), undercooling (ΔT_u), and alloy composition also play significant roles in determining the development of microstructure in welds. The temperature gradient and growth rate are important in the combined forms G/R_s and GR_s (cooling rate) since they influence the solidification morphology and the scale of the solidification substructure, respectively. In welding, where the molten pool is translated through the material, both G and GR_s vary considerably across the FZ. Figures 3 and 4 show schematically the influence of G and R on the microstructural variations within the weld metal.

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. However, at present, attempts are being made to interpret these microstructures by considering classical ideas of nucleation theory as well as growth behavior used for conventional solidification processes. Further, recent advances in rapid solidification theories are also being extended to understand the development of microstructures in welds.[12-15,43-59] 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.[55-59] Figure 5. shows a fully austenitic stainless steel weld microstructure in a laser weld, which would normally contain a duplex austenite plus ferrite microstructure. This microstructure has been attributed to a change in the mode of freezing from primary ferrite to primary austenite during rapid solidification. During weld pool solidification, unlike in castings or ingot solidification, there is no nucleation barrier and, accordingly, no undercooling of the liquid required for nucleation of the solid. Solidification occurs spontaneously by epitaxial growth of the partially melted grains in the base metal, especially for autogenous (melt run) processes. For non-autogenous welds in which a filler metal is used, in addition to epitaxial growth, heterogeneous nucleation may also occur. Innoculants and other grain refining techniques may be used during welding in much the same way as they are employed in casting practices.[12]

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 or 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. 6. Solidification theories have been developed for interface stability under the conditions of equilibrium at the interface,[47-48] 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.[49,60-65] These may be extended to weld pool solidification.

Another significant aspect of weld pool solidification is the solute redistribution. During solidification extensive solute redistribution occurs, resulting in segregation that can drastically affect weldability, microstructure, and properties. Most of the FZ hot cracking problems (the potential for the weld to crack as the FZ cools), associated with a wide variety of common engineering materials as well as advanced materials, is in large part due to elemental segregation during welding. Segregation on a fine scale (μm) is called microsegregation while segregation on a large-scale (mm or greater) is known as macrosegregation. It is only recently that some attention is being given to this important aspect of weld pool solidification.[44,66] In evaluating solute redistribution under dendritic growth conditions, the dendrite tip temperature is extremely important.[12] 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.

A critical microstructural feature that controls hot-cracking tendency and properties of welds is the FZ grain structure. Since solidification proceeds spontaneously by epitaxial growth of the partially melted grains in the base metal, the FZ grain structure is determined, to a large extent, by the base metal grain structure. Crystallographic effects and welding conditions have been found to influence significantly the development of grain structure.[12,67] Often, the grains during weld pool solidification tend to grow along a crystallographic direction i.e., the easy growth direction.[12,67-68] 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. Recent developments in this area include theoretical and experimental analyses of the dendrite growth selection process,[13-15,43] and transitions in the grain structure.[69] 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. 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. 7). Finally, significant progress on the beneficial effects of having a fine-equiaxed grain structure in the FZ center is being made.[69]

2.5 PHASE TRANSFORMATIONS

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.[70-73] 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.[74-79] Models have been developed based on physical metallurgy principles. Efforts are also underway to use Monte Carlo techniques to simulate grain growth behavior in the HAZ and to quantitatively predict microstructural evolution in the HAZ.[80-81]

3. CHARACTERIZATION OF MICROSTRUCTURE AND PROPERTIES

In both the FZ and the HAZ of a weldment, gradients in the composition and microstructural features exist because of heating, cooling, and steep thermal gradients, partitioning of elements, and extensive phase transformations. Extensive gradation in composition and microstructures in a weldment are very common and unique to welded structures. In addition, due to localized heating during welding, complex thermal and transformation stresses are generated that add to the complexity of the structural integrity. 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.[82-83] It is now possible to characterize microstructures on scales as fine as a few nanometers or less. 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.[82]

One of these complexities include nano-scale compositional changes in the microstructure. Complete understanding of these features is crucial for designing of high integrity welded structures. The use of sophisticated characterization techniques to understand the weld metal microstructure development is illustrated below with an example. Type 308 stainless steel welds are used in welded power plant structures that operate at high temperature (~900 K) and at high stress (~100 MPa). Hence, these welded structures must be creep resistant. It is known that the addition of small amounts of boron (60 wt ppm) to these welds increases the creep strength. It is speculated that this improvement in property is due to segregation of the boron atoms to interphase (austenite-ferrite) interfaces; however there is no experimental proof for this type of segregation. It is important to note that width of the segregation will be about one or two lattice plane spacings (0.5 to 1 nm). Atom probe field ion microscopy is capable of analyzing this type of segregation in atomic scale resolution. A field ion image of the austenite-ferrite interface is shown in Fig. 8. The interface is decorated by series of brightly imaging atoms indicative of solute segregation. The measured compositional profile in the atom probe indicated the segregation of boron and carbon to the austenite -ferrite interface.[84] This example shows that by employing a combination of various characterizing techniques, the macro, micro, and nano-scale features of weld metal microstructure can be characterized and this information can be used in the design of weld metal composition.

Testing of welds to determine their mechanical properties is equally complex, because each of the various regions has distinct characteristics of its own in composition and microstructural gradients. Hence, properties vary from region to region. In addition to large-scale testing, testing of properties on a fine-scale is often required. Recent techniques have made it possible to test welds either by performing tests on very small areas or by miniaturizing test specimens. These techniques include mechanical properties microprobe, indentation creep testing and miniature Charpy specimen testing.[82] Sometimes, direct characterization of structure and properties of weldments is not easy. In such situations, simulation techniques have been successfully used for characterization purposes.[82,85-86] These techniques include thermal simulation techniques such as differential thermal analysis, thermomechanical simulation, and finally, use of single-crystals to understand the microstructural development during welding. Recently, application of thermal neutrons to characterize residual stresses in weldments is gaining importance.[87-89] Thermal neutrons can penetrate 50 mm into steel and scattering analysis of the material found in depths of this range can characterize stresses in the material on a mm scale. In addition to stress measurements, the potential exists for neutron scattering techniques to be successfully used for microstructural characterization.

4. INTELLIGENT 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.[90]

One of the critical elements of adaptive control is sensors. In making a manual weld, a master welder uses his sensory perceptions such as touch, sight, 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. For example, novel approaches have been used to view the welding operation using optical sensing systems.[91] Some of them have the resolution to not only view the puddle area, but to clearly see the solidification substructure formed on the pool surface.[92-93] Some of the systems can be used for real-time control. Recent investigations on infrared sensing have demonstrated the potential of this type of sensing for seam tracking, and detection of weld geometry and discontinuities.[94-95] Although these sensors are all critical for the ultimate process control, significant emphasis should be placed on sensing for microstructures and properties. 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, and 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 intelligent control. These include development of a connectionist fuzzy logic system for welding control,[96] independent control of electrode melting,[97] and multi-output process dynamics.[98] Significant progress is yet to be made in all these facets of intelligent control to improve quality and productivity of weldments.

5. 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 base tailoring of composition, structure and properties of welds through intelligent control automation of the welding process to improve weldment quality and productivity.

6. ACKNOWLEDGEMENT

The authors would like to thank Dr. Debra Joslin and Dr. G. Prabhu for their review and many helpful comments, and Carolyn Wells for preparing the manuscript. Research is sponsored by the Division of Materials Sciences, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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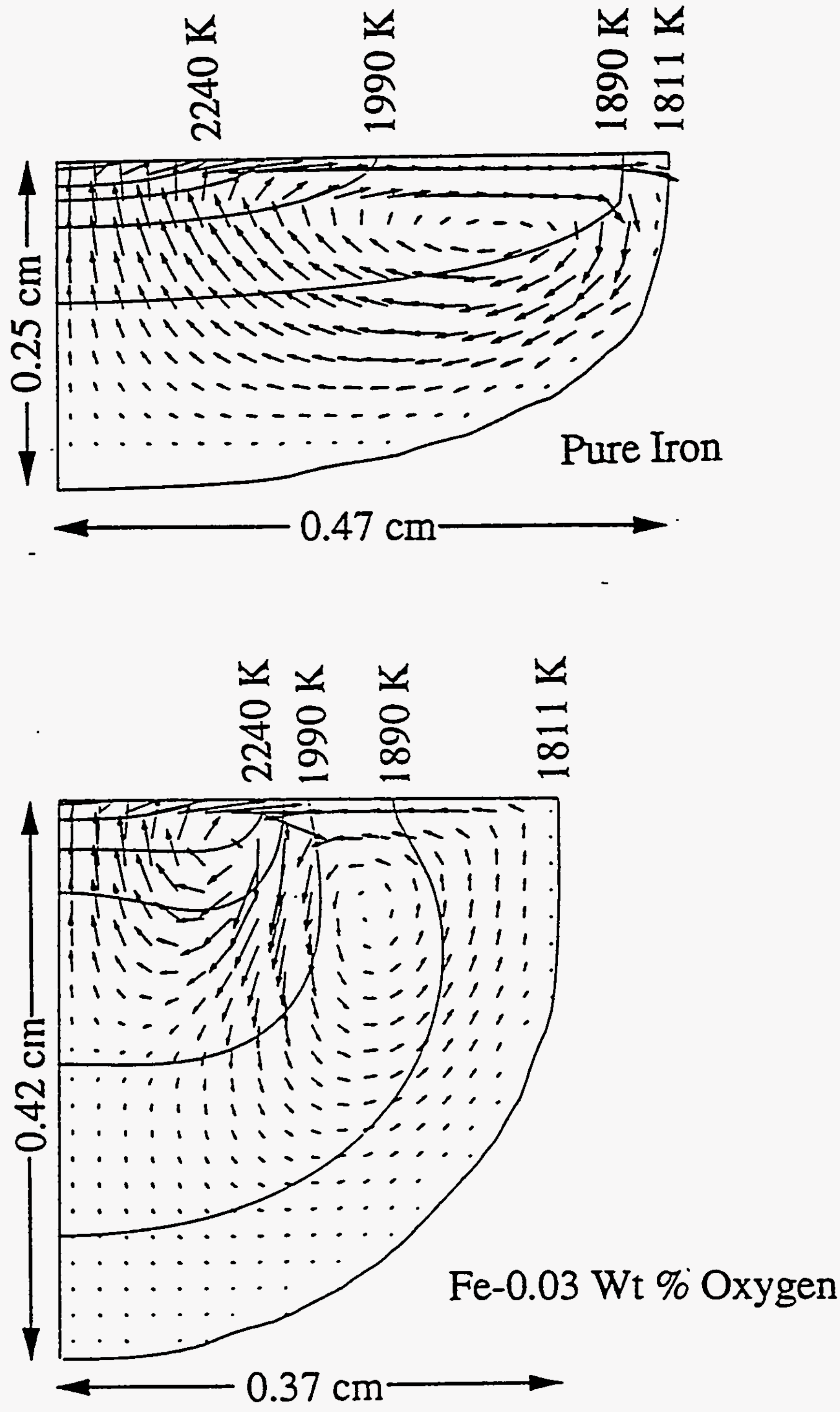

Fig. 1 Velocity and temperature fields for two different cases: (a) for pure iron and (b) iron with 0.03 wt % oxygen.

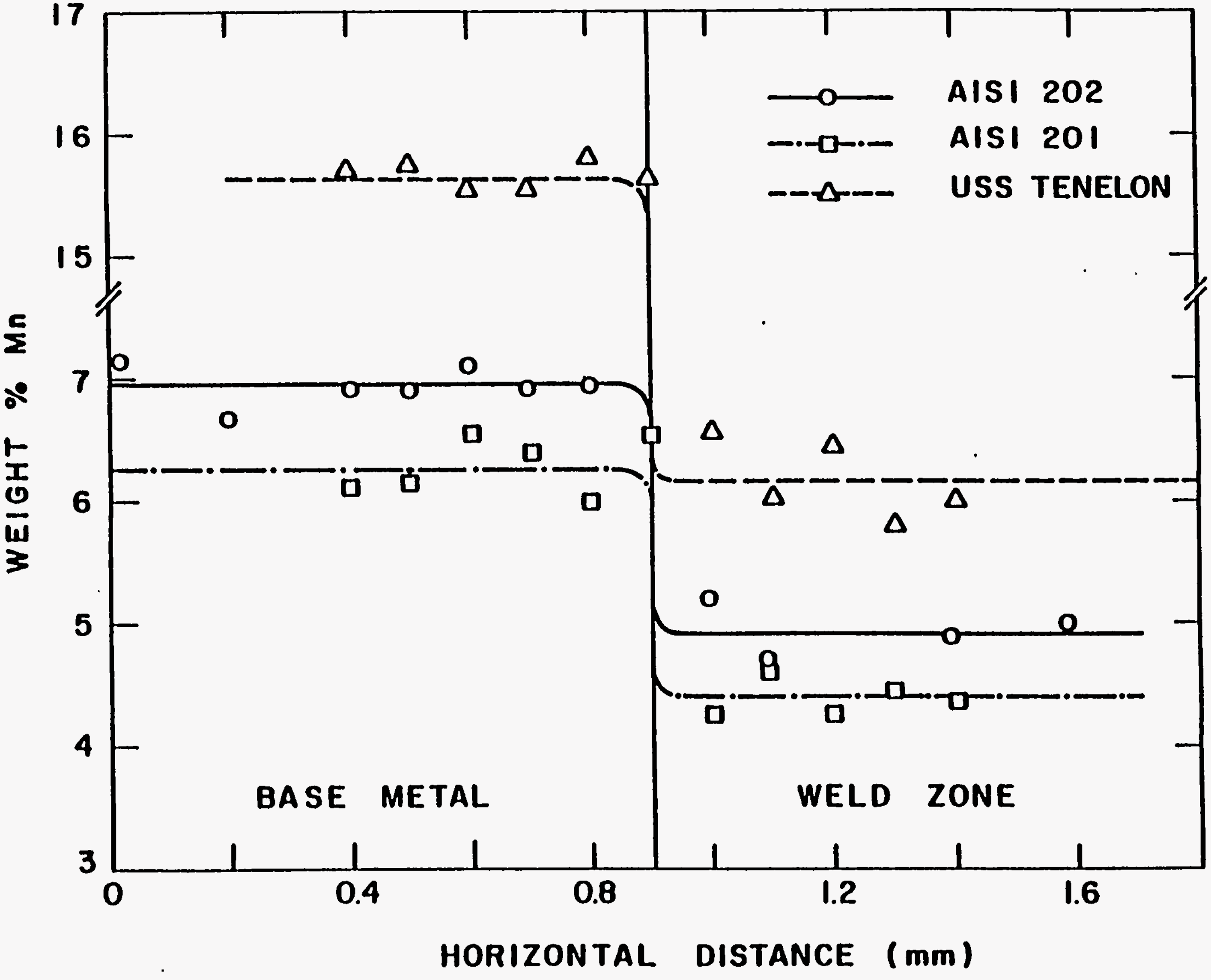

Fig. 2 Concentration of manganese versus distance in the base metal and in the weld zone for continuous wave carbon dioxide laser welding. Laser power: 560 watts, welding speed: 3.5 x 10^{-3} m/s, shielding gas flow rate: 10^{-4} m^3/s, and sample thickness: 7 x 10^{-4} m.

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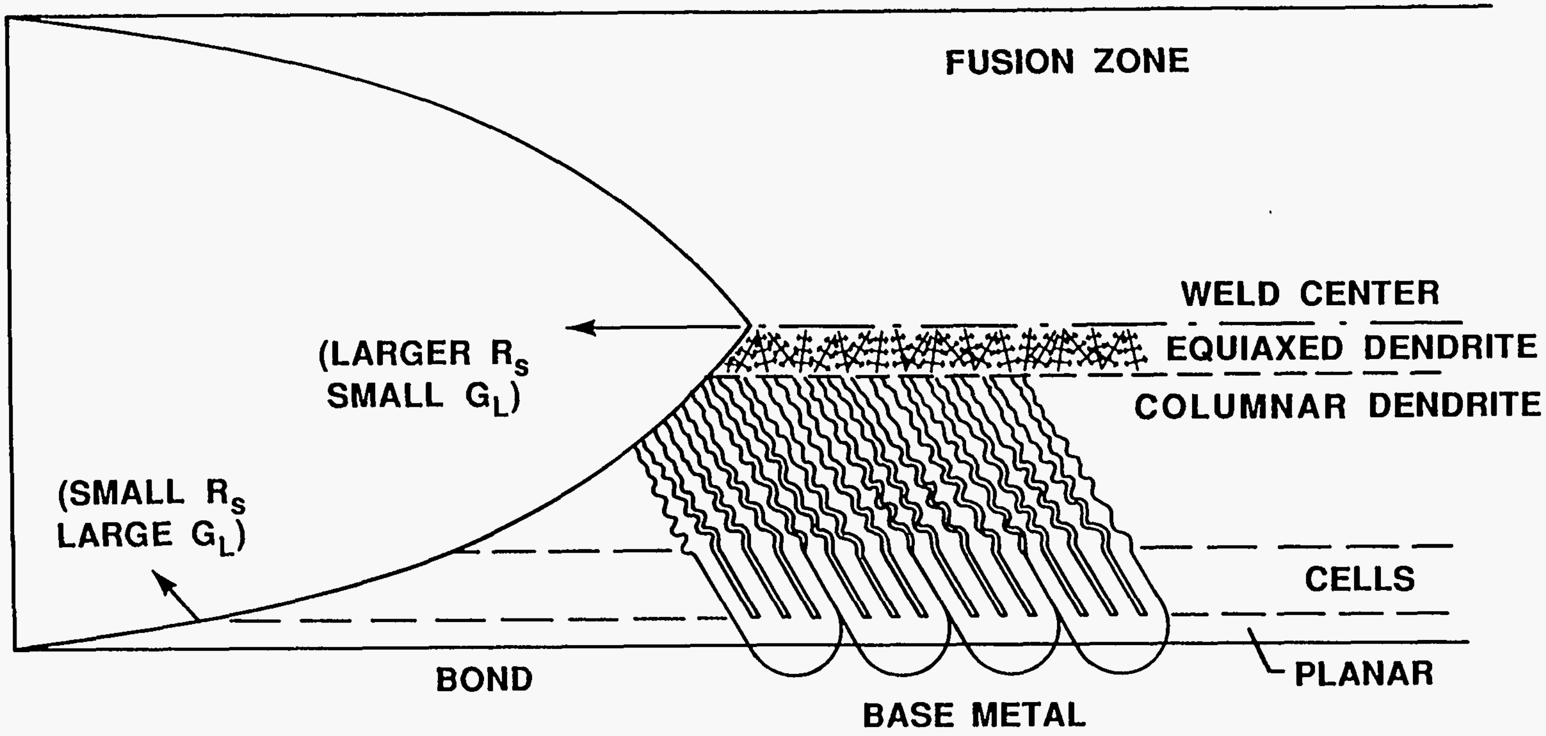

Fig. 3 Schematic drawing of structural variation of weld microstructure across fusion zone

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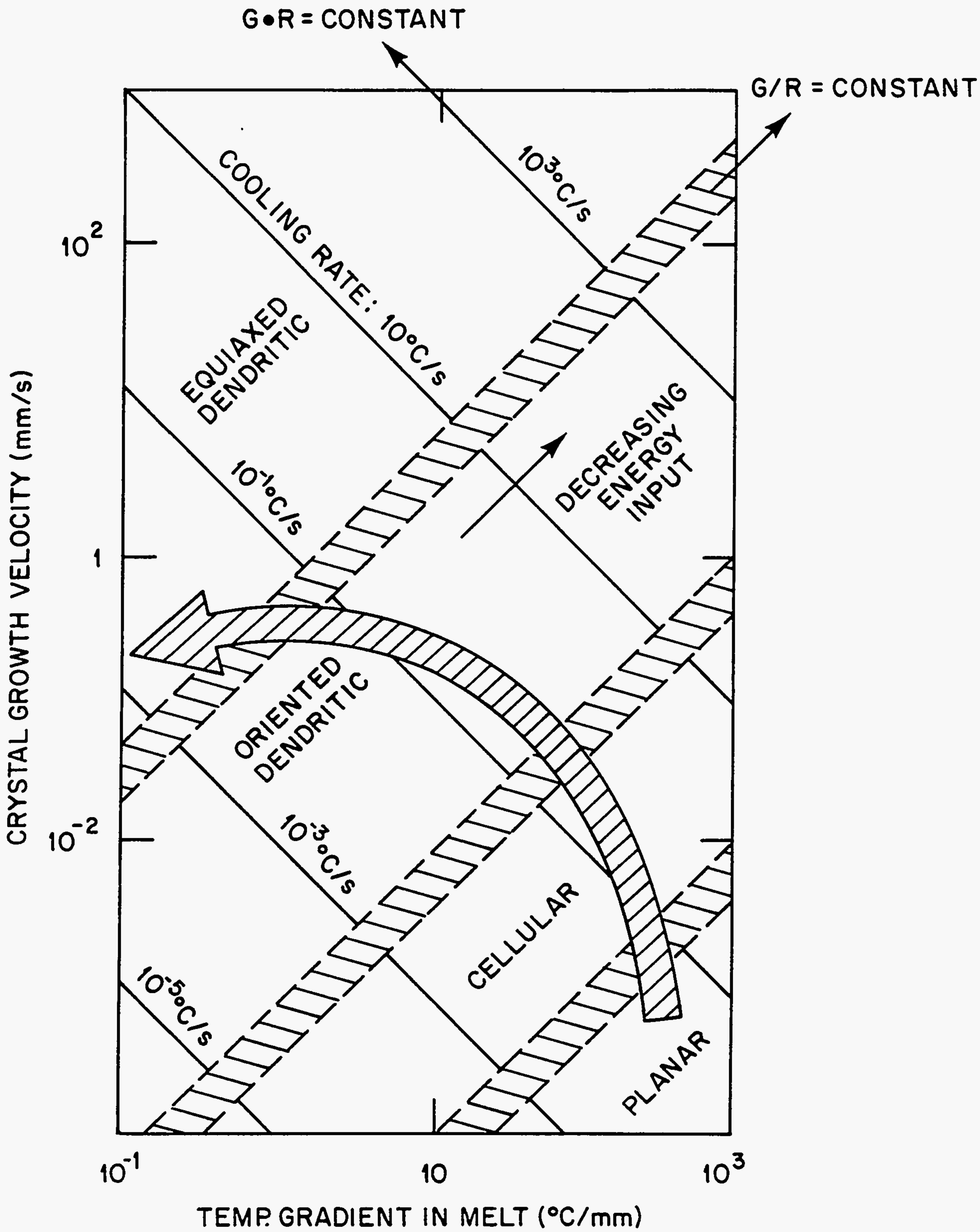

Fig. 4 Variation of weld microstructure as function of temperature gradient, growth rate, and combination of these variables (G_L, G/R). The arrow indicates the range of microstructures and growth conditions encountered in a weld.

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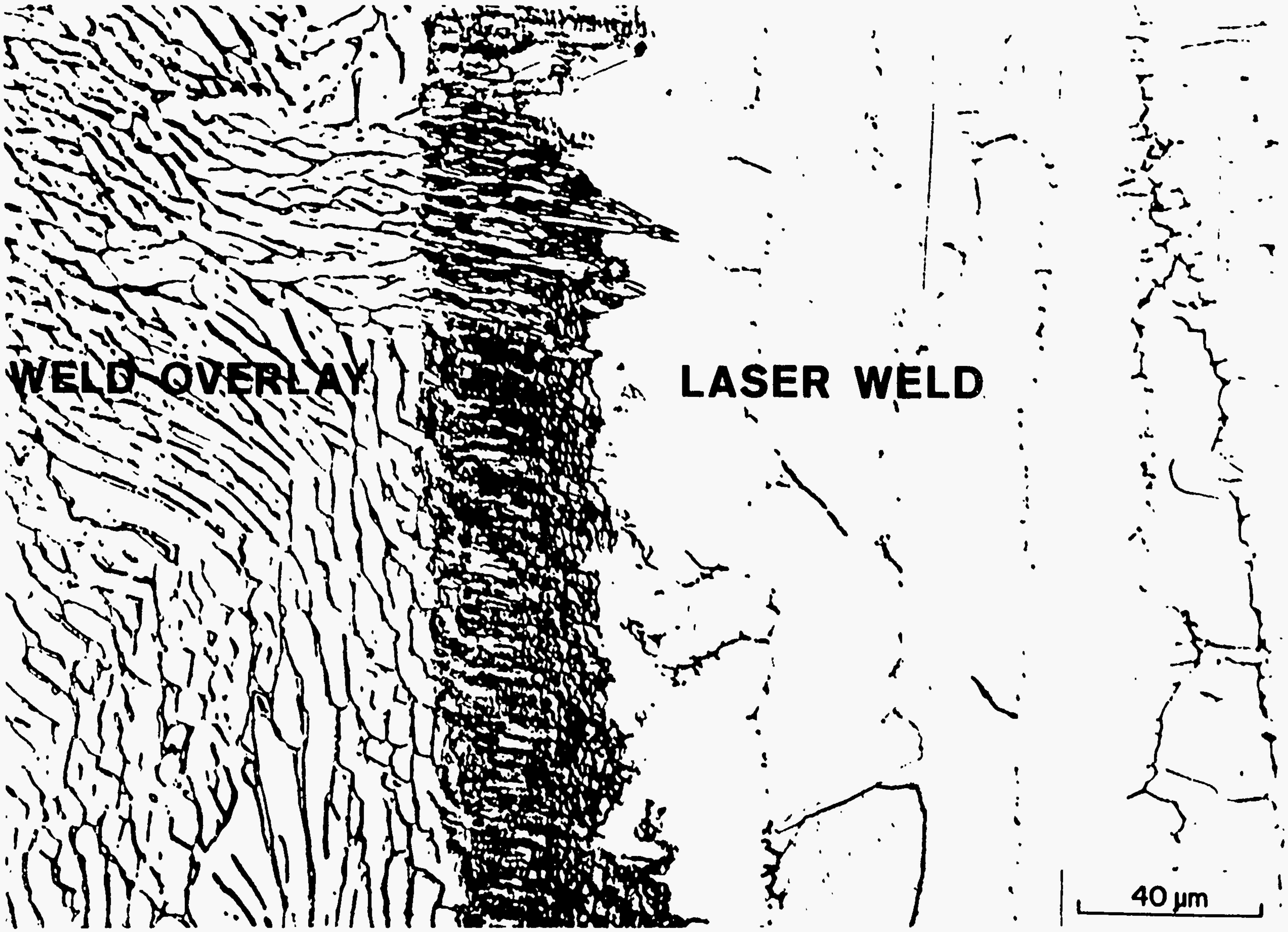

Fig. 5 Duplex (austenite plus ferrite) structure in conventional weld overlay and fully austenitic structure in laser weld region of type 308 stainless steel.

Fig. 6 Scanning electron micrograph showing the development of dendrites in a nickel-based superalloy single-crystal weld.

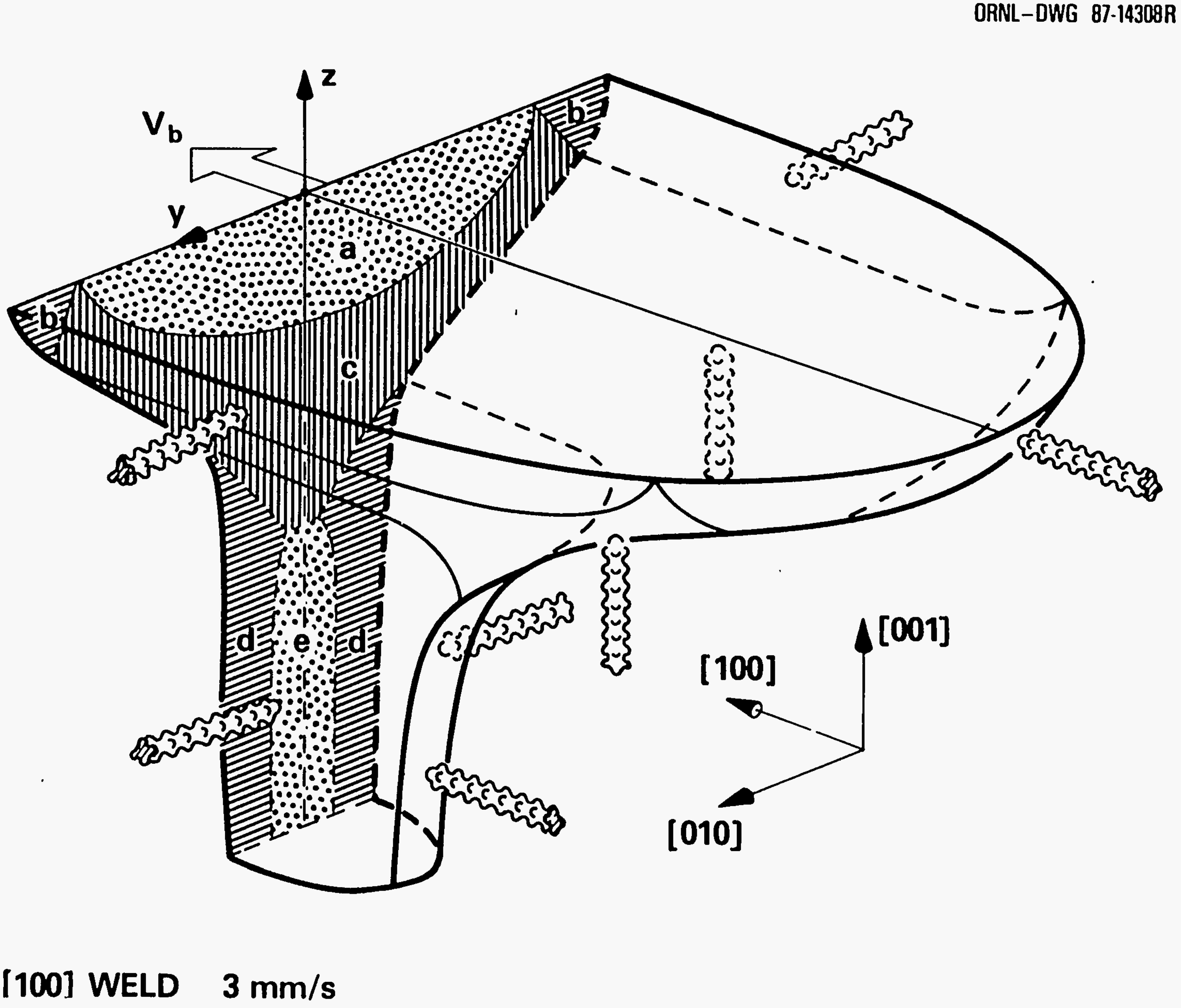

Fig. 7 Reconstructed three-dimensional diagram of a weld pool showing the development of weld microstructural features.

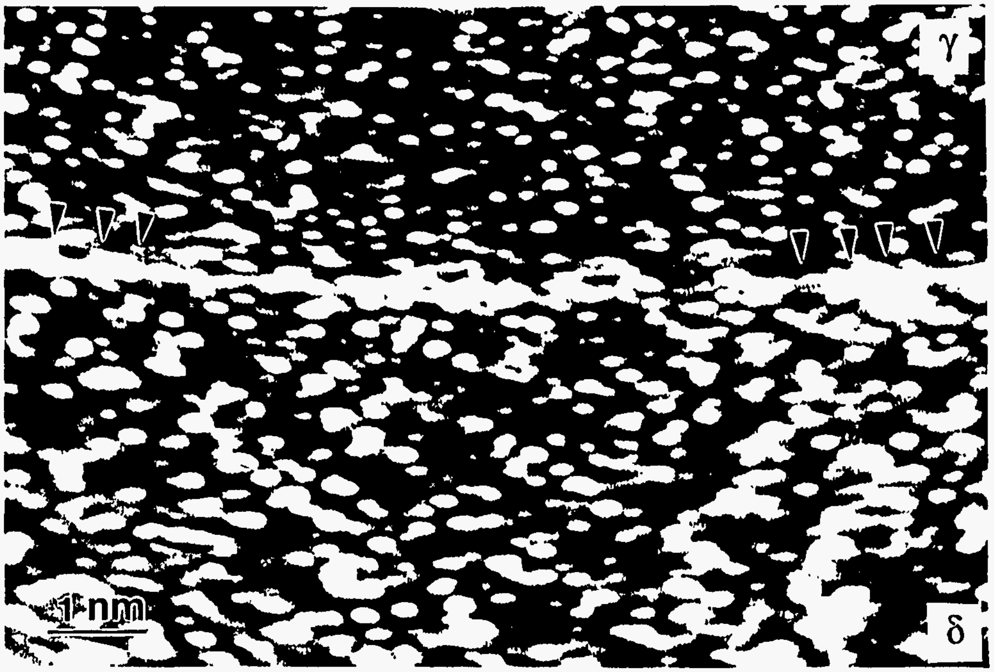

Fig. 8 Field ion micrograph of the as-welded sample showing austenite (γ) - ferrite (α) boundary.