

## The Use of Complex, but Inexpensive, Thermo-Mechanical Processing to Illustrate a Range of Engineering Principles in an Integrated and Synergistic Manner

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### Abstract

The events that occur in metallic materials heated to high temperatures in the dynamic processing environment associated with an arc or beam welding operation can be used to illustrate a broad range of fundamental scientific and engineering concepts in a holistic manner. Moreover, the process and resultant weld are of inherent interest to students. The specific application studied in this laboratory is the addition of small amounts of nitrogen to alter microstructure in the weld deposit. Understanding the process requires the integrated use of thermodynamics, kinetics, physics, chemistry, solidification, heat and mass transfer, phase stability and materials engineering.

Few laboratory experiences allow engineers to explore the performance of real engineering materials at homologous temperatures greater than 0.8. Fewer still enable students to relate material performance at these temperatures to the microstructure of the material. Moreover, the relationship of material properties at lower temperatures are rarely graphically and directly connected to the conditioning of a material at higher temperatures. This paper describes the conception and execution of a laboratory to improve undergraduate students understanding of complex material behaviors. In addition it includes portions which enable the student to quantify phenomena often discussed only in a qualitative fashion. Laboratory procedure for the experiment is described in detail. The laboratory presents theory and application in natural fashion, linked and mutually supportive. The paper discusses the exceptionally positive impact that this immediacy has on student learning.

### Introduction

There is renewed emphasis on laboratory experience and project based learning in undergraduate engineering education, coupled with widespread belief that interdisciplinary exposure is critical to the development of the prototype engineer for the 21<sup>st</sup> Century. The Accreditation Board for Engineering and Technology, (ABET), has asserted as much in their newest criteria for engineering programs. Emphasis on a more holistic approach to engineering education has gained widespread acceptance. A new “premise” is evolving in education, simply stated this assertion could be phrased “It is much better to learn by doing something, even in a very controlled environment, than to learn by simply talking about something *or talking about doing something*, even in a very free and open environment.” Furthermore, this “postulate” has a corollary associated with it – that the need to “learn by doing” becomes more critical as students progress through the curriculum, as does the need for interdisciplinary and multidisciplinary

exposure. The closer students come to leaving the discipline-dominated world of academia and entering the function-driven world of corporate America, the more their academic experience and environment should resemble the world beyond the “ivy-covered” walls.

Therefore, well-developed and well-conceived laboratories are a key component in student learning, underpin subsequent independent project based learning and support the development of engineering judgment. Moreover, laboratories and project based learning opportunities provide alternative means of accommodating the ever-increasing variety of learning styles represented in our classrooms. Laboratories can re-energize students and give them the skill-set required to demonstrate the outcomes mandated in ABET’s Engineering Criteria 2000. (1) This paper describes an inexpensive approach to providing a rich laboratory experience accessible to a broad cross-section of engineering majors. Indeed, this laboratory experience is embellished by the participation of students from different majors, who ostensibly would have different core competencies. Even in difficult economic times laboratories can provide a return much greater than the investment required to create them, and a value far in excess of their cost.

To be effective laboratories must put students “in the moment”. That is, laboratories must have an apparent reality, they must be challenging and they must have verisimilitude to engineering practice. In creating the laboratory we must walk a very fine line. We must ensure that our students understand the goals of the laboratory, but not rob them of the joy of discovery. We cannot waste laboratory time, but must avoid being formulaic or plodding. Most of all, we must keep a novelty and a healthy uncertainty associated with the laboratory experience. Paradoxically, the willingness to embrace uncertainty, and the ability to make decisions when data is incomplete are key features in the make-up of successful engineers. Thus, laboratory experiences should hold the same attraction and delight for our students as research and applications laboratories possess for our graduates. Applied researchers go to the laboratory to entice truth from an impassive natural world. Their aim is to sense, to assess, and, eventually, to advance. A well planned instructional laboratory enables students to realize these same goals.

Laboratories are a necessary interlude during which students discover the value of collective experience and collaboration, and develop skills in sharing and exchanging information. Laboratories, then, create a microcosm of, and a brief segue to, behaviors that are analogous to the stimulating milieu encountered in authentic occupational environments. They provide a prospect for legitimate eureka events that can rouse intellectual fires which can blaze for decades and which can afford illumination that reaches far beyond evident borders of the exercise. Laboratories that immerse students in significant tasks engender acceptance of ambiguity and apparent contradictions that place students on the path to the development of engineering judgment.

### **Theoretical Background Importance**

Welding operations are used for fabrication of stainless steel materials employed in components of systems used in a variety of industries, most notably the power, nuclear, food processing and chemical industries. Welding alters the microstructure of the materials welded, through the rapid thermal cycling, the solidification processing and the alloying inherent to the process. The amount of delta ferrite present in weld deposits associated with welds in stainless steel is

recognized to have a key role in hot cracking, fissuring, corrosion and embrittlement during service.

### **Bead Shape**

Melting and solidification are two of the most important reactions involved in fusion welding. In a sense they may be regarded as competing processes which occur simultaneously, each at its own characteristic rate. Thus, at the melting temperature of a pure metal, both solid and liquid may coexist in equilibrium with one another, and one can say that the rates of melting and solidification are equal. If we cool the pure metal to slightly below its melting temperature, the rate of solidification becomes dominant, and the rate of growth of the solid phase is controlled by the rate at which the latent heat liberated can be conducted to the surroundings. Thus, one can say that the control of melting and solidification of a pure metal is strictly a heat flow problem.

Most metals of commercial importance are alloys and, as such, impose an additional constraint on the melting and solidification processes. Except for eutectics and the comparatively rare congruent-melting alloys which exhibit discrete melting points, alloys exhibit a melting temperature range. In general, the composition of the solid and liquid phases in equilibrium with each other are a function of temperature within the melting temperature range. Thus, in addition to the necessity of dissipating the latent heat of fusion, solidification of an alloy involves the redistribution of solute as well. Therefore, the solidification of an alloy involves both heat transfer and mass transfer, and it is important to understand their roles in the solidification of a fusion weld.

### **Solidification Mechanics (2,3)**

In the production of a fusion weld, a molten weld pool is established and, through control of the process variables, is made to travel at a constant rate without significantly changing its shape. Figure 1 is a schematic representation of an elliptical weld pool with a bounding surface defined by locus of the liquidus temperature of the alloy. Surrounding the weld pool in figure 1 is a dashed curve corresponding to the locus of the effective solidus of the alloy – which is always lower than the nominal solidus expected for any given composition. The volume of the molten phase present varies in a continuous fashion from 0 at the dashed line to 100% at the solid line bounding the weld pool. Unfortunately, the existence and practical significance of this region, called the *partially melted zone*, is not widely recognized. Nor is the presence of a completely liquid “unmixed zone” between the partially melted zone and the weld pool where convection occurs. This unmixed zone forms as a result of basic fluid mechanics, it is the boundary layer in this fluid system. It presents a barrier where mass transfer occurs only by diffusion.

Assume that the weld pool shown in Figure 1 is created by a heat source located at 0 and moving from right to left with a velocity,  $V$ . In an autogenous bead-on-plate weld, melting will be occurring along the leading edge, ABC, of the weld pool. This requires that the latent heat of fusion be supplied to convert the solid to a liquid at the liquidus temperature. At the trailing surface of the weld pool, CDEA, the latent heat of fusion must be liberated to cause solidification to occur. On the average, the growth of the solid occurs parallel to the maximum temperature gradient, which is perpendicular to the advancing solid-liquid interface, CDEA.

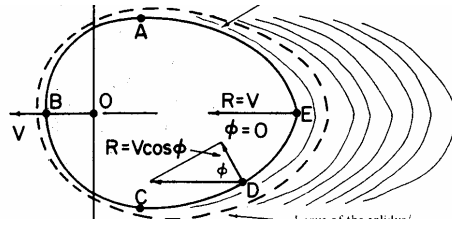


Figure 1. Schematic of a moving pool.

This means that if the shape of the weld pool remains constant, the growth rate of the solid must be given by:

$$R = V \cos \varphi \quad (\text{Eq. 1})$$

Where,  $R$  = growth rate of the solid at a given point on the moving solid-liquid interface,  $V$  = welding velocity and  $\varphi$  = angle between the normal to the interface at the particular point (in other words, the average growth direction) and the welding velocity vector. Thus, the growth velocity would vary from  $R = 0$  at the sides of the pool (Points A and C) where  $\varphi = 90$ , to a maximum of  $R = V$  at the centerline of the weld (Point E) where  $\varphi = 0$ .

Since the rate of liberation of latent heat is directly proportional to the rate of growth of the solid, the rate of heat liberation is maximized at the weld centerline. Unfortunately, the minimum temperature gradient, and therefore the minimum capability to conduct the latent heat to the cooler surroundings, is found at this location. Consequently, when welding velocity reaches a critical value,  $V_c$ , such that the rate of growth parallel to the welding direction can no longer be sustained, the weld pool will assume a teardrop shape. Note that, when the pool assumes a teardrop shape, the minimum value of  $\varphi$  is increased, and therefore, since  $R = V \cos \varphi$ , the maximum growth rate is reduced. As the velocity is further increased above  $V_c$ , the minimum value of  $\varphi$  also increases in order to balance the maximum rate of liberation of latent heat with the rate of conduction of this heat to the surroundings.

The volume of the weld pool ( $\text{Vol}_p$ ) is directly proportional to the welding current ( $I$ ) and inversely proportional to the welding velocity ( $V$ ).

$$\text{Vol}_p = c (I/V) \quad (\text{Eq. 2})$$

Therefore, increasing the welding current at constant velocity increases the volume of the weld pool without greatly altering its shape. On the other hand, increasing the welding velocity at constant current both decreases the volume of the pool and increases the ratio of its length to its width. The critical velocity at which the pool assumes a teardrop shape is inversely proportional to the welding current.

### Epitaxial Growth (2-4)

In a properly made fusion weld, the base metal is wet by the molten metal in the weld pool and, being similar in composition, acts as an ideal substrate upon which growth of the solid phase can occur. Thus, to extend the solid phase, atoms from the liquid merely surrender their latent heat of fusion to the surroundings and occupy positions corresponding to lattice sites in an extension of the crystal structure of the existing solid. All grain boundaries are continuous across the

boundaries of the fusion zone. During solidification, atoms from the liquid liberated their latent heat of fusion to join and extend the crystal structure of the individual grains along the moving solid-liquid interface. The continuity of the orientation luster and the complete absence of grain boundaries parallel to the boundaries of the fusion zone provide visual evidence in support of this growth mechanism, known as epitaxial growth. Investigators have conclusively proven that growth is indeed epitaxial with the aid of microbeam x-ray diffraction techniques.

### **Competitive Growth (3,4)**

The shape of the grains in the fusion zone is controlled by the shape of the weld pool through the action of a phenomenon known as competitive growth. As noted earlier, the average growth direction during solidification of a fusion weld is approximately perpendicular to the solid-liquid surface at all points in the weld pool. However, the growth of each individual grain tends to occur parallel to a particular crystallographic direction, called the *easy growth direction*. In cubic metals, this is a  $\langle 100 \rangle$ , or cube-edge direction. In hexagonal-close-packed metals, it is the  $\langle 1010 \rangle$  direction, which corresponds to the close packed direction in the basal plane. Because of this phenomenon, the shape of the weld pool has an important influence on the shape of the grains in the fusion zone.

Since growth is epitaxial, certain grains growing out of the partially melted region across the fusion boundary will have their easy growth direction parallel, or nearly parallel, to the maximum temperature gradient. Such favorable orientation gives these grains a competitive advantage over adjacent, less favorably oriented grains, in the region just inside the fusion boundary. In the case of an elliptical weld pool, the temperature gradient changes continuously from normal to the welding direction at the fusion boundary to parallel to the welding direction at the weld centerline. Thus, with an elliptical weld pool, the grains tend to curve in the direction of welding as they follow the moving solid-liquid interface, and the competitive advantage shifts from grain to grain as the continual reorientation of the maximum temperature favors differing crystallographic orientations. Note also that each grain in an elliptical shaped pool tends to maintain contact with the moving solid-liquid interface until it is pinched off in a random fashion by neighboring grains.

On the other hand, within a teardrop shaped pool the orientation of the maximum temperature gradient is invariant over a significant portion of the trailing edge of the weld pool. Consequently, when a grain which has a favorably oriented easy-growth direction encounters this region where the orientation of the maximum temperature gradient no longer changes, the favorably oriented grain crowds out its less favorably oriented neighbors. Thus, only grains whose easy growth directions parallel the direction of the invariant maximum gradient survive the competitive growth process. This causes impingement of favorably oriented grains from opposite sides of the weld pool along the center of the weld. A teardrop shaped pool tends to produce a high degree of preferred orientation in the weld. Such a texture could, in some instances, cause dangerous directional differences in the mechanical properties of the weld.

### **Interface Stability (5-9)**

Commercial solidification processes are never equilibrium in nature, since the transformation from liquid to solid occurs in finite time. Thus, the interpretation of the solidification process through the phase diagram must be modified to account for the kinetics of the diffusional processes involved.

Scheil made an initial attempt, modifying the mass balances inherent in the lever law by assuming that no diffusion occurred in the solid state once a solid had been formed. He also assumed that mechanical mixing in the remaining liquid would be complete, that the solid interface was planar and that at any given temperature, and that the composition of the solid forming from the liquid would be as dictated by the phase diagram. This approach was refined by Tiller, who used all of the assumptions of Scheil, save for that of complete mixing of the solute in the liquid. Because of this last refinement, a processing parameter,  $R$ , the growth rate, appears in the equations for the composition found in the liquid as a function of distance from the solid-liquid interface. This approach leads to the modeling of the composition of the liquid near the interface as a transient region in which the liquid composition falls from  $C_0/k$  to  $C_0$  over five characteristic distances from the interface- the characteristic distance is given by the expression  $5D_l/R$ , where  $C_0$  is the nominal composition of the material,  $k$  is the equilibrium distribution coefficient, and  $D_l$  is the diffusion rate in the liquid. The major difference between the two approaches is that in Tiller's model, the majority of the solid forms in a steady state stage, and is of nominal composition. In Scheil's model, the solid composition varies continuously because no steady state is reached. Both predict the same invariant composition at the end of solidification.

The value of Tiller's contribution is in its establishing the existence of a solute field in the liquid ahead of the solid – liquid interface. This development led directly to the discovery of the phenomenon of constitutional supercooling, and an understanding of the breakdown of the planar solidification interface which leads to different solidification morphologies. Chalmers first recognized this, and combined an expression for the solute concentration ahead of the interface with one for the phase diagram liquidus curve to generate a relation between the “effective liquidus” and position. The result showed that the liquidus temperature reaches a minimum at the solid-liquid interface and rises to a maximum at the end of the solute spike. Depending on the actual temperature distribution in the liquid, a region of “constitutional supercooling” can extend into the liquid, and chance protuberances at the interface can grow into this region. Depending on the extent of this supercooling, different solidification substructures can form, which drastically alter the properties of the solid.

### **Solidification and Transformation Structures Specific to Austenitic Stainless Steel**

The equilibrium solidification behaviors of austenitic stainless steels may be determined from the Fe-N-Cr ternary diagram. This diagram is provided to students in this laboratory. A eutectic trough extends from the iron-rich corner of the diagram toward the Cr-Ni side of the diagram. Alloys located on the Ni rich side of this trough exhibit primary-austenite solidification, those located on the Cr rich side of the trough exhibit primary-ferrite solidification. This solidification behavior becomes even more clear when students are given a Fe-Cr-Ni pseudobinary diagram taken at 70% Fe. Alloys on the Ni-rich side of the eutectic triangle solidify as primary austenite, during the final stages of solidification, some eutectic ferrite may form in intercellular regions of the solidification substructure. The austenite and most of the ferrite are then stable to room temperature. Alloys located on the Cr-rich side of the eutectic triangle solidify in the primary-ferrite solidification mode. The ferrite transforms to austenite on subsequent cooling, some ferrite will remain at room temperature. The amount, distribution and morphology of the retained ferrite is thus a function of the primary solidification mode and of the composition of the base material. Other factors can also affect these characteristics, including heat input, solidification rate, cooling rate, shielding gas composition and weld dilution. These conditions

control the primary-ferrite dendrite size, the segregation of alloying elements and the extent of the transformation.

Hot cracking has been studied extensively, and even early works pointed to the benefits of ferrite content.(10,11) Alloying, solidification mode and cooling rate in concert determine the total amount of residual delta ferrite in a weld. As understanding of the phenomenon has evolved, the importance of primary solidification mode in stainless steels, and the relation this has to residual ferrite content has become more clear. (12-15) Alloys that solidify as primary ferrite partition damaging impurities to locations where they are less harmful, and are less susceptible to cracking than alloys which solidify as primary austenite. Alloys that solidify as primary ferrite will retain some stabilized ferrite to room temperature, with the balance transforming to austenite in solid-state reactions on cooling. Those that solidify as primary austenite do not produce appreciable ferrite on-cooling. Thus, residual ferrite is a proxy for solidification mode. Researchers demonstrated a clear relationship between primary solidification mode, alloy composition and crack sensitivity. Welds which solidified as primary ferrite were impervious to cracking over a wide range of sulfur or phosphorous contents, while those which solidified as primary austenite were susceptible to cracking at all but the lowest sulfur contents. Though delta ferrite content has a remarkable effect in decreasing the susceptibility to hot cracking, there are compositional effects which it does not overcome. Phosphorous, nitrogen, niobium and silicon still do cause serious cracking in deposits with significant delta ferrite content.

Weldability cannot be achieved by sacrificing the basic corrosion resistance of austenitic stainless steel. Wrought stainless steel is alloyed and processed to provide a corrosion resistant chemistry and austenitic microstructure. Austenitic stainless steels derive their high resistance to corrosion from the passive film which develops with sufficiently high levels of chromium. Carbon, a strong austenite stabilizer, is controlled at reduced levels in welded base metals to decrease the risk of sensitization by loss of grain boundary chromium through precipitation of chromium-rich  $M_{23}C_6$  carbides. Once 'sensitized' the HAZ becomes susceptible to subsequent intergranular corrosion. In general high ferrite content can lead to reduced resistance to pitting corrosion and to stress corrosion in hot chlorides or sour  $H_2S$  exposure. The amount and type of ferrite present also has a profound effect on corrosion behavior. Investigators have noted this in general corrosion, pitting corrosion, stress corrosion and intergranular corrosion. The importance of the ferrite-austenite boundary, and the amount of ferrite-austenite boundary in weldments has been discussed in detail. An optimal amount of ferrite appears to be particularly critical in the prevention of intergranular and stress corrosion cracking.(16-19) Efforts center on developing alternative stainless compositions which retain strength, but are not susceptible to sensitization or to intergranular stress corrosion cracking. Carbon and nitrogen have been reduced in such alloys, and Nb has been added. A group of alloys with controlled Mn and reduced phosphorous has also been added to target the latter problem.

Clearly predictable control of delta ferrite is crucial for two reasons. First a minimum of 4-5% of delta ferrite is required to provide the needed hot-crack resistance when welding fully austenitic stainless steels. Second, an upper limit to delta ferrite content must be maintained (7—8 %) to avoid segregation of Cr, Mo, and N out of austenite, or austenite-ferrite boundaries, and the accompanying loss of corrosion resistance to either pitting corrosion or stress corrosion cracking. The amount and distribution of the Cr, Mo, and N have been identified with specific

corrosion mechanisms. Thus a range for residual delta ferrite is established as between 4-7%. If carbon contents in the deposit are kept low, and appropriate levels of Cr are maintained in the electrode, controlled residual delta ferrite provides the needed resistance to hot cracking without markedly compromising the corrosion resistance.

Tremendous effort has been exerted by a number of investigators to correlate ferrite content to weld deposit chemistry. (20-23) A similar effort has been made to improve and to standardize methods to measure the ferrite content, and to reduce the variability in these measurements. (24,25) Schaffler was the first to publish a diagram which related austenite formers and ferrite formers, through a Ni equivalency and Cr equivalency concept, to deposit ferrite content. The diagram was based in the simple concept expressed in the Hume-Rothery rules of solid solubility. FCC elements, or those highly soluble in the FCC phase, would tend to stabilize the FCC phase in stainless steel. And likewise, BCC elements would tend to stabilize the BCC phase. Subsequent investigators have made incremental improvements to this diagram. More recent treatments have examined the effects of new elements added to stainless steel filler materials and extended the range of prediction to accommodate prediction of FN in dissimilar metal welds and cladding operations. The simple Cr and Ni equivalent approaches, though useful, do not take into account the full complexity of the elemental interactions, neither are they applicable over all ranges of operating parameters.

Researchers also examined the effect of welding process parameters on weld cracking sensitivity, and often related some of these effects to composition, and to ferrite content as well. (26-33) Much of the work which related nitrogen into the diagram was based in a knowledge that welding process often caused the acquisition of nitrogen. Furthermore, these investigators demonstrated that HAZ and base metal grain size can play a significant role in cracking sensitivity and even in solidification mode. Fine grained materials tend to promote ferrite formation. A number of investigators have demonstrated that the weld thermal cycle itself can have a profound affect on primary solidification mode. The rapid thermal cycle associated with high energy density processes, and the grossly non-equilibrium conditions actually suppresses the formation of ferrite, and causes a shift to primary austenite solidification at lower ratios of Ni equivalent to Cr equivalent. The original and residual ferrite content of primary austenite welds decreases with increased cooling rate, because solute segregation, which stabilizes ferrite, is reduced. Similarly, the residual ferrite content of primary ferrite welds increases because of the greater amount of ferrite that forms initially, and the reduced amount of ferrite which forms in solid state reactions during cooling.(34-38)

### **Desired Outcomes / Laboratory Objectives**

In accordance with ABET outcomes oriented assessment, laboratory objectives are shared with students at the beginning of each laboratory, as are the instructor's desired outcomes. The course objectives are measurable goals that indicate how well the instructor's laboratory outcomes are achieved. Benjamin Bloom developed a taxonomy for categorizing the level of abstraction in questions that commonly occur in educational settings.(39) Bloom listed six levels in his taxonomy. Bloom's first level was **knowledge**, which involved observation and recall of information, knowledge of facts, and knowledge of major ideas. Activities to measure outcomes desired at this level involve listing, defining, describing, identifying, labeling, and quoting. The second level is **comprehension** which involves understanding information, grasping meaning,



translating knowledge into new context, interpreting facts, inferring causes, and predicting consequences. Activities to measure outcomes desired at this level involve summarizing, contrasting, predicting and estimating, differentiating and extending. The third level is **application**, which involves using information, methods, concepts and theories in new situations, and solving problems using required skills or knowledge. Activities to measure outcomes desired at this level involve demonstrating points, calculating solutions, and solving challenges. The fourth level is **analysis**, which involves seeing patterns, organizing parts and identifying components. Activities to measure outcomes desired at this level involve analyzing, separating and classifying. The fifth level is **synthesis**, which involves using old ideas to create new ones, generalizing from given facts, relating knowledge from several areas and drawing conclusions. Activities to measure outcomes desired at this level involve combining information, integrating concepts, planning additional experiments, formulating hypothesis, and generalizing based on experience. The sixth level is **evaluation**, which involves comparing and discriminating between ideas, assessing the value of theories, reasoned argumentation and verifying value of evidence. Activities to measure outcomes desired at this level involve assessing, ranking, recommending, convincing, judging, explaining and concluding.

*Each laboratory should provide the opportunity to exercise all of these cognitive levels. Each student's personal interaction with equipment/tools will lead to the accumulation of knowledge and skills required in the practice-oriented engineering profession.*

### **Laboratory Learning Objectives**

This laboratory is meant to satisfy well known ABET outcomes. By completing this laboratory participating students will demonstrate an ability to:

1. Use simple and inexpensive engineering tools to create a profound educational experience.
2. Devise an experimental approach, specify appropriate equipment and a set of procedures and implement those procedures.
3. Demonstrate the ability to collect, analyze, interpret data, and form and support conclusions. Make order of magnitude judgments about data correctness.
4. Identify the limitations of theoretical models as predictors of real world behaviors. Be able to evaluate whether theory adequately describes a physical event and establish and/or validate a relationship between data and underlying physical principles. Integrate thermodynamic and kinetic data.
5. Recognize unsuccessful outcomes and faulty construction or design, and modify the experimental approach accordingly.
6. Demonstrate appropriate levels of independent thought, creativity, and capability in problem solving in the real world.
7. Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources.
8. Recognize health, safety, and environmental issues related to technological processes and activities and deal with them responsibly.
9. Communicate effectively with a specific audience, both orally and in writing, ranging from executive summaries to comprehensive technical reports.
10. Demonstrate the ability to work in teams, including structuring individual and joint accountability, assigning roles and responsibilities, partitioning work, monitoring progress, meeting deliverable deadlines, and effectively integrating individual contributions into a final deliverable.

### **The Instructor's Desired Outcomes**

Many outcomes are universally associated with laboratories, and differ only in context. However, several key outcomes, specific to this laboratory exist.

**The first outcome** is that students will understand the complex coupling between energy transfer from the welding power source and weld bead shape. **A second outcome** is that students will appreciate the phenomena of epitaxial nucleation and of competitive growth. These phenomena determine much of the microstructure we observe in the weld deposits. Furthermore, these phenomena underpin technologies critical the MEMS and even nanotechnology. **A third outcome** is that students will realize that the flow in molten pool is a critical factor in determining the bead shape, and that energy transfer in the pool is determined more by convection than conduction. Furthermore, they will realize that surface tension is a key force in weld pool fluid dynamics – and thus in pool shape determination. **A fourth outcome** is that students will appreciate that the effects of “minor” elements are not minor. Some elements, even at very low concentrations, can have dramatic impact on critical material properties. Apparently disproportionate affects are usually attributable to the concentration of the element at locations of singular importance in a material. This is seen in this laboratory in the effects of sulfur on macroscopic bead shape and in the effects of dissolved nitrogen on solidification mode. **A fifth outcome** is that students will understand the effects of non-equilibrium solidification on structure and elemental distribution in weldments. Students will understand the ramifications these have for subsequent behavior of welded structures in a variety of engineering applications. **A sixth outcome** is that students will be aware of the effects that the inherent heterogeneity characteristic of materials creates in material behavior. Students will easily observe how rapid heating creates liquid phases in otherwise solid systems. The abrupt appearance of liquid in a solid body can have drastic effects on mechanical properties, particularly when the liquid forms a continuous inter-granular film. Rapid heating can cause the formation of a liquid phase at temperatures far below that predicted by equilibrium treatments.

### **Equipment**

The equipment necessary for this laboratory is:

- A GTAW Welding Power Supply, and welding system. (An automated system is preferred, but a manual system is acceptable).
- Welding Safety Equipment
- A source of welding grade Argon
- A source of welding grade Argon containing 1 to 2 % Nitrogen
- Optical Microscopy Sample Preparation
- Optical Microscopy System with Image Capture and Quantitative Image Analysis Capability
- Magnegage apparatus

### **Materials and Procedure**

Two different heats of AISI 304 stainless steel are required for this laboratory. The materials should be provided in the annealed condition, as bars 10” X 2” X 1/2”. Both heats should be of a standard composition that produces primary ferrite solidification. (The majority of AISI 304 SS produced solidifies in the primary ferrite mode.) One heat should contain sulfur at compositions less than 50 ppm. The other heat should contain sulfur in excess of 100 ppm. Student groups are given one of each type of sample. They are asked to clean and degrease the surface of the sulfur rich sample and fix it to the surface of the welding table, ensuring good electrical contact. Using Ar shielding the students are asked to deposit a weld bead approximate 3/8” wide over a 8” length of the sample. The students are then asked again clean the sample, turn it over and weld it

in a similar fashion using the Ar – 1% Nitrogen as shielding. Students are asked to make a transverse cut in the welded sample, mount it, and polish through 1u alumina. The sample is then etched using oxalic acid in an electrolytic procedure, in order to render the microstructure visible. The students then repeat the process with the sulfur-poor sample.

Microstructures typical of the sulfur-poor weld with and without added nitrogen are shown in Figure 2. Note the profound difference in solidification substructure, but the striking similarity of substructure at weld interface. This result typically creates a stir among the students!

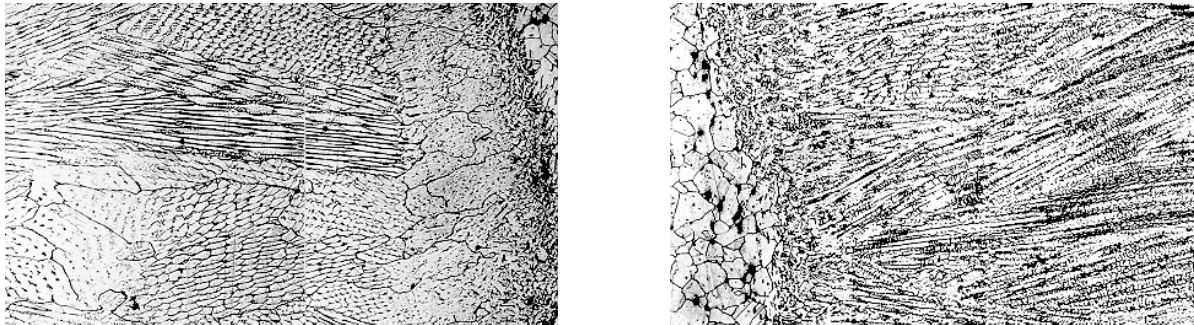


Figure 2. Primary austenite structure, driven by additions of nitrogen to the shielding gas (left). Primary ferrite substructure (right).

Students are asked to explain both the similarities and the difference in the two structures in terms of both bead shape and of primary solidification microstructure. They are asked to explain why the beads in the sulfur-rich materials and sulfur-poor materials have such different bead shapes. The sulfur present in excess of approximately 75ppm alters the flow in the weld pool so that the depth to width ratio in the pools differ greatly. High sulfur pools have ratios near or in excess of one, low sulfur pools have ratios far below one.

Students are asked to describe the microstructures observed, and then to quantify the ferrite present using both optical methods and magnegage measurement.

Students are asked to measure primary dendrite arm spacing using the image analyzer. They are asked to relate this to processing parameters.

Students are asked to discuss the implications these structures have for material behavior in hypothetical environments, typical of those encountered by stainless steel assemblies.

### **Reporting**

Students are required to keep a laboratory logbook, listing work done and observations made on each lab day. The lab book is signed and dated by all group members. Each group is asked to prepare a detailed formal laboratory report describing the experiment, providing data, discussing results and offering conclusions and suggestions for further study. The report must contain a one-page executive summary. In their report, the students are also asked to evaluate the laboratory and asked to suggest improvements. In addition to the verbal communication inherent in daily laboratory operation, groups are also asked to report their findings orally. During the oral presentation groups are asked questions about other alloy systems, and the effects of other

process parameters that provide the students with “intellectual launch-pads” and mental “room to roam”.

### **Evaluation**

Students are evaluated by group and as individuals. Rewards (grades) are provided based on a corporate model. The instructor evaluates groups; rewards (points) available to each lab group are based on group outcomes, such as the quality of the report and presentation. The instructor bases individual rewards (grades) to group members on a collective assessment of each member by other members of the group; however, the total points available to the group delimit rewards. As instructors, we can take a lesson from corporate America – rewards available to each lab group are based on group outcomes, individual rewards to group members are based on a collective assessment of each member by the instructor and by the group. This Shared Responsibility / Shared Reward model is critical to intellectual and social growth . One key to productive laboratories is the acknowledgment of each student’s individual responsibility for group achievement. The effort required to accomplish laboratory goals should exceed the capacity of any single student, and require the sustained coordinated effort of the laboratory team. The instructor must develop an open learning environment and promote interdependence while fostering individual responsibility.

### **Conclusion**

Student experience with the laboratory has been very positive. Comments indicate that students are interested in the material and energized by it. The opportunity for genuine discovery, even though “engineered” into the laboratory, is considered a strong vehicle to help students develop true professionalism, even while cloistered in the academic setting.

Solidification processing and other manufacturing processes based on epitaxial nucleation and growth are critical to a number of technologies. Arguably, they support much of the metals industry, underpinning transportation and transport, infrastructure, and many other sectors. In addition, our current communications, electronics and computing industries – the keys to our information age and the basis for our development of the “knowledge” economy of the 21<sup>st</sup> century rely on epitaxial processing. Clearly, from ships to chips, our economy relies on an ability to manipulate process parameters to produce desirable structures at inter-phase interfaces – in large welds or in minute electronic or electro – mechanical systems. Sadly, the study of nucleation, growth and interfacial stability often lacks immediacy and any connection to the commercial world. This laboratory has remedied that for many of our students, in an inexpensive way.

### **References**

- 1) ABET: Criteria for Accrediting Engineering Programs, Engineering Accreditation Commission, Accreditation Board for Engineering and Technology, Baltimore, MD, November, 2001.
- 2) W.F. Savage, C.D. Lundin, A.H. Aronson, “Weld Metal Solidification Mechanics” , *Welding Journal*, 44, 4, 175s, 1965
- 3) W.F. Savage, C.D. Lundin, T.F. Chase, “An Investigation of the Solidification Mechanics of Fusion Welds in Face-Centered Cubic Materials” , *Welding Journal*, 49, 11, 522s, 1968.
- 4) W.F. Savage, A.H. Aronson, “Preferred Orientation in the Weld Fusion Zone” , *Welding Journal*, 45, 2, 85s, 1966

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- 5) E. Scheil, *Zeit. Metallk.*, 1942, Vol. 34, p70.
- 6) W.A. Tiller, J.W. Rutter, "The Effect of Growth Condition on the Solidification of Binary Alloys", *Canadian Journal of Physics*, 34, 96, 1956.
- 7) W.A. Tiller, K.A. Jackson, J.W. Rutter, B. Chalmers, "The Redistribution of Solute Atoms During Solidification of Metals", *Acta Metallurgica*, Vol. 1, 1953.
- 8) L.R. Morris, W.C. Winegard, "The Cell to Dendrite Transition", *Journal of Crystal Growth*, 6, 134, 1969
- 9) B. Chalmers, *Principles of Solidification*, p260ff, John Wiley and Sons, Inc. New York, 1964
- 10) J.C. Borland, R.N. Younger, "The Ferrite Content of Austenitic Stainless Steel Weld Metal," *British Welding Journal*, 7, 12, p22, (1960)
- 11) C.J. Long, W.T. DeLong, "The Ferrite Content of Austenitic Stainless Steel Weld Metal," *Welding Journal*, 52, 7, 281s, (1973)
- 12) C.D. Lundin, W.T. DeLong, D.F. Spond, "The Ferrite Fissuring Relationship in Austenitic Stainless Steel Weld Metal," *Welding Journal*, 54, 8, 241s, (1975)
- 13) AWS Standard A4.2-74, "Standard Procedure for the Calibration of Magnetic Instruments to Measure Delta Ferrite Content of Austenitic Stainless Steel Weld Metal", Miami, FL, 1974
- 14) D.J. Kotecki, T.A. Siewert "WRC 1992 Constitution Diagram for Stainless Steel Weld Metals," *Welding Journal*, 71, 5, 171s, (1992)
- 15) V.P. Kujanpaa, S.A. David, C.L. White, "Formation of Hot Cracks in Austenitic Stainless Steel Welds," *Welding Journal*, 65, 8, 203s, (1986)
- 16) V.P. Kujanpaa, S.A. David, C.L. White, "Characterization of Heat Affected Zone Cracking in Austenitic Stainless Steel Welds," *Welding Journal*, 66, 8, 221s, (1987)
- 17) S.A. David, G.M. Goodwin, D.N. Braski, "Solidification Behavior in Austenitic Stainless Steel Filler Metals," *Welding Journal*, 58, 11, 330s, (1979)
- 18) G. Rabensteiner, J. Tosch, H. Schaberiter, "Hot Cracking Problems in Different Fully Austenitic Weld Metals," *Welding Journal*, 62, 1, 21s, (1983)
- 19) W.W. Baeslak III, D.J. Duquette, W.F. Savage, *Corrosion*, 35, 3, p45, (1979)
- 20) D.A. Vermilyea, *Corrosion*, 31, 7, p421, 19750
- 21) T.M. Devine, *Jnl Electrochemical Society*, 126, 3, p374, 1979
- 22) T. Ogawa, E. Tsunetomi, "Hot Cracking Susceptibility of Austenitic Stainless Steels," *Welding Journal*, 61, 3, 87s, (1982)
- 23) T.G. Gooch, J. Honeycombe, "Welding Variables and Microfissuring in Austenitic Stainless Steel Weld Metal," *Welding Journal*, 59, 8, 233s, (1980)
- 24) T.J. Hebble, D.A. Canonico, D.P. Edmonds, G.M. Goodwin, R.K. Nanstad, "Analysis of Delta Ferrite Data from Production Welds on Stainless Steel Pipe," *Welding Journal*, 54, 9, 260s, (1975)
- 25) J.C. Lippold, "Centerline Cracking in Deep Penetration Electron Beam Welds in Type 304L Stainless Steel," *Welding Journal*, 64, 5, 127s, (1985)
- 26) K. Prasad Rao, S. Prasnnakumar, "Assessment Criterion for Variability of Delta Ferrite in Austenitic Weld and Clad Materials," *Welding Journal*, 67, 2, 35s, (1988)
- 27) C.D. Lundin, C.H. Lee, R. Menon, V. Osorio "Weldability Evaluations of Modified 316 and 347 Austenitic Stainless Steels," *Welding Journal*, 71, 5, 171s, (1992)
- 28) J.C. Lippold, W.F. Savage, "Solidification of Austenitic Stainless Steel Weldments: Part 1," *Welding Journal*, 58, 12, 362s, (1979)
- 29) J.C. Lippold, W.F. Savage, "Solidification of Austenitic Stainless Steel Weldments: Part 2," *Welding Journal*, 59, 2, 48s, (1980)
- 30) J.C. Lippold, W.F. Savage, "Solidification of Austenitic Stainless Steel Weldments: Part3," *Welding Journal*, 61, 12, 388s, (1982)
- 31) M.J. Cieslak, W.F. Savage, "Weldability and Solidification Phenomena of Cast Stainless Steel," *Welding Journal*, 59, 5, 164s, (1980)
- 32) T.G. Gooch, P.H.M. Hart, "Solid State Phase Transformations in Steel During Welding," International Conference on Advances in Welding Science and Technology, ASM, Gatlinburg, TN, p161, May, 1986
- 33) Chang-Pin Chou, Peir-Shin Wu, "Effect of Nitrogen on the Austenitic Stainless Steel Weld Metal HAZ Cracking," International Conference on Advances in Welding Science and Technology, ASM, Gatlinburg, TN, p703, May, 1986
- 34) D.E. Clark, R.B. Loop, "Weldability of Rapidly Solidified Type 304 Stainless Steel," International Conference on Advances in Welding Science and Technology, ASM, Gatlinburg, TN, p817, May, 1986

- 35) H. W. Kerr, "Solidification and Grain Structures in Welds," International Conference on Advances in Welding Science and Technology, ASM, Gatlinburg, TN, p157, May, 1986
- 36) T. Koseki, H. Inoue, A. Nogami, "Prediction and Control of Weld Solidification in Steels," International Conference on Trends in Welding Research, ASM, Pine Mountain, GA, p51, May, 1998
- 37) N. Suutala, T. Takalo, T. Moisisio, "Ferritic-Austenitic Solidification Modes in Austenitic Stainless Steel Welds," *Met Trans A*, 11A, 5, p717, (1980)
- 38) N. Suutala, T. Takalo, T. Moisisio, "Single Phase Ferritic Solidification Modes in Austenitic-Ferritic Stainless Steel Welds," *Met Trans A*, 10A, 8, p1183, (1979)
- 39) Bloom, B., 1956 *Taxonomy of Educational Objectives: Handbook I, Cognitive Domain*. New York; Toronto: Longmans, Green.

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