Solidification Mechanisms in Fusion Welds

During weld solidification, the size of cellular substructure growth increases linearly relative to the reciprocal of the thermal gradient at the solid-liquid interface.

BY W. F. SAVAGE, E. F. NIPPES AND J. S. ERICKSON

ABSTRACT. Fusion welds in a 49% nickel-iron alloy were studied to determine the influence of the thermal gradient in the solid, $G_s$, and the growth velocity of the solid-liquid interface, $R$, on the nature of the cellular and cellular dendritic growth modes formed during weld solidification.

Toward this end, an experimental technique was developed for measuring the temperature distribution in the solid around the weld pool which was solidifying under two-dimensional heat-flow conditions.

The direction in which cellular growth occurred was controlled by welding on a 49% nickel-iron alloy which exhibited a cube-on-face texture with a <100> direction parallel to the rolling direction in the plane of the sheet. By pre-orienting the test specimens prior to welding, it was possible to control the direction in which the cellular substructure grew relative to the solid-liquid interface.

It was found that the temperature in a direction perpendicular to the trailing edge of the weld pool decreased in an exponential manner with distance from the solid-liquid interface. The thermal gradient in the solid continuously decreased from the fusion line toward the weld centerline at the trailing edge of the weld pool.

The size of the cellular substructure increased linearly as a function of $1/G_s$, where $G_s$ equals the thermal gradient in the solid under constant growth velocity conditions. Furthermore, the size of the cellular substructure decreased with an increase in growth velocity under constant thermal gradient conditions.

The cellular-to-cellular dendritic transition was found to occur at essentially the same ratio of $G_s/R^2$ during the solidification of fusion welds in this material.

Introduction

It has long been recognized that an inevitable consequence of alloy solidification is the redistribution of solute and, therefore, the presence of compositional variations within the casting. Segregation, whether it be on a macro or micro scale, can be detrimental in that it produces localized variations in both the solidification temperature and mechanical properties of cast material. Furthermore, the presence of chemical inhomogeneities in the material cannot be removed, in many instances, even after prolonged exposure at elevated temperatures.

A great deal of research has been directed toward determining how changes in the growth conditions present during solidification affect the observed segregation patterns. Unfortunately, this wealth of information has not been applied extensively to the understanding of weld solidification in general. The problem of studying the weld solidification process has been complicated by the fact that weldments solidify under thermal and growth conditions widely different than those found in larger sized castings. For example:

1. The growth velocity of the solid-liquid interface can be 10 to 100 times greater during welding than that found in castings.

2. The thermal gradient present in both the liquid and solid at the solidifying interface can be 1,000 to 10,000 times greater in the case of weld solidification than that experienced in larger castings.

3. The welding parameters employed exert a significant influence on the geometry of the solid-liquid interface present at the trailing edge of the weld pool. This results in substantial variations in both the thermal gradients and growth velocities present at the solidifying interface during welding.

This paper describes an investigation which was designed to gain a more thorough understanding of the weld-solidification process.
Solidification Mechanics Considerations

The concept of constitutional supercooling (Ref. 1) was probably one of the most significant factors leading to a theoretical explanation of alloy solidification. This theory was mathematically described by Tiller et al. (Ref. 2) and more recently applied to the understanding of weld solidification by Savage and coworkers (Ref. 3, 4). In these investigations it was shown that the liquid metal ahead of a solidifying interface could be supercooled and, therefore, be unstable even in the presence of a positive thermal gradient in the liquid. This supercooling was attributed to the inability of the alloy system to redistribute solute from the liquid to solid phases effectively during the solidification process. Correlations were found to exist between the stability of the solidifying interface and the degree of constitutional supercooling present.

Solidification parameters such as alloy solute content, thermal gradient in the liquid, and the growth rate of the solidifying interface were found to influence the resultant solidification substructure. In the absence of constitutional supercooling (which for a given alloy system is indicative of steep thermal gradients and low growth rates), a planar interface would prevail. On the other hand, if the thermal gradients or growth rates were such that constitutional supercooling existed, then the interface would become unstable and break down into one of the several dendritic-growth modes.

In addition to the constitutional-supercooling criterion, other dynamic changes must be considered in order to describe planar-interface stability fully. A mathematical perturbation analysis was formulated by Mullins and Sekerka (Ref. 5) who considered the dynamic changes that occur in the solute and thermal fields surrounding a perturbation or cell formed on the solidifying interface.

In addition the free-energy change associated with the formation of a curved interface was considered. Their analysis showed that the stability of the interface was affected by the solute, heat transport, and free-energy conditions which exist at the solidifying interface; also, these conditions were influenced by the curvature present at the tip of the cell or perturbation. For example, Fig. 1 offers a comparison between solute flow from a curved and planar interface. Note that the presence of a curved interface reduces the overlap present between the solute fields on adjacent points on the interface. Consequently, the redistribution of solute is accomplished more readily at a curved interface than at a planar interface. Therefore, the effect of a curved interface (often referred to as the "point effect of diffusion") is to promote instability or cell formation. Heat transport from the liquid to the solid has an opposite effect on planar-interface stability. Figure 1 compares a planar and curved interface in the presence of a positive temperature in the liquid similar to that which exists during welding. From the geometry it can be seen that heat transport is more efficient for a planar interface than for an interface with a positive curvature in the solid. Therefore, heat transport will tend to promote planar-interface stability.

Interfacial free-energy was also considered in the analysis in that as the interface becomes curved then the interfacial free-energy of the system will increase. Therefore, the presence of a planar interface tends to reduce the free-energy of the system and promotes interface stability. Perturbation analysis predicts that whether a planar interface remains stable or breaks down into a cellular growth mode will ultimately depend on the magnitude of each of the factors mentioned above.

A number of experimental investigations have also been conducted which examined the relationship between the size of the various solidification substructures and solidification variables such as solute content, thermal gradient and growth rate. Rutter and Chalmers (Ref. 1), for example, showed in decanting experiments that corrugation or cell spacing decreased with increasing growth rate. In addition their investigation showed that the cell size increased as the solute content of the alloy increased or the thermal gradient in the liquid decreased.

Other investigators (Refs. 6, 7) have shown that for a given solute content, cell size varied linearly with the parameter \( \frac{1}{G_0 R} \). These investigations also showed that cell size could vary by a factor of three or four de-
pending on orientation of the cells relative to the solid-liquid interface. More recently, Savage et al (Ref. 8) have examined the size of the cellular microstructure formed in the synthesis of weld solidification using crystalline organic materials. The results of this investigation was in agreement with the observations reported above, in that cell size was found to be linearly related to the parameter \(1/G_L\). Also, orientation of the cell-growth direction relative to the solid-liquid interface could significantly influence cellular spacing.

**Statement of the Problem**

Previous work in the area of solidification mechanics has in general shown correlations between the observed solidification substructures and parameters such as thermal gradient, alloy solute content, and growth rate. The experimental studies conducted to date, however, have not been able to study each of these variables independently over a large range of values. The welding process offers a unique opportunity to study the independent relationships between solidification variables and the observed microstructures.

**Objectives**

It became apparent that an experiment should be designed which could measure each of the previously mentioned variables in an independent fashion while maintaining control of orientation of the cellular-growth direction relative to the solidifying interface. Keeping these factors in mind, a research program was initiated with the objectives outlined below:

1. To determine the thermal distribution about a weld pool solidifying under two-dimensional heat-flow conditions.
2. To determine how variations in the following parameters individually influence the size of the cellular substructure observed during solidification of fusion welds:
   (a) \(G_s\) — the thermal gradient present in the solid at the solid-liquid interface.
   (b) \(R\) — the growth velocity of the solid-liquid interface.
3. To determine how variations in the following parameters influence the cellular-to-cellular dendritic transition during the solidification of fusion welds:
   (a) \(G_s\) — the thermal gradient present in the solid at the point of transition.
   (b) \(R\) — the growth velocity of the solid-liquid interface at the point of transition.

**Materials and Experimental Procedure**

**Material Selection**

The material used throughout this investigation was a 49% nickel-iron alloy with the following chemical analysis: Ni — 48.51%; C — 0.023%; Mn — 0.42%; P — 0.004%; S — 0.003%; Cr — 0.03%; Mo — 0.02%; Cu — 0.02%; Fe — balance.

The material was in the form of 0.014 in. (0.36 mm) thick sheet. After annealing in dry hydrogen for four hours (4 h) at 2150 F (1177 C) followed by a slow cool at the rate of 100 F/h (55 C/h), this material ex-
hibits a cube-on-face texture with a \{100\} plane in the plane of the sheet and a <100> direction parallel to the rolling direction.

**Welding Equipment and Procedure**

All welds evaluated in this investigation were full-penetration fusion welds made by the GTAW process using straight-polarity, direct current. During welding the test specimens were clamped in a stainless steel hold-down fixture equipped with cartridge heating elements which could be heated as high as 1200°F (649°C) prior to welding. This provided an additional means of varying the thermal gradient in the solid.

Argon shielding was supplied both from the torch and a separate inlet to the welding chamber at 35 cfh (99 liters/h) and 15 cfh (43 liters/h), respectively. The welding conditions for each test specimen are listed in Table 1.

**Crystallographic Orientation of Weld Specimens**

It has been shown (Refs. 3,9) that weld solidification occurs by epitaxial nucleation from the existing grains in the unmelted base metal. Growth then occurs in the easy growth direction most favorably aligned with the maximum thermal gradient present at the solid-liquid interface.

As noted earlier, the 49% nickel-aluminum alloy iron studied during this investigation exhibits a cube-on-face texture with a <100> direction in the rolling direction. This corresponds to the <100> easy-growth direction found in face-centered cubic materials. Therefore pre-orienting the test specimens in the weld fixture, it was possible to control the direction of cellular growth relative to the solidifying interface.

For all welds studied, the rolling direction (a <100>) was oriented perpendicular to the welding direction. In addition the welding parameters were adjusted so that a tear-drop-shaped weld puddle was obtained. This procedure ensured that, for those grains exhibiting the proper orientation, growth would occur in the plane of the sheet perpendicular to the fusion line along a <100> direction and could continue to grow in this direction to the weld centerline as depicted in Fig. 2.

**Measurement of Thermal Gradient and Solidification Rate**

In order to obtain the thermal distribution in the solid about the weld pool, 0.005 in. (0.13 mm) chromel-alumel thermocouples were inserted along the underside of the test specimen at predetermined distances from the weld centerline. This permitted the temperature to be obtained at known points relative to the weld centerline as the weld pool traveled past the thermocouples.

The output from the thermocouples was fed into a direct-developing, recording oscillograph along with the output from a linear transducer activated as the electrode traversed past the first thermocouple. This allowed the conversion of temperature-time data to temperature-distance plots. Photographs of the weld crater and weld ripple marks were used to construct a composite diagram of the instantaneous position of the solid-liquid interface about the periphery of the weld pool. Figure 3 summarizes in graphical form a typical set of thermal-distribution data obtained using this technique.

Since the specimens were full-penetration fusion welds on 0.014 in. (0.36 mm) thick material, there is essentially no thermal gradient through the sheet thickness. Therefore, a two-dimensional heat-flow condition was present during welding. It was determined experimentally that the temperature distribution in the solid in a direction perpendicular to the solidifying interface followed an exponential decay of the form:

$$T - T_0 = Ae^{-BZ}$$

where Z is the perpendicular distance from the solidifying interface, T is the temperature at distance Z, T₀ is the initial plate temperature, and A and B are constants. A linear relationship results if equation (1) is converted to logarithmic form:

$$\ln(T - T_0) = -BZ + \ln A$$

Fig. 4 shows typical temperature-distance data plotted in this manner. The temperature gradient in the solid, G₂, at the solid-liquid interface is defined as:

$$G_2 = \left| \frac{dT}{dZ} \right|_{Z=0} = -A \cdot B$$

where A equals the solidus temperature of the alloy, 2550°F (1399°C) minus the initial plate temperature, T₀, for the particular test considered, and B is in the slope of the line defined by equation 2.

The growth velocity of the solid-liquid interface at the trailing edge of the weld pool is determined, on the other hand, by the dynamic equilibrium which prevails during welding.
After the weld proceeds for a short distance, this dynamic equilibrium is established and the weld pool assumes a constant shape. In order to maintain an invariant puddle shape, at any point on the interface, the component of growth velocity parallel to the welding direction must equal the welding velocity. The growth velocity in any other direction on the solidifying interface is a vector quantity equal in magnitude to the welding velocity multiplied by the cosine of the angle between the growth vector and the welding direction. Therefore, the growth rate of the interface from the fusion line to the weld centerline is a function of the geometry of the weld puddle.

To circumvent the problem of measuring the angular relationships precisely and to provide an accurate evaluation of interface growth rate, a graphical technique was employed to determine the cell size at a particular location. Figure 5 illustrates this technique. From a 10X macrograph of the ripple markings on the surface of the weld, an accurate outline was obtained of the trailing edge of the weld puddle. This outline was reproduced by shifting a distance \( \Delta Y \) from Position 1 to Position 2, as indicated in Fig. 5.

If \( \Delta Y \) is equal to a constant, \( C \), times the welding velocity, \( V \), the distance between the two positions measured in any given direction will be equal to the product of the constant, \( C \), and the growth velocity, \( R \), required to maintain dynamic stability of the interface. Thus, since only grains with \(<100>\) directions normal to the welding direction were considered, the distance, \( r \), in Fig. 5 would be equal to \( R/C \), and the growth rate, \( R \), is simply the product, \( Cr \).

**Table 2 — Summary of Test Data Showing Relationship Between \( G_x \) and \( G_{max} \) at the Trailing Edge of the Weld Pool for a Tear-Drop Shape Weld Configuration**

<table>
<thead>
<tr>
<th>Weld Test</th>
<th>Average growth velocity normal to trailing edge of weld pool, km</th>
<th>( \theta ), angle between ( G_x ) and ( G_{max} ), degrees</th>
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**Determination of Cell Size**

Consider the diagram shown in Fig. 6. As the weld pool progresses, the point A on the solid-liquid interface will trace out a line AA'A" parallel to the weld centerline. Therefore, any point along AA'A" has been exposed to the same thermal gradient and growth velocity during solidification. Since the cells are growing perpendicular to line AA'A", any cells along this line have been exposed to the same thermal gradient and growth velocity at the solidifying interface. A line-intersect measuring technique was employed to determine the cell size along line AA'A" for each combination of thermal gradient and growth velocity studied.

**Discussion and Results**

**Thermal Distribution in the Solid About the Weld Pool**

An evaluation of the experimental thermal data showed that the temperature as a function of the perpendicular distance from the weld interface decays in an exponential manner. A three-dimensional model illustrating the nature of this decay is shown in Fig. 7. It was further noted that the maximum thermal gradient in the solid, normal to the solid-liquid interface, progressively decreased in magnitude from the fusion line to the weld centerline along the trailing edge of the weld pool.

The locus of peak temperature as a function of distance from the weld centerline was found to be a straight line tangent to the leading edge of the weld puddle, as can be seen in Fig. 3. This would indicate that the thermal wave generated in the solid during welding behaves in a fashion similar to that of the bow wave created by a boat as it passes through the water.

It has been shown by Savage and Aronson (Ref. 4) that the geometry of the solid-liquid interface at the trailing edge of the weld pool can substantially influence the nature of the competitive growth process during solidification. This, in turn, influences the amount of preferred orientation found within the weld fusion zone.

The two extreme types of weld geometry normally encountered during welding are the elliptical-shaped weld puddle and the tear-drop-shaped weld puddle illustrated in Fig. 6. In the case of two-dimensional heat flow, the maximum thermal gradient, \( G_{max} \), will be perpendicular to the trailing edge of the weld pool and will lie in the plane of the sheet. This gradient can be resolved into two component gradients in directions perpendicular and parallel to the welding direction, as illustrated in Fig. 8. Defining the directions perpendicular and parallel to the welding direction as \( x \) and \( y \), respectively, the following...
expressions can be written for these two component gradients, $G_x$ and $G_y$:

$$G_x = G_{max} \cos \theta$$  \hspace{1cm} (4)  

$$G_y = G_{max} \cos (90 \text{ deg} - \theta)$$  \hspace{1cm} (5)

where: $\theta$ = the angle between $G_{max}$ and $G_x$.

The magnitude of the thermal gradient in the solid is a direct measure of the ability of the system to extract heat from the weld pool to the cooler surroundings. Therefore, the larger the value of the thermal gradient, the greater the heat-sinking capacity of the system.

In the case of an elliptical-shaped weld puddle, the direction of the maximum thermal gradient continuously changes from the fusion line to the weld centerline along the trailing edge of the weld pool. This reflects the ability of the system to extract more heat in the longitudinal, or $y$-direction, as compared to the transverse, or $x$-direction, as solidification proceeds from the fusion line towards the weld centerline.

In the case of a tear-drop-shaped weld puddle, the same relationships hold. However, the puddle tends to elongate along the centerline due to the inability of the system to extract heat fast enough in this direction to maintain an elliptical shape.

It was found that for a given growth velocity (measured normal to the solid-liquid interface) the angle $\theta$ between the maximum thermal gradient, $G_{max}$, and the transverse thermal gradient, $G_x$, varied less than 4 deg for those welds exhibiting a tear-drop configuration. These data are reported in Table 2.

Therefore, for a given growth velocity normal to the solid-liquid interface, the ratio of $G_y$ to $G_x$ was essentially constant. The puddle elongated along the weld centerline until this dynamic equilibrium was established. Under more severe conditions a point was reached in the system where the heat-sinking capacity in the $y$ direction was minimal. At this point along the weld interface, the puddle was forced to assume a shape parallel to the weld centerline — Fig. 9. This indicates that there is a limit to the amount of heat which can be dissipated in a direction parallel to the weld centerline. The point at which this occurs depends upon the thermal properties of the material and the type of fixturing employed.

**The Influence of Temperature Gradient and Solidification Rate on Cell Size**

The objective of this phase of the investigation was to determine the influence of the temperature gradient in the solid, $G_s$, and the growth velocity of the solidifying interface, $R$, on cell size. Since all experiments were performed on the same heat of material, the nominal solute content of the system was held constant.

A typical photomicrograph of the solidification substructure observed is shown in Fig. 10. It was noted that at the fusion line a region of planar growth existed. Since constitutional supercooling cannot occur until a solute spike forms ahead of the advancing solid-liquid interface, it follows that cells should not form at the onset of solidification. In fact, the critical condition for constitutional supercooling will not be met until the initial transient buildup of solute causes the effective liquidus of the liquid near the solid interface to fall below the actual temperature present at that point. Therefore, during the initial transient buildup of solute, the planar growth mode will prevail. However, when sufficient constitutional supercooling exists at the advancing interface, the planar interface will break down into the cellular growth mode.

Since the base metal exhibited a $<100>$ crystallographic direction in the plane of the sheet perpendicular to the fusion line, the cells shown in Fig. 10 grew epitaxially from the unmelted base metal in this direction. The cellular substructure, therefore, appears as a parallel array of corrugations on the sheet surface.

It was further observed that under constant growth velocity conditions, the cell size increased linearly with the inverse of the temperature gradient in the solid, $G_s$. In this case, $G_s$ is taken as the temperature gradient resolved along the cell-growth axis. These results are reported in Table 3 and in Fig. 11 for three different growth velocities resolved along the cell-growth axis.

The relationships found between $G_s$, $R$ and cell size are in agreement with theoretical considerations. Consider the flow of solute from a planar and curved interface as depicted in Fig. 1. Note that for both interface shapes, solute tends to flow between the solid and liquid phases in a direction normal to the interface. The presence of a curved interface, such as that which would exist at the cell tips, tends to reduce the overlap present between the solute fields at adjacent points on the interface, thereby promoting the redistribution of solute.
As the thermal gradient \( G_s \) or \( G_L \) increases, the cell size should decrease if growth velocity and solute content remain constant. This results from the fact that an increase in thermal gradient will reduce the amount of constitutional supercooling or the available driving force for formation of the cellular substructure.

For the cells to remain stable, they must continue to grow into the liquid even though the driving force is being reduced. This can only be accomplished if the radius of curvature at the cell tips decreases in order to provide more effective redistribution of solute to the liquid. Since cell size depends on cell-tip radius, an increase in thermal gradient results in a decrease in cell size.

In a similar manner, an increase in growth velocity results in a decrease in cell size under constant thermal gradient and solute content conditions. This can be visualized if two cellular interfaces are considered that are growing at two different growth velocities. For the faster growing interface to remain stable, it must increase the amount of solute being redistributed to the liquid. This can be accomplished if the faster growing cells exhibit a smaller radius of curvature of the cell tips due to the point effect of diffusion mentioned earlier. Figure 12 shows the influence of growth velocity on cell size under constant temperature gradient conditions. Consistent with theory, cell size decreases as the growth velocity increases.

The Influence of Growth Velocity and Temperature Gradient on the Cellular-to-Cellular Dendritic Transition

The objective of this phase of the investigation was to determine whether the influence of thermal gradient and growth velocity on the cellular-to-cellular dendritic transition as reported by other investigators (Refs. 6, 10, 11) is valid when applied to the welding situation.

Previous investigators (Refs. 6, 10, 11) have reported that for a given solute content and cell orientation relative to the solid-liquid interface, transition occurs at a particular ratio of \( G_L / R^{1/2} \) where \( G_L \) and \( R \) are measured in a direction perpendicular to the solidifying interface. Furthermore, the \( G_L / R^{1/2} \) ratio could vary depending on the orientation of the cells relative to the solid-liquid interface.

| Table 3 — Summary of Data Correlating Cell Spacing with the Component of \( R \) and \( G_s \) Oriented Parallel to the Cell Growth Axis |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Weld test | \( R \), parallel to the cell growth axis, ipm | \( G_s \), parallel to the cell growth axis, deg F/in. | \( I/G_s \) in \( \text{deg } \text{F} \times 10^{-8} \) | Averages cell diameter, microns ± 2r limits |
| 15 | 3 | 31,900 | 3.13 | 6.37± .37 |
| 11 | 3 | 26,325 | 3.80 | 7.02± .28 |
| 18 | 3 | 22,580 | 4.49 | 7.74± .30 |
| 16 | 3 | 18,970 | 5.26 | 8.47± .28 |
| 13 | 3 | 13,550 | 7.37 | 10.20± .44 |
| 21 | 3 | 18,000 | 5.55 | 8.56± .52 |
| 25 | 3 | 22,500 | 4.44 | 7.47± .32 |
| 27 | 3 | 15,680 | 6.36 | 9.29± .36 |
| 29 | 3 | 13,800 | 7.24 | 10.07± .46 |
| 15 | 6 | 24,190 | 4.13 | 6.36± .23 |
| 11 | 6 | 20,600 | 4.85 | 7.06± .28 |
| 18 | 6 | 17,790 | 5.61 | 7.60± .37 |
| 21 | 6 | 13,160 | 7.60 | 9.30± .38 |
| 25 | 6 | 18,240 | 5.46 | 7.57± .26 |
| 27 | 6 | 12,565 | 7.95 | 9.72± .38 |
| 29 | 6 | 9,050 | 10.35 | 11.53± .40 |
| 11 | 8 | 14,795 | 6.76 | 7.42± .29 |
| 15 | 8 | 17,565 | 5.69 | 8.46± .27 |
| 21 | 8 | 10,580 | 9.45 | 9.71± .36 |
| 25 | 8 | 12,080 | 8.33 | 8.46± .30 |

Fig. 10 — Example of the Planar-to-Cellular Growth Transition: (a) schematic illustration; (b) photomicrograph of planar-to-cellular growth transition in a GTA weld made on a 49% nickel-iron alloy. Etchant: 10% ammonium persulfate solution, X370 (reduced 68% on reproduction)

The summary of data correlating cell spacing with the component of \( R \) and \( G_s \) oriented parallel to the cell growth axis is presented in Table 3.
The $G_L / R^{1/2}$ ratio was, therefore, considered to be a measure of the amount of constitutional supercooling or driving force for cellular breakdown.

During weld solidification, the thermal gradient ($G_s$ or $G_L$) perpendicular to the solid-liquid interface continuously decreases from the fusion line to the weld centerline along the trailing edge of the weld pool. Concurrent with this decrease in thermal gradient is a corresponding increase in the growth velocity of the solidifying interface. As a result, the $G_L / R^{1/2}$ ratio continuously decreases as solidification proceeds from the fusion line to the weld centerline along the trailing edge of the weld pool.

It was observed that, as solidification proceeded from the fusion line toward the weld centerline, a stage was reached in the solidification process where the cellular substructure started to break down into a cellular-dendritic growth mode. Since all welding was performed on the same heat of material, the nominal solute content of the system was held constant. The problem, therefore, became one of determining the value of thermal gradient and growth velocity corresponding to the point of transition.

Some difficulties arise, however, in determining exactly what point in the solidification process corresponds to breakdown of the cellular substructure. Figure 13 shows a region in the weld fusion zone where the cellular-to-cellular dendritic transition was first observed. Line A-A represents the locus of points in the fusion zone which have been exposed to essentially the same thermal gradient and growth velocity during solidification. The $G_L / R^{1/2}$ ratio is therefore essentially constant along line A-A.

Examination of the solidification substructure shows that a mixture of cells and cellular dendrites coexist at this stage in the solidification process. Therefore, an estimate of the transition criterion must include a definition as to what constitutes the onset of cellular-dendritic growth.

Previous investigators (Refs. 6, 10, 11) have defined the transition as that point where continuous side branching is first observed along the cell walls. This definition was adopted for this investigation.

An estimate of the transition point was made by calculating the $G_s / R^{1/2}$ ratio which corresponded to the onset of cellular dendritic growth, as defined above. The utilization of $G_s$ rather than $G_L$ was necessary since the value of $G_L$ was not experimentally determined.

Since the two thermal gradients are related to one another, as previously described, they both reflect the extent of constitutional supercooling ahead of the solid-liquid interface. Therefore, the $G_s / R^{1/2}$ ratio serves the same function as $G_L / R^{1/2}$ in determining the transition point.

For those welds where data were available, the value of $G_s / R^{1/2}$ at the point where transition was first observed was calculated. Both $G_s$ and $R$ were measured in a direction perpendicular to the solid-liquid interface. In addition, the angle between the cell growth axis and the normal to the solid-liquid interface was determined. These data are reported in Table 4.

A 13% variation in the value of $G_s / R^{1/2}$ was found to exist. These results indicate that the cellular-to-cellular dendritic transition tends to occur at essentially the same ratio of $G_s / R^{1/2}$ during the solidification of welds. Therefore, the $G_s / R^{1/2}$ ratio is a reasonable measure of the onset of cellular-dendritic growth during the solidification of fusion welds.

No systematic variation was observed between the value of $G_s / R^{1/2}$ calculated and orientation of the cellular growth axis relative to the solid-liquid interface.

The influence of solute content on the cellular-to-cellular dendritic transition on the other hand can be seen in Fig. 14. It was observed that in those regions adjacent to grain boundaries where the solute content was higher, the cellular-to-cellular dendritic transition tended to occur at a much larger ratio of $G_s / R^{1/2}$. This observation is in agreement with data previously reported by other investigators. As the solute content of the system is increased, the ratio of $G_s / R^{1/2}$ where cellular dendrites are first observed increases. This reflects the influence of solute content.

Table 4 — Summary of Data Showing the Influence of Thermal Gradient and Growth Velocity on the Cellular-to-Cellular Dendritic Transition

<table>
<thead>
<tr>
<th>Weld test</th>
<th>Angle of inclination of cell growth axis perpendicular to solid-liquid interface</th>
<th>R, perpendicular to solid-liquid interface, km</th>
<th>$G_s$, perpendicular to solid-liquid interface, deg F/min.</th>
<th>$G_s/R^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>44</td>
<td>7.5</td>
<td>12,100</td>
<td>4.432</td>
</tr>
<tr>
<td>11</td>
<td>27.5</td>
<td>8.0</td>
<td>13,650</td>
<td>4.823</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>7.0</td>
<td>13,310</td>
<td>5.022</td>
</tr>
<tr>
<td>27</td>
<td>23</td>
<td>6.0</td>
<td>11,300</td>
<td>4.612</td>
</tr>
<tr>
<td>29</td>
<td>20</td>
<td>5.5</td>
<td>10,500</td>
<td>4.496</td>
</tr>
</tbody>
</table>

Fig. 11 — Average cell diameter vs. $1/G_s$ under constant growth velocity conditions

Fig. 12 — Average cell diameter vs. $R$ under constant thermal gradient in the solid

Table 4 — Summary of Data Showing the Influence of Thermal Gradient and Growth Velocity on the Cellular-to-Cellular Dendritic Transition

Fig. 13 — Average cell diameter vs. $1/G_s$ under constant growth velocity conditions

Fig. 14 — Average cell diameter vs. $R$ under constant thermal gradient in the solid

The influence of solute content on the cellular-to-cellular dendritic transition on the other hand can be seen in Fig. 14. It was observed that in those regions adjacent to grain boundaries where the solute content was higher, the cellular-to-cellular dendritic transition tended to occur at a much larger ratio of $G_s / R^{1/2}$. This observation is in agreement with data previously reported by other investigators. As the solute content of the system is increased, the ratio of $G_s / R^{1/2}$ where cellular dendrites are first observed increases. This reflects the influence of solute content.
on the extent of constitutional supercooling present at the solidifying interface.

Conclusions

1. The following conclusions pertain to the thermal distribution around the weld pool solidifying under two-dimensional heat-flow conditions:
   (a) The temperature in a direction perpendicular to the trailing interface of the weld pool decreases with distance in an exponential manner.
   (b) The thermal gradient in the solid, $G_s$, at the solid-liquid interface continuously decreases from the fusion line to the weld centerline along the trailing edge of the weld pool.
   (c) The locus of peak temperatures in the solid tend to lie on a straight line tangent to the leading edge of the weld pool.
   (d) The geometry of the solid-liquid interface at the trailing edge of the weld pool is a function of the dynamic equilibrium established between the heat-sinking capability of the system in directions perpendicular and parallel to the welding direction.

2. The following conclusions pertain to the influence of $G_s$ and $R$ on the nature of the cellular and cellular-dendritic growth modes formed during the solidification of fusion welds in a 49% nickel-iron alloy:
   (a) The cell size increases linearly with the inverse of the thermal gradient in the solid, $G_s$, under constant growth velocity conditions.
   (b) The cell size decreases with increasing growth velocity of the solid-liquid interface, $R$, under constant thermal gradient in the solid.
   (c) The cellular-to-cellular dendritic transition tends to occur at essentially the same ratio of $G_s/R^2$ for the welding conditions studied.

References