Sources and Effects of Growth Rate Fluctuations During Weld Metal Solidification

Fluctuations in the thickness of the solid-liquid transition region are used to explain cyclic growth rate effects and formation of weld surface ripples

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ABSTRACT. This paper is primarily concerned with isolating factors responsible for and influencing growth rate fluctuations inherent in weld metal solidification. These factors and their interactions are discussed with respect to their role(s) in producing microstructural features such as "transverse solute banding" and porosity banding and the formation of weld surface ripples. Growth rate fluctuations are attributed to the cyclic variation in the thickness of the solid-liquid transition region (the diffuse interface).

A simple heat flow analysis of the effect of a varying thickness interface on heat transfer is discussed. A mechanism for weld surface ripple formation is proposed based on the interaction of growth rate fluctuations and surface tension effects of the weld pool surface. The variations in ripples developed under steady state (during welding) and terminal (arc and spot welds) conditions of solidification are discussed.

Introduction

The inherent periodic fluctuation in growth rate during weld metal solidification is one of the most significant and least understood phenomena occurring during the freezing of weld metal. These fluctuations are responsible for cyclic variations in solute content in the weld fusion zone (transverse solute banding), porosity distribution in a banded fashion, and growth substructure characteristics.

As a result, growth rate fluctuations can be assumed to directly influence the mechanical and corrosion behavior, and the response to thermal and/or mechanical treatment of the weld fusion zone microstructure. A recent communication also associates the formation of surface ripples to this periodicity in growth rate.

"Transverse solute banding" and porosity band networks have been observed along the length and in the crater region of arc fusion welds and in resistance spot and seam weld cross sections. These observations indicate that factors contributing to growth rate fluctuations are consistent with, or common to, steady-state and terminal conditions of weld solidification. The effects of growth rate fluctuations are also noted in other solidification processes, suggesting some of these factors may be inherent characteristics of metal and alloy solidification, per se, rather than features peculiar to weld metal solidification.

The purposes of this paper are to:
1. Isolate the important factors which influence growth rate fluctuations during weld metal solidification and discuss their possible interactions,
2. Propose a mechanism for weld surface ripple formation.

Effects of Growth Rate Fluctuations

Cyclic variations in growth rate experienced during weld metal solidification produce a variety of effects observed by metallographic examination and revealed by the fracture morphology of weld metal. The most significant is that of "transverse solute banding" as often noted by alternately light and dark etched bands in metallographic weld fusion zone cross sections—Fig. 1. These bands are diffuse contours (discrete positions) of the solid-liquid interface and represent intercepts of planes containing structure of alternately higher and lower solute content than the average solute content of the weld fusion zone.

In essence, the weld fusion zone of multi-element systems (alloys) is a structure of periodic stoichiometry which can be expected to vary locally in its chemical and mechanical behav-
ior response. The alternately light and dark etched structure shown in Fig. 1 is an example of local variations in chemical response and also an indication of the probable local variation in the response of the structure to corrosion attack. The cyclic variation in stoichiometry is also responsible for local variations in response of the weld fusion zone to postweld strengthening which is indirectly revealed by the fracture topography of the natural aged X7002 aluminum alloy weld metal impact fracture shown in Fig. 2. The fracture surface on this specimen shows the relief of contours which can be associated with transverse solute banding.

Another effect of growth rate fluctuations is that of the distribution of porosity in a banded network as shown in Fig. 3. This effect is identical to that of "transverse solute banding" and simply involves a cyclic variation in the partitioning of gas element solute. The formation of porosity is the result of interdendritic microsegregation of the gas element (hydrogen) during the slow growth rate interval in which there is sufficient time to permit accumulation of molecular hydrogen to form the observed varying sized pores.

The influence of growth rate fluctuations on growth morphology is somewhat more subtle and less obvious than the previously mentioned effects. These fluctuations significantly affect the competitive growth process permitting favorable growth orientations to more conveniently win out over less favorably oriented ones. It should be noted that the preferred growth orientations of neighboring grains is the same in all cases; moreover, the orientations of the "seed" grains (nucleating substrates) at the edge of the weld and the curvature of the solid-liquid interface are primarily responsible for the development of multiple orientations.

Some of the more significant effects on growth morphology may be attributed to external factors such as arc oscillations which perturb the solid-liquid interface. These effects are readily distinguished from growth rate fluctuation effects in that distinct changes in orientation are observed due to the lateral or vertical translation of the solid-interface.

Commonly observed weld surface ripples can also be associated with inherent growth rate fluctuations experienced during weld metal solidification. In many instances, the ripple frequency and spacing along the length of a weld (steady-state conditions) can be correlated with power supply ripple characteristics. An example of ripples developed under steady-state conditions of welding is shown in Fig. 4. This correlation cannot be made where external factors such as arc perturbations, nonsynchronous filler metal feed conditions, and nonuniform filler metal melt-off, interact with the effects of steady-state conditions attributed to power supply characteristics.

Surface ripples observed with terminal solidification structures (weld craters and arc spot welds), welds made with a non-rippled d-c current source, and certain products of other solidification processes (i.e., button melts) are obviously associated with inherent growth rate fluctuations. The primary questions in this regard are: "Why do growth rate fluctuations occur during terminal solidification and how do these fluctuations affect weld surface ripple formation?" Answers to these questions are suggested and discussed in detail in later sections.

Sources of Growth Rate Fluctuations

The nature of the solid-liquid interface is one of the most important considerations with regards to the solidification process. Interface mechanics establish the chemical and growth substructure characteristics of the solid substrate and, consequently, the resultant weldmetal structure. The effects of weld process parame-

Fig. 1—"Transverse Solute Banding" revealed in cross sections of gas tungsten-arc weldments in QE22A magnesium alloy sheet (top) and X7006 aluminum alloy plate (bottom). Etchant: ethylene glycol (top) and 10% NaOH (bottom). Top—X8; bottom—X5 (reduced 28% on reproduction)

Fig. 2—Effects of "Transverse Solute Banding" on fracture morphology of impacted ¼ in. wide liquid-nitrogen cooled X7002 aluminum alloy weld metal specimen

Fig. 3—Porosity banding observed in transverse cross section of gas tungsten-arc X7106 aluminum alloy plate weldment. Etchant: 10% NaOH, X49 (reduced 50% on reproduction)

Fig. 4—Weld surface ripples observed on 0.030 in. AISI 321 stainless steel gas tungsten-arc sheet weldment (left) and in crater stop of a Ti-6Al-4V gas tungsten-arc weld (right). Left—X25; right—X100 (reduced 32% on reproduction)
ter variations and base metal and filler metal alloy adjustments (use of inoculants, etc.) on the resultant weld metal structure can be attributed to their specific influence on interface kinetics—that is, they are only effective to the extent in which they alter the thermal and/or physical characteristics of the interface. As a result, growth substructure control, within limits, can only be achieved by the judicious adjustment of external variables which manipulate or affect the interface.

The Solid-Liquid Interface

Most of the classic discussions dealing with solidification mechanics treat the solid-liquid interface as a planar separation of the solid substrate and the liquid melt. In reality, the interface is diffuse, complex in nature, and a region having some finite thickness dimension. This thickness dimension can be considered as the nominal length of the growth projections extending into the liquid (or in the primary growth direction). Consequently, the diffuse interface region usually consists of primary and secondary growth projections surrounded by solute enriched liquid which increases in solute content towards the solid substrate.

It is suggested here that the observed effects of growth rate fluctuations in weld metal are directly associated with this diffuse interface and, specifically, to cyclic variations in the thickness of this interface. The proposed mechanism for interface thickness variations is based on essentially two considerations: discrete growth stages of the interface and heat flow variations due to interface thickness fluctuations. These considerations are discussed separately herein; however, it should be emphasized that they are interacting aspects of the solidification process.

Interface Thickness Fluctuations

The concept of a diffuse interface of cyclically varying thickness is based on a model of an interface, which advances by the progressive extension of primary growth projections (primary crystals) and the simultaneous consolidation of the trailing portions of the interface by lateral competitive growth of secondary projections (dendritic side branching). The growth form of commonly observed cellular-dendritic and dendritic weld metal substructures suggests a characteristic of the interface which may also be intuitively deduced. The growth of primary projections must precede that of the secondary projections, and it is obvious that this process must be accomplished sequentially. For reasons discussed later, the primary projections must grow at alternately rapid and slower growth rates or intermittently.

The suggested two-stage growth of the diffuse interface, responsible for cyclic variations in interface thickness during solidification, is shown schematically in Fig. 5. As indicated for the first-stage, growth occurs predominantly along the direction of heat flow by the extension of primary projections into the liquid. The driving forces for the growth of these primary projections (solute-lean dendrite cores) include maximum supercooling effects and alignment of the most favorable growth orientations and heat transfer directions.

Factors responsible for producing the suggested second-stage condition include lateral competitive growth (growth of secondary projections) required to consolidate the interface and the retardation of primary projection growth due to several physical and thermal effects. The main reasons for the stunting or slowing-down of the growth of primary projections are thermal in nature and include:

1. The necessity of extracting heat arising from lateral growth within the diffuse interface, and
2. Extension of the primary projection tips into liquid of increasing superheat and weld pool convective effects.

In essence, it is suggested that the cyclic thickness variations of the diffuse interface are associated with alternating advances and changes in growth rate of the leading and trailing edges of the diffuse interface. From constitutional supercooling considerations, the growth rate of the leading edge of the interface would undoubtedly be greater than that of the trailing edge.

Discussion to this point has been concerned with interface mechanics with little regard to interactions and the effects of external factors which would influence the kinetics of the interface. Interface thickness fluctuations would occur for both steady-state (during welding) and terminal (arc and resistance spot welding) conditions of solidification. Factors inherent to steady-state conditions of welding which would influence interface thickness fluctuations include arcos and power supply ripple.

These factors affect interface...
mechanics by periodically varying the temperature of the liquid at the interface which, in turn, controls the growth rate of the leading edge of the interface; this effect is substantiated by the regularity in "transverse solute banding" and the ability to correlate the spacing of bands with the ripple frequency of the power source. For terminal conditions of weld solidification, as experienced with arc and resistance spot welds, the spacing of "transverse solute bands" is irregular and generally increases as solidification proceeds. This irregularity in spacing can be attributed to the absence of the influence of a power supply ripple and the progressively lower temperature of the liquid at the interface as solidification proceeds.

Another consideration with respect to the proposed two-stage movement of the interface is that of solute enrichment of the liquid during the rapid growth (first stage) interval. This intermittent piling (layering) of solute is the direct consequence of growth rate fluctuations and results in the previously noted "transverse solute banding" effect. It is suggested that "transverse solute bands" are formed during the solidification interval represented by the transition from the first to second-stage and most of the second-stage—Fig. 5. Second-stage growth is influenced by:

1. Interactions of the effects of progressively increasing degrees of constitutional supercooling due to the higher solute content of interdendritic liquid.
2. The gradual increase in temperature of the solid within the diffuse interface resulting from heat extraction upon lateral growth (consolidation of the interface).
3. Temperature changes in the liquid due to external factors.

With regard to the latent heat of fusion, its influence, if any, would complement those factors promoting the two-stage growth suggested in Fig. 5. It should be noted here that the proposed model of growth is based on alternating advances of the leading and trailing edges of the interface and that the dissipation of latent heat would be a continuous and cyclic process. It might be reasonable to assume that growth rate fluctuations during steady-state conditions of welding are not influenced by cyclic variations in the dissipation of latent heat; the latent heat of fusion is appreciably less than the total heat required to produce a local melt in an infinite heat sink.

**Heat Flow Characteristics**

A simplified heat flow analysis of the influence of a varying thickness interface on heat transfer provides additional information with regard to the possible effects of the diffuse interface. This analysis is made using the schematic representation shown in Fig. 6 along with the relationship on the quantity of heat flow, \( H \), to the temperature difference between the solid and liquid, \( \Delta T \), and the thickness of the interface, \( \Delta x \).

This relationship is taken from the general equation of heat conduction. For the purpose of this discussion, \( \Delta x \) is being treated as the "effective thickness" (see Fig. 5) of the diffuse interface, and \( \Delta T \) as the temperature difference between the solid and liquid on each side of the diffuse interface. As indicated by this relationship, the rate of heat flow is proportional to the temperature difference between the solid and liquid substrates and inversely proportional to the thickness of the interface.

With regard to fluctuations in \( \Delta T \), it can be assumed that the temperature of the solid does not vary and that variations in \( \Delta T \) are associated with temperature changes in the liquid. If the temperature difference between the solid and liquid substrates is assumed to be constant (as should be the case with a non-rippled power source), the rate of heat flow is simply a function of the thickness of the diffuse interface. Consequently, as the thickness of the interface increases, the rate of heat flow decreases and vice versa.

If \( \Delta T \) varies, as with a rippled power source which causes cyclic variations in the temperature of the liquid, the rate of heat transfer would then be primarily a function of the temperature difference between the solid and liquid substrates. The correlation of "transverse solute band" spacings with ripple frequency is an example where the \( \Delta T \) parameter is more predominant than the \( \Delta x \) parameter.

For conditions of terminal solidification (i.e., arc craters, arc and resistance spot welds), \( \Delta T \) would decrease due to the gradual drop in the temperature of the liquid and, as with the use of a non-rippled power source, heat flow fluctuations would be associated with variations in the thickness of the interface (\( \Delta x \)).

**Mechanism of Weld Surface Ripple Formation**

The formation of weld surface ripples can be directly associated with growth rate fluctuations by considering the effects of surface tension of the weld pool met during solidification. The mechanism of ripple formation is easily explained by the schematic models shown in Fig. 7 for steady-state (during welding) and terminal conditions (arc crater) of welding. Referring to the cyclic rate of advance of the solid-liquid interface discussed earlier, the formation of the ripple "peaks" are associated with the increasing growth rate interval (first stage) and the ripple "valleys" with the decreasing growth rate interval (second stage)—Fig. 5.

These stages of surface ripple development are noted in Fig. 7. During the rapid growth interval the rate of extension of primary projections is greater than the rate of melt recession due to surface tension effects. As noted in Fig. 7 at points A, the reverse effect is encountered during the slow growth interval; the rate of recession of liquid due to the surface tension component of the weld pool melt is greater than the rate of movement of the solid-liquid interface.

The differences between surface ripple height and spacing during steady-state and terminal conditions of solidification are easily explained. The progressive decrease in ripple height towards the center of weld craters is due to the decreasing influence of surface tension as the weld
pool melt volume diminishes. The increase in ripple spacing towards the center of the weld crater may be attributed to the progressive drop in the temperature of the liquid which permits the first-stage of interface growth to proceed for progressively longer intervals; as noted in earlier discussions, extension of primary projections is impeded as the projection tips advance into superheated melt.

Since weld surface ripples are associated with growth rate fluctuations, it is possible in some cases to correlate these ripples with solidification effects such as "transverse solute banding" and porosity banding. There are several reasons why this correlation cannot be made in all cases. Most of these reasons can be attributed to the fact that surface ripple formation is influenced by both the thermal aspects of the solidification process and weld pool hydrokinetics, whereas growth rate fluctuations are more strongly influenced by thermal considerations.

The hydrokinetics of the weld pool surface can be greatly affected by factors peculiar to the welding process or technique which are not inherent to the solidification process. For example, the rate of filler metal melt-off in gas tungsten-arc welding, mode of metal transfer in gas metal-arc welding, joint design, and manual welding technique (weaving, etc.) would have differing effects on the hydrokinetics of the surface of the weld pool. A correlation of solidification effects arising from growth rate fluctuations with weld surface ripple formation can be made only when specific thermal aspects of the solidification process are synchronous with factors controlling weld metal hydrokinetics.

Summary

Growth rate fluctuations inherent to weld metal solidification are responsible for a variety of microstructural features which, in turn, affect the mechanical and physical characteristics of weld metal. These fluctuations are considered to be the result of the nature of the solid-liquid interface and how it is specifically influenced by thermal aspects of the solidification process. The solid-liquid transition region is described as a diffuse interface which cyclically varies in thickness during solidification.

These cyclic variations in interface thickness are considered to be the result of alternating advances (change in growth rate) of the leading and trailing edges of the diffuse interface. The movement of the interface during solidification is considered to be a two-stage growth process—the first-stage involves the rapid growth of primary projections (dendrite stalks) for some finite distance into the liquid followed by the second-stage consists of secondary (lateral) growth which advances the trailing edge of and consolidates the interface.

The growth rate fluctuations in weld metal are affected by interactions of thermal effects inherent in weld metal solidifications and external factors associated with the welding process. The influence of these interactions explains some of the differences in microstructural detail observed in structures developed during steady-stage (during welding) and terminal conditions of weld metal solidification.

Using a simple heat flow model, it is shown that the rate of heat flow through the diffuse interface is a function of the thickness of the interface. As the thickness of the interface increases, the rate of heat flow decreases and vice versa, which is consistent with the proposed two-stage interface growth mechanism and its effects on weld metal microstructures.

A mechanism for weld surface ripple formation is proposed based on the interaction of growth rate fluctuations and surface tension effects associated with the weld pool surface. The formation of ripple "peaks" is associated with increasing (rapid) growth rate intervals and ripple "valleys" with decreasing (slower) growth rate intervals.

Variations in the height and spacing of ripples observed with weld metal structures developed during steady-state and terminal conditions can be explained by variations in the thermal aspects of the solidification process. The ability to correlate weld surface ripples with solidification effects (transverse solute banding, porosity banding, etc.) is dependent upon whether the factors responsible for each are synchronous or non-synchronous events.

References


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