WELD METAL SOLIDIFICATION ....

Sources and Effects of growth rate fluctuations in ripples formation during weld metal solidification

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This paper is primarily concerned with isolating factors responsible for and influence on growth rate fluctuations inherent in weld metal solidification. These factors & their interactions are discussed with respect to their role(s) in producing micro-structural features such as "traverse solutebanding" 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 slidifactions are discussed.

A. INTRODUCTION :

The inherent periodic fluctuation in growth rate during weld metal solidification is one of the most significant and least understood phenomena during the freezing of weld metal. These fluctuations are responsible for cyclic variations in solute content inthe 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 behaviour, and the response to thermal and/ or mechanical treatment of the weld fusion zone micro structure. It also associates the formation of surface ripples to this periodicity in growth rate.

"Transverse solute banding" and porisity band networks have been observed along the length and in the crater region of arc fusion welds and in resistance spot and seam welds 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 effect of growth rate fluctuations are also noted in other solidification process, suggesting some of these factors may be inherent characteristics of metal and alloy solidifications, rather then features peculiar to weld metal solidifications.

The purpose of this paper are to :

1) Isolate the important factors which influence growth rate flucutations during weld metal solidifications & discuss their possible interactions.

2) Propose a mechanism for weld surface ripple formation.

B. 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 morhphology of weld metal. The most significant is that of "transverse solutebanding" as often noted by alternately light and dark etched bands in metallographic weld fusion zone cross sections. 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 that 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 stochiometry which can be expected to vary locally in its chemical and mechanical behaviour response.

The alternately light and dark etched structure 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 stoichio metry is also responsible for local variations in response of the weld fusion zone to postweld strengthening which is indirectly revealed by the fracture topography. The fracture surface 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 the banded network. 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 interderndritic 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 flucuations on growth morphology is somewhat more subtle and less obvious than the previously mentioned effects. These fluctuations significantly affect the competitive growth process permitting favourable growth orientations to more conveniently win out over less favourable growth orientations to more conveniently win out over less favourably oriented ones. It should be noted that the preferred growth orientations of neighbouring 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 interfact 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 sold-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 sold-interface.

Commonly observed weld surface ripples can also be associated with inherent growth rate fluctuations experienced during weld metal solidification. In many instances, the ripples frequency and spacing along the length of a weld (steady-state conditions) can be correlted with power supply ripple characteristics. This corelation can not be made where external factors such as arc perturbations, non synchronous 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 solidifications process (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 question are suggested and discussed.

C. Source of Growth Rate Fluctuations :

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

The effects of weld process parameter variations and base metal & filler metal alloy adjustments on the result and 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 charactersistics of the interface. As a result, growth substructure control, within limits, can only be achieved by the judicious adjustment of external variable which manipulate or affect the interface.

C.1 The solid-liquid Interface

Most of the classic discussions dealing with solidification mechanics treat the solid-liquid interface as a planar seperation of the solid sub-strate 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 lenght 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 flucuations in weld metal are directly associated with this diffuse interface and, specially, to cyclic variations in the thickness of this interface. The proposed mechanism for interface thickness variations is based on essentially two considerations: a discrete growth stages of the interface and heat flow variations due to interface thickness fluctuations. However, It should be emphasized that they are interacting aspects of the solidification process.

C.2 Interface Thickness Fluctuations

The concept of 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/cystals) and the simulataneous 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 suggest a charactersistic of the interface which may also be 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 alternatively 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. 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 favourable growth orientations and heat transfer directions.

Factor 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 :

● The necessity of extracting heat arising from lateral growth within the diffuse interface,

● Extension of the primary projection tips into liquid of increasing super heat 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 occour 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 arc oscillations due to resonance and hydro-kinetic effects 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 sustantiated by the regularity in "transverse solute banding" and the ability to correlate the spacing of bands with the ripples frequency of the power source. For terminal conditions of weld solidifications, as experienced with arc and resistance spot welds, the spacing of "traverse solute bands" is irregular and generally increases as solidification proceeds. The irregularly in spacing can be attributed to the absence of the influence of 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 "transerve solute banding" effect. It is suggested that "transverse solute bands" are formed during the solidication interval represented by the transition from the first to second stage and most ofthe second-stage. Second-stage growth as influenced by :

● Interactions of the effects of preogressively increasing degrees of constitutional supercooling due to the high solute content of interdendritic liquid.

● The gradual increase in temperature of the solid within the diffuse interface resulting from heat extraction upon lateral growth (consolidation of the interface).

● 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. It should be noted here that the proposed model of growth is based on alternating advances of the leading & trailing edges of the interface and that the dissipation of latnet 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.

C.3 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, along with the relationship on the quantity of heat flow, H, to the temperature difference between the solid & liquid, ∇_T, and the thickness of the interface, ∇_x.

This relationship is taken from the general equation of heat conduction. For the purpose of this discussion, ∇_x is being treated as the "effective thickness of the diffuse interface, and ∇_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 ∇_T it can be assumed that the temperature of the solid does not vary and that variations in ∇_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 vice versa.

If ∇_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 substraces. The correlation of "transverse solute band" spacings with ripples frequency is an example where the ∇_T parameter is more predominent than ∇_x parameter.

For conditions of terminal solidification (i.e arc craters, arc and resistances spot welds), ∇_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, ∇_x

D. 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 during solidification. The mechanism of ripple formation is easily explained by the schematic models shown 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-state) and the ripple "valleys" with the decreasing growth rate interval (second stage.)

These states of surface ripple development are noted in figure 1, 2 and 3. During the rapid growth internal the rate of extension of primary projections is greater than rate of melt recession due to surface tension effects.
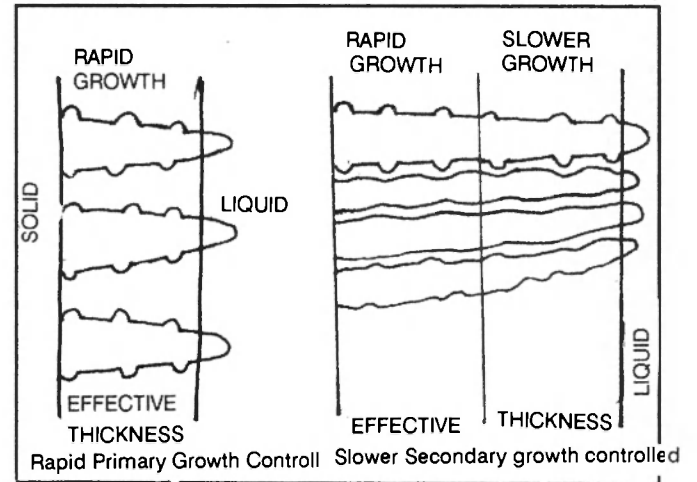

Fig. 1

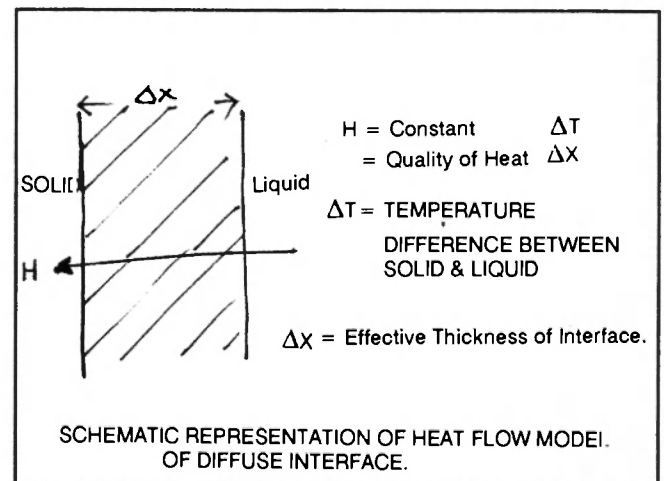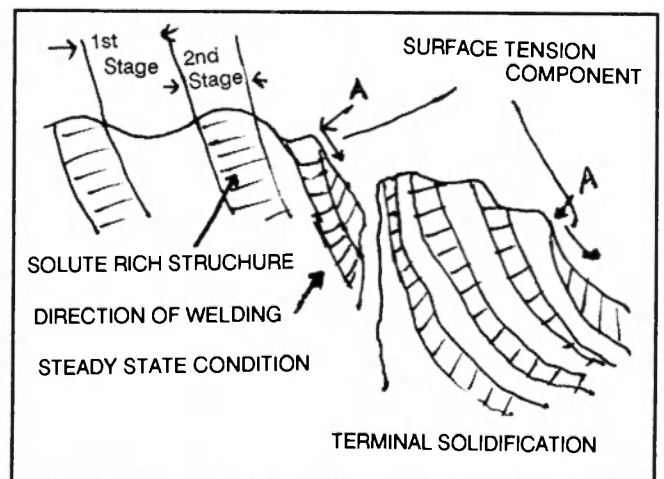SCHEMATIC REPRESENTATION OF HEAT FLOW MODEL OF DIFFUSE INTERFACE.

Fig. 2

Fig. 3

As noted in fig 3 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 centre of weld craters is due to the decreasing influence of surface tension as the weld pool melt volume diminishes. The increase in ripple spacing towares the center of the weld cratre 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 atrributed to the fact that surface ripple formation is influenced by both the thermal aspects of te solidification process and weld pool hydro-kinetics, wherease growth rate fluctuations are more strongly influenced by thermal considerations.

The hydrokinetics of the wild 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 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 factor controlling weld metal hydrokinetics.

E. CONCLUSION

Growth rate flucturation inherent to weldmetal solidification are responsible for a variety of microstructural features, which, in turn, affect the mechanical & physical characteristics of weld metal. These fluctua-

tions are considered to be the result of the nature of the solid-liquid interface and its influence on thermal aspects of the solidification process. The solidliquid 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 & 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 micro-structures.

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 associates 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 constitutions 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 arc synchronous or non-synchronous events.