Microstructural Aspects of Weld Metal Solidification in Large Grain Aluminum

Growth mechanisms in welds made on polycrystalline base metal, including nucleation, competitive growth, and columnar bending, are explained, and conditions favoring fusion zone nucleation are summarized

BY C. R. LOPER, JR. AND J. T. GREGORY

ABSTRACT. The nature of the contribution of individual elements of the weld metal solidification process such as epitaxial growth, columnar bending, terminated growth, fusion zone nucleation, preferred growth directions, crystallographic orientations, etc., can be studied by eliminating the competitive aspects of growth; this may be done by welding large grain base metal.

Autogenous bead-on-plate welds were made between 24 and 426 ipm (1 and 18 cm/s). The weld centerline plane of sectioning revealed five classes of fusion zone morphologies corresponding to distinct epitaxial base-metal crystallographic orientations. Columnar grains were found to maintain their original crystallographic orientation with bending and distance from the fusion boundary after initial epitaxial growth.

Extensive nucleation occurred in two-thirds of all wide fusion zone columnar grains and rarely at more than a relatively short distance from the fusion boundary. Such nucleation was found to be a function of crystallographic orientation, alloy content, and thermal conditions.

Centerline sections of welds made on conventional polycrystalline base metal revealed that columnar bending was limited due to grains failing to maintain growth normal to the instantaneous freezing interface. Competitive growth mechanisms operated sluggishly over relatively long distances, if at all. No evidence of the development of preferred orientation was found and no discrete nucleation events were observed. It was concluded that fusion zone nucleation is a rare event.

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Introduction

The microstructure of an arc weld fusion zone is generally a result of the interaction of several columnar grain growth mechanisms. The dynamic nature of the welding process combines transient thermal conditions, localized chemical variations, and individual grain crystallographic orientations to produce constantly changing growth conditions resulting in various growth morphologies. Knowledge of the mechanics of weld metal solidification provides a basis for controlling certain characteristics of these morphologies, such as columnar bending, columnar substructure, and grain coarseness.

Two significant features of welds made on typically polycrystalline base metal are the beginning and termination of columnar grains at various points throughout the fusion zone. Of the numerous columnar grains which initially start growing at the fusion boundary, only a small fraction of that number are present at the center of the weld bead surface per inch of weld.

Subsequent to nucleation processes within the fusion zone, columnar grains grow in the presence of neighboring grains competitively wherein they are either more or less favorably oriented than their neighbors for continued growth. This competitive growth law continually operates throughout the fusion zone to not only allow those grains which are better oriented to continue to grow but to also effectively reduce the final number of columnar grains which reach the upper surface of the weld bead.

Weld Metal Solidification

The dynamic nature of the mechanics of solidification occurring within the fusion zone is revealed by sectioning the weld bead along its longitudinal centerline. Figure 1 schematically illustrates the numerous salient features of weld zone morphology revealed by this centerline section, namely:

1. Recrystallization of the cold worked base metal in the heat-affected zone (HAZ), if applicable
2. Partial melting of the base metal grains at the fusion boundary
3. Initial solidification by epitaxial growth at the fusion boundary
4. Competitive growth of columnar grains after initial stages of solidification (numerous columnar grains throughout the fusion zone starting and being terminated)
5. Continual columnar grain bending towards the welding direction
6. Solute rejection lines (transverse banding) normal to the direction of columnar growth

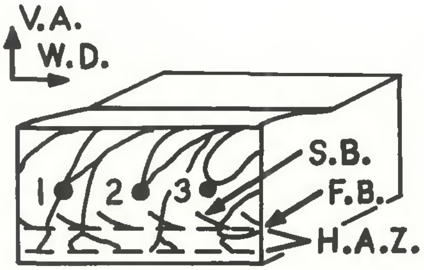

Fig. 1 — Schematic representation of longitudinal centerline plane section of a bead-on-plate weld. V.A. = vertical axis; W. D. = welding direction; F.B. = fusion boundary; H.A.Z. = heat-affected zone; S.B. = solute banding

In forming an autogenous weld bead, heat from the arc causes a cold-worked base metal to recrystallize in the heat-affected zone (HAZ) surrounding the weld bead. In the absence of cold work, strain induced recrystallization does not occur, although some grain growth may take place, and metallographically the HAZ changes by tending to follow phase equilibria considerations, such as phase transformations, solution and precipitation, etc. Points closer to the arc heat experience sufficiently high temperatures to cause melting, thus delineating the fusion boundary by partially melting the grains of the base metal.

As the arc heat source moves along, initial solidification occurs by epitaxial growth upon the partially melted base metal. The argument for an expitaxial relationship between base metal and weld metal is that the solid and the liquid have sufficiently similar composition to produce perfect wetting and to provide a microstructural continuity at the fusion boundary (Ref. 1). The existence of such epitaxial growth has been demonstrated by studies (Refs. 1-3) involving x-ray diffraction and continuity of slip lines, grain boundaries, and twins across the fusion boundary.

Savage and Aronson (Ref. 1) have shown that the shape of the weld pool significantly influences the weld metal growth morphology as the pool changes from elliptical to tear drop shape with increased welding speed. Since the direction of solidification occurs normal to the solid-liquid interface and since the interface curves away from the fusion boundary, columnar grains of the fusion zone bend progressively toward the moving heat source. Columns exhibit a greater curvature the more curved the weld pool becomes and the essential principles of competitive growth detailed by Chalmers (Ref. 4) for ingot solidification apply.

As with ingot solidification, the substructure of columnar grains within the fusion zone is generally either dendritic or cellular, depending upon thermal and compositional conditions within the weld zone as well as welding speed (Ref. 3). Because growth can occur faster along specific crystallographic directions, depending upon the metal, some columnar grains will be more favorably oriented for rapid growth than others, giving rise to the competitive growth mechanism. This growth mechanism, combined with columnar grain bending, produces a fusion zone morphology of columnar grains beginning and terminating throughout the fusion zone.

The instantaneous shape of the weld pool may be evident from the solute bands formed within the fusion zone during solidification. Any abrupt change in the rate of solidification causes solute to be either incorporated into or rejected from the advancing freezing front, depending upon whether the freezing rate becomes faster or slower, respectively (Refs. 5, 6).

Nucleation Within the Fusion Zone

With the high solidification rates associated with conventional arc-welding process, growth mechanisms necessarily operate rapidly under conditions which would seem to favor nucleation at the freezing interface. Savage et al (Ref. 3) states that nucleation in the weld fusion zone is an insignificant event due to the presence of conditions favoring epitaxial growth and successful growth of favorably oriented columnar grains.

A successful nucleation event may be defined as one which starts at a point and diverges into a columnar grain growing in competition with its neighbors. Columnar grains originating at a point are commonly seen in microstructures of weld beads but each originate at a junction of two other columnar grains, for example point 1 in Fig. 1. This point may be

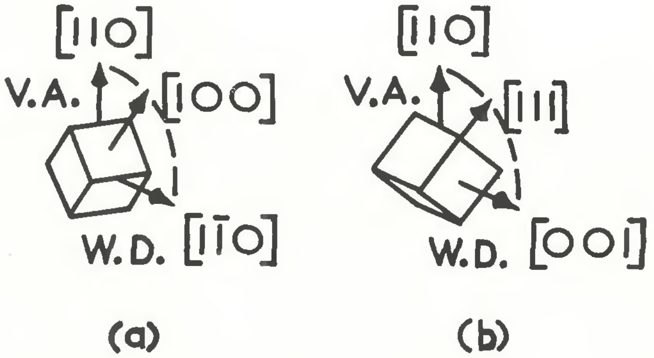

Fig. 2 — Unit cell crystallographic orientation representation of two partially melted base metal grains having identical vertical axes (V.A.) but different welding directions (W.D.). (a) [110] W. D. (b) [001] W. D.

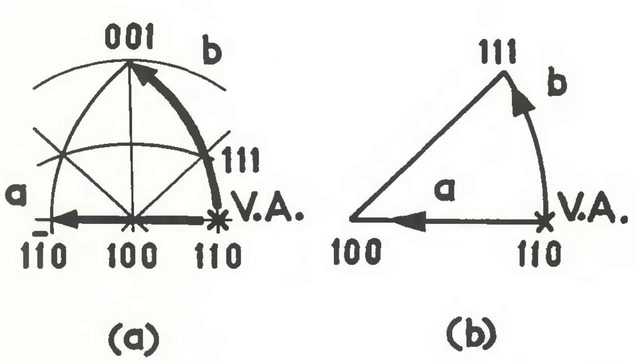

Fig. 3 — Stereographic projection representation of the two unit cells of Fig. 2. (a) Portion of the Wulff net; (b) Standard triangle in the standard position

caused by a discrete nucleation event or by a two-dimensional effect of the "new" columnar grain growing up wards in three-dimensional space either in front of or behind the plane of sectioning and pinching off its neighbor. Rarely is a diverging pointed columnar grain seen to emerge from a single parent columnar grain, as shown at point 2 of Fig. 1. Not only is such a nucleation event apparently rare but the plane of specimen sectioning would have to intersect the newly nucleated grain exactly at its point of origin, since nucleated columnar grains are essentially long, thin cones and sectioning slightly off of the point of origin would produce a parabolic shape at the bottom, as is shown at point 3 in Fig. 1.

An explanation for the ostensible absence of fusion zone nucleation is that welds made on typically polycrystalline base metal result in fine columnar grains which, when possessing unfavorable growth orientations, are pinched-off by competitive-growth mechanisms by their neighbors before conditions of supercooling favor embryo formation or before nuclei fragmentation or other phenomena occur which result in fusion zone nucleation. Frequently a columnar grain is pinched-off by its neighbors after having grown only a distance equal to one or two grain diameters; such a columnar grain can readily be said to have had unfavorable orientation for growth even at the point of initial fusion boundary epitaxy. Unfavorable orientation allowed initial growth to take place followed by mechanisms of competitive growth which operated sooner than mechanisms of nucleation. This is verified by the fact that epitaxy (and not discrete nucleation) at the fusion boundary always occurs initially (as will be demonstrated below) regardless of the crystallographic orientation of the partially melted base metal grain.

Savage et al (Ref. 3) contend that competitive growth, not nucleation, is the primary mechanism of interest in fusion zone solidification. In the absence of competitive growth the frequency and distribution of discrete nucleation events, the growth conditions which favor nucleation, and the general nature of subsequent columnar grain development has yet to be demonstrated.

Fusion zone nucleation may be studied by eliminating the competitive growth factor by welding large grain base metal. Unfavorably oriented columnar grains are allowed to grow unimpeded by their more favorably oriented neighbors when the ratio of columnar diameter to fusion zone depth is near one or greater. This can be arranged by welding large grain base metal.

Crystallography of Columnar Grains

The crystallographic orientation of a large grain (essentially a single crystal) is conveniently represented as points in the standard triangle of the Wulff net using sterographic projection techniques, where each point represents a crystallographic axis of the grain (see any good text on x-ray diffraction). Crystallographic orientation representation of large welded grains has to not only designate the grain axis (here taken as the vertical axis; see Fig. 1) but also the welding direction and the locus of all axes lying between these two principal axes.

The vertical direction alone does not present information on instantaneous growth directions experienced as the columnar grain bends towards the welding direction with distance from the fusion boundary. Consider the case of two partially melted base metal grains having crystallographic orientations as shown in Fig. 2. Initial expitaxial growth at the fusion boundary will be equally favorable (or unfavorable) for both grains, since the [110] is the initial growth direction in both cases.

Figure 3a shows a portion of the Wulff net representation for the two growth conditions of Fig. 2. In case "a", the growth direction becomes more favorable as the [100] direction is approached, whereas in case "b" the opposite is true: the growth direction rapidly changes to the unfavorable [111] direction. (It has been observed that for most welds the locus of later directions near the welding direction are inapplicable since complete columnar bending seldom occurs).

The standard triangle portion of the Wulff net in the standard position may be used to condense the representation of these two growth conditions as seen in Fig. 3b. The specimen vertical direction is the point of origin (at X) and the location of the welding direction is only indicated by the locus of directions (trace) leading to it. The exact location of the welding direction is always 90 deg from the vertical axis.

Such standard triangles adequately provide all of the information required for representing crystallographic conditions present in welds made on individual large grains.

Object

An investigation was conducted to examine solidification mechanisms operative in the absence of competitive growth and to determine what the effect of base-metal-grain crystallographic orientation has upon these mechanisms. Information gained through the study of welds made on large grain base metal was to be analyzed for applicability to welds made on conventional polycrystalline base metal. The weld bead longitudinal centerline plane of sectioning was exclusively used not only for the fundamental study of weld metal solidification on large grain base metal but also for revealing additional information relevant to welds made on polycrystalline base metal.

Experimental Procedure

Specimen Preparation

The strain-anneal technique was used to produce extremely large grains in alloy 1100 aluminum (commercially pure) by cold rolling 4% and annealing for 4 h at 1050 F (566 C). Finished specimens were square plates 2 in. (51 mm) on a side, ¼ in. (6.3 mm) thick, having an average grain size of 0.2 in. (5 mm) diam.

Autogenous bead-on-plate welds approximately 0.04 in. (1 mm) deep and 0.12 in. (3 mm) wide were made using the gas tungsten-arc process with a ⅛ in. diam (3.1 mm), thoriated tungsten electrode mounted on an automatic horizontal-travel torch carriage and argon gas shielding.

The longitudinal centerline plane, as shown in Fig. 1, was used for all specimen sectioning. The torch carriage produced welds which were uniform in depth and longitudinally straight. Welds were first sectioned transversely on opposite ends and then polished and anodized. Using low magnification, a line was scribed on each transverse end section coincident with the radial line of fusion zone growth which was perpendicular to the surface of the plate. Both scribed lines were joined by lightly scribing a line down the center of the

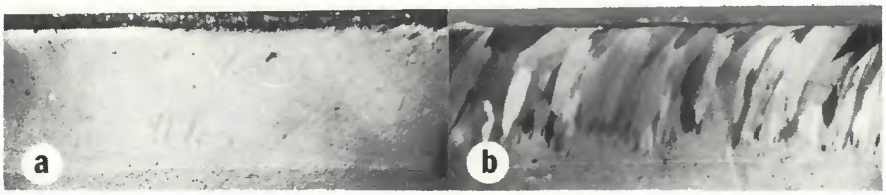

Fig. 4 — A typical longitudinal centerline-plane section. (a) Continuous growth. (b) Discontinuous growth. 84 ipm welding speed; direction of welding left to right; anodized; polarized light. X25, reduced 30%

top of the weld bead. This latter line joined opposite sides of the end lines so that it was slightly skewed to the weld axis. This slight skew insured that a substantial segment of the true centerline plane was subsequently revealed.

A specially constructed steel sectioning block was used to hold a 1 in. (25 mm) long specimen to grind down to the centerline plane. Fine grinding and polishing were completed with the specimen remaining in the sectioning block. Specimens were electropolished using the solution of Bales et al (Ref. 7) consisting of 6 ml perchloric acid, 59 ml methanol, and 35 ml ethylene glycol monobutyl ether (butyl cellosolve) at 500 mA/cm^2 and 25 V for 30-40 seconds. Specimens were anodized using 7 ml fluorboric acid in 93 ml distilled water at 8 A/cm^2 and 50 V for 8 seconds (Ref. 8). Polarized light was used for all metallographic work.

Microscopy and Crystallography

Photomicrographs of the centerline sections of several hundred fusion zone grains were made and each fusion zone grain was subsequently marked by scratching the specimen with a fine needle point attached to the microscope objective lens. The marks were used to position a fluorescent marker for x-ray diffraction studies.

The crystallographic orientation of individual grains was obtained by x-ray diffraction using the back reflection Laue technique with copper radiation. The essential principles used by Savage and Aronson (Ref. 1) for x-ray beam location was used to impinge a finely collimated beam, 0.004 in. diam (0.1 mm), upon selected areas of each specimen. Instead of using a removable magnetic x-ray beam locator ring on thinned specimens, a cellophane tape strip with a fine fluorescent particle was attached to the specimen and removed after positioning the x-ray beam upon the marker. Conventional stereographic techniques for single crystal orientation were used for the initial stages of the work.

Epitaxy and Columar Grain Bending

Since a fundamental principle upon which the present work was based was that epitaxial growth takes place at the fusion boundary, several sets of adjacent base metal and fusion zone grains were investigated by x-ray diffraction to verify epitaxy at the fusion boundary.

The fusion zone depth was of the order of 0.04 in. (1 mm) while the average grain diameter was 0.2 in. (5 mm), thus producing wide columnar grains having widths greater than their heights with fusion boundary lengths averaging 0.2 in. (5 mm). Polarized light microscopy and grain boundary continuity were also used to detect the presence of epitaxial growth.

To determine if the crystallographic orientation changes with distance from the fusion boundary in individual nucleation-free columnar grains, the crystallographic orientation of both the upper and lower areas of large columnar grains were compared using x-ray diffraction.

Results and Discussion

A typical microstructure revealed by centerline sectioning the fusion zone of a weld made on large grain base metal is shown in Fig. 4. Two large base metal grains are seen to have resulted in different columnar grain growth morphologies in the fusion zone. Columnar grain (a) is called *continuous* since growth was uninterrupted and columnar grain (b) is called *discontinuous* since extensive nucleation occurred during weld metal solidification in the plane of sectioning.

Approximately 30% of all columnar grains observed in welds made on large grain aluminum were of the continuous type, that is, essentially nucleation free on the centerline plane. The majority of fusion zones displayed extensive nucleation of the discontinuous type.

Epitaxy and Columnar Grain Bending

Columnar grains of the fusion zone were found to have the same crystallographic orientation as the respective base metal grains from which they grew. Identical back reflection Laue x-ray diffraction patterns were obtained for 12 randomly chosen pairs of base metal/columnar grains, thus verifying epitaxial growth at the fusion boundary.

Additional evidence of epitaxial growth was provided by polarized light microscopy. Rotation of each specimen about its normal axis under polarized light illumination resulted in pairs of grains adjacent across the fusion boundary changing light intensity identically and simultaneously. Also, grain boundaries were continuous at the fusion boundary in all cases.

Idential back reflection Laue patterns were obtained for the upper and lower portions of a large nucleation-free columnar grain, similar to grain (a) of Fig. 4. Although the columnar grain curved towards the welding direction, the orientation was found to remain constant as the columnar grain grew upward. An analogy may be seen here between this growth phenomenon and a deck of playing cards sheared parallel to the surface upon which they rest: the crystallographic planes of the columnar grain remain parallel with progressive columnar bending.

Microstructure/Orientation Correlation

Fusion zone microstructures were either essentially nucleation free or distinctly characterized by various patterns of nucleation and growth. After initial epitaxial growth these nucleation and growth patterns were composed of combinations of the following features:

1. Extensive nucleation at various distances from the fusion boundary
2. Feathery columnar grains

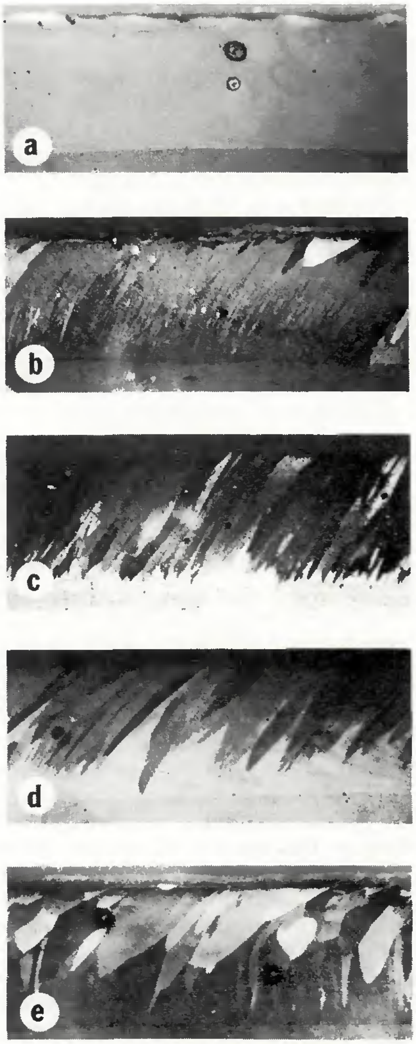

Fig. 5 — Five classes of fusion zone microstructures. Welding direction left to right; anodized; polarized light; X25, reduced 35%. (a) Class 1 (nucleation free), 156 ipm; (b) Class 2 (feathery growth), 84 ipm; (c) Class 3 (nucleation near fusion boundary), 36 ipm; (d) Class 4 (nucleation at quarter height), 96 ipm; (e) Class 5 (random nucleation), 72 ipm

3. Fine, medium, or coarse columnar grains
4. Various sized columnar groups
5. Isolated, nucleation free regions

As seen in Figs. 2 and 3, the crystallographic growth direction changes progressively with distance from the fusion boundary and the growth conditions initially present change to favor or inhibit continued uniform growth, thus contributing to various nucleation morphologies.

A significant correlation was found between patterns of fusion zone solidification morphologies and their respective stereographic projection standard triangle plots. Representative microstructures of five distinct fusion zone classes are shown in Fig. 5 and their corresponding standard triangle plots are shown in Fig. 6. Specific microstructural characteristics were attributed to each class of fusion zones as follows:

Class 1, Fig. 5(a). Continuous, uninterrupted growth in the fusion zone resulted from base metal grains being favorably oriented with their vertical axis near the <100> direction and initial columnar bending being towards the general direction of <100>.

Occasionally, isolated fusion zone nucleated columnar grains grew up through continuous type fusion zones. Evidence of impingement by neighboring fine columns growing across the centerline plane was frequently found but only in the extreme upper regions of the weld bead.

Significantly, nucleation within this class of fusion zone was seldom observed to occur in the upper half of the weld bead. Considering the fact that the growth direction was constantly changing with distance from the fusion boundary, it was anticipated that some significant fraction of all continuous type grains would eventually become sufficiently unfavorably oriented for continuous growth, thereby yielding to discrete nucleation events. But no unambiguous instances of upper region nucleation were observed, although the impingement morphology mentioned above was frequently seen. Two reasons for this are that nucleation off of the centerline plane and subsequent growth upwards and across the plane of sectioning (impingement) may occur to pinch off the continuous grain, or that centerline plane nucleation may result in Class 5 fusion zones (see below).

Class 2, Fig. 5(b). A feathery type growth was characteristic of this class. Rotation of the specimen under polarized light caused the entire feathery area to change in light intensity simultaneously. This was interpreted as indicative of twinned growth. Preliminary work to determine the twin composition plane of Class 2 microstructures by x-ray diffraction is presently underway.

Frequently the feathery portion of the fusion zone was segmented. In these cases segments of feathery growth appeared to be terminated within the matrix in which they originated, producing a steaked appearance.

The standard triangle plots for this class could not be separated from those of Class 1. Often a fusion zone appeared to be the continuous type except for rather uniformly distributed fine streaks or feathery segments.

Class 3, Fig. 5(c). Fusion zones of this class develop various nucleation patterns immediately after initial epitaxial growth. The photomicrograph representing this class of fusion zone shows an exceptionally uniform nucleation pattern. Often a series of tight clusters of nucleation appeared near the fusion boundary separated by small, widely spaced, relatively nucleation free regions, producing structures somewhat similar to Class 4 (below) morphologies but closer to the fusion boundary.

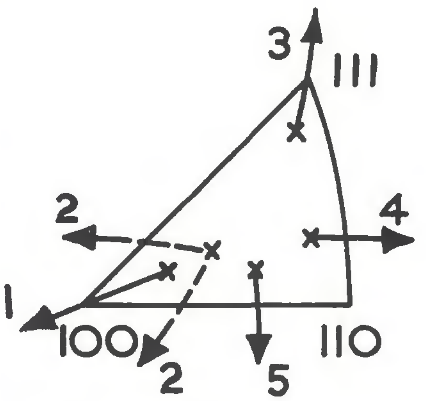

Fig. 6 — Standard triangle representations of the five classes of fusion zones

Class 4, Fig. 5(d). Tight clusters, random individual columns, and nucleation points at approximately quarter fusion zone height are characteristics common to this class. This class of fusion zone is similar to Class 3 with the exception of distance from the fusion boundary where gross nucleation takes place. Both classes are heavily nucleated and neither has significant nucleation free regions.

Class 5, Fig. 5(e). This class appears to be intermediate between continuous and discontinuous types of fusion zones. This is true for the microstructures as well as for the standard triangle plots. Large regions of nucleation free growth exist adjacent to heavily nucleated areas. Several of these fusion zones displayed substantial regions of feathery growth which merged into distinct columnar grains.

The classification criteria for the five fusion zones was based on the apparent orderliness of the fusion zone morphology: Class 1 being completely void of nucleation and Class 5 being randomly nucleated with the least apparent regularity. An interpretation of the various classes is that Class 1 and Class 2 are essentially continuous types and Class 3 and Class 4 are discontinuous types while Class 5 is intermediate. The standard triangle plots of Fig. 6 bear this out: Class 5 orientations are between the two extremes.

Preferred Growth Directions

It was postulated that the crystallographic orientation would have a direct effect upon the nature and extent of fusion zone nucleation. In FCC metals four (111) close-packed planes, the fastest growing planes, contribute strong growth components to the favored <100> growth direction at their mutual planar intersection. Only two such close-packed planes contribute to growth in the <110> direction and effectively only one contributes in the <111> direction. Applying this geometric consideration to growth in the fusion zones of welds made on large grain aluminum, nucleation events could reasonably be expected to occur most readily in metal solidifying upon a base metal grain having a <111> direction oriented vertically (Class 3), less readily upon a <110> oriented grain (Class 4), and not at all on a <100> oriented grain (Class 1).

Correlation between fusion zone microstructures and their respective stereographic projections of crystallographic orientations provide further evidence that the <100> is the favored growth direction in aluminum.

Fusion-Zone Nucleation

If the initially growing epitaxial columnar grain was not terminated by nucleation before it had grown to half-height in the fusion zone, nucleation did not occur at all. Few cases to the contrary have been observed, although impingement by small columnar grains growing across the centerline plane in the upper region is common.

An analysis of the conditions present during solidication reveals that the following factors govern solidification within the weld zone:

1. Thermal gradient
2. Growth rate
3. Amount of superheating
4. Weld metal turbulence
5. Solute concentration
6. Growth rate uniformity
7. Amount of supercooling
8. Parent columnar grain crystallographic orientation

Of these eight factors, those believed to have influence upon the mechanisms of nucleation within the fusion zone are the latter four.

Within the fusion zone of the single specimen shown in Fig. 7 the first four factors above did not change significantly from one end of the weld to the other since the welding conditions were uniform along the specimen length. Although the first four factors were essentially identical for the entire weld, a spectrum of growth structures resulted, indicating an apparently insignificant structure dependence upon these factors. In all fusion zones made on large grain base metal within the range of welding speeds between 24 and 426 ipm (1 to 18 cm/s), nucleation always occurred near the fusion boundary where growth rate uniformity and significant supercooling were absent (as verified by solute banding lines and coarse cellular growth, respectively). Nucleation morphology dependence upon base metal grain orientation has previously been demonstrated.

Solute concentration definitely is a factor affecting nucleation as seen in Fig. 8. Large grain aluminum having 99.7% purity displayed no fusion zone nucleation whatsoever, regardless of crystallographic orientation, welding speed, etc. But for 98% aluminum, solute rejection by both solute banding and extremely coarse cellular growth was so great that polarized light microscopy on anodized specimens was ineffective, although nucleation did not appear to be similar to the 99%-purity aluminum used throughout the investigation.

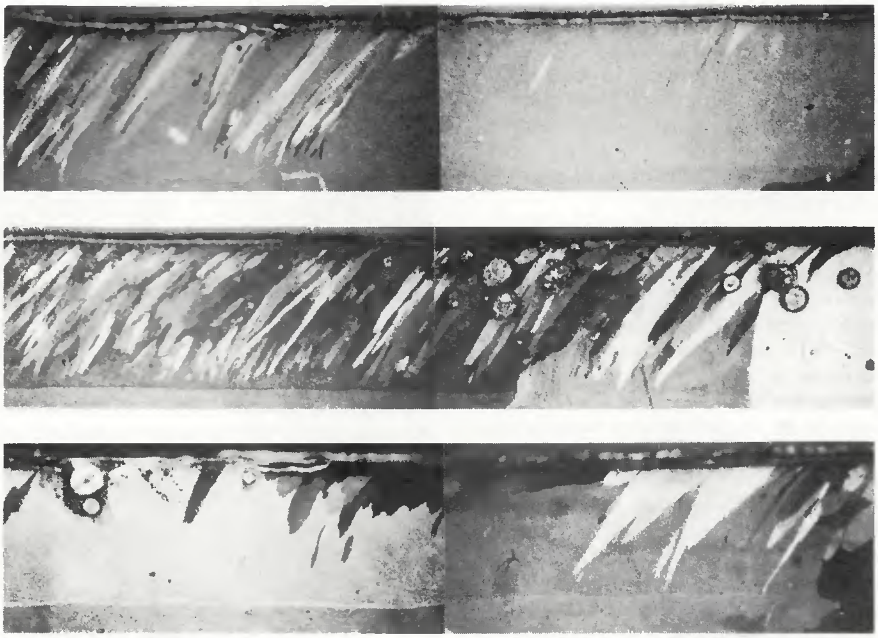

Fig. 7 — Fusion zone of a single specimen displaying a spectrum of growth structures, 36 ipm; welding direction left to right; anodized; polarized light. X 25, reduced 30%

Transverse Sectioning

A conventional transverse section through a weld made on large grain aluminum is shown in Fig. 9 along with its centerline section which is seen to be a Class 5 microstructure. The crystallographic orientation of the base metal grain is shown in the standard triangle of Fig. 10(a) and the centerline plane section corresponds well with the Class 5 standard triangle of Fig. 6.

The transverse section of Fig. 9 gives further evidence of the structure dependence on orientation. Comparing this transverse section with the five classes of fusion zones, it would be reasonable to say that longitudinal sections along lines "a" and "b" of the figure would display microstructures of Classes 3 or 4 and Class 1, respectively.

A model of the unit cell of the base metal grain of Fig. 9 is shown in Fig. 10(b) where the vertical axis, welding direction, and the initial instantaneous growth directions of planes "a" and "b" are shown. This model shows that initial growth in plane "a" immediately tends to change towards the<111>corner of the unit cell cube, approximately, while growth in plane "b" tends towards the (100) face of the unit cell cube. Knowing that these two growth directions are, respectively, the most unfavorable and the most favorable, nucleation in plane "a" and the absence of nucleation in plane "b" would be expected.

Fig. 10(a) shows the two welding orientations obtained by opposite 45 deg rotations of the centerline plane orientation about the weld axis for the two sections. These two orientations confirm the conclusion reached from the transverse section that plane "a" is Class 3 and plane "b" is Class 1. The significant point to be underlined here is that fusion zone morphologies are strongly dependent upon the orientation of their parent base metal grain, indeed, even predictable on the basis of this dependence.

Polycrystalline Base Metal

For welds made on typically polycrystalline base metal conventional transverse sections of weld beads are easier to prepare for metallography then longitudinal centerline sections but the latter reveal additional information, namely:

1. The shape and extent of columnar grain bending
2. Competitive columnar grain growth
3. Instantaneous solidification interface shape
4. Uniformity of weld bead depth

The centerline section of a weld made on conventional polycrystalline base metal is shown in Fig. 11. The two micrographs illustrate a section made exactly on the centerline plane and a section made slightly off of the centerline plane. A high proportion of the columnar grains in the exact centerline plane can be seen to grow almost completely throughout the depth of the fusion zone. The section made slightly off of the centerline plane shows what could be interpreted as competitive growth in the conventional sense, that is, various grains crowding out and pinching off their neighbors.

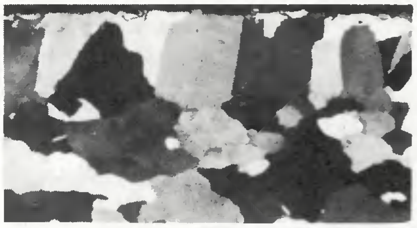

Fig. 8 — Nucleation free fusion zone of 99.7% aluminum, 84 ipm; welding direction left to right; anodized; polarized light. X 15, reduced 35%

Limited Competitive Growth

Several growth characteristics have been observed on the centerline section of welds made on polycrystalline base metal which seem to be somewhat at variance with conventional rules of columnar growth in the fusion zone. In specimens welded in the range of 24 to 426 ipm (1 to 18 cm/s), growth morphologies frequently failed to display evidence of competitive growth, considered a fundamental mechanism of weld metal solidification.

In the fusion zone shown in Fig. 11(a) numerous long, thin columnar grains can be seen to grow completely through the fusion zone depth. In the heavily nucleated fusion zone of the large grain base metal of Fig. 5(c) numerous columnar grains fan out slightly near the point of nucleation but thereafter maintain near parallel sides. To explain this apparent absence of competitive growth, other mechanisms of weld metal solidification must be examined.

Columnar Grain Curvature

It has been stated above that the degree of columnar grain bending is determined by the shape of the weld pool since columnar growth is usually normal to the freezing interface. Ostensible exceptions to this rule are seen in all centerline sections where columnar grains appear to have little or no curvature (bending) after some small amount of initial tilt or curvature. Also, the columns do not appear to have maintained growth normal to the instantaneous weld pool interface (as delineated by the solute transverse banding lines).

Poppmeier et al (Ref. 9) applied a controlled rotary magnetic field to solidifying steel and were able to show that dendritic columnar growth could be less than 90 deg to the freezing interface, depending upon the motion of the liquid metal; such angled columnar growth was found to be always in the opposite direction to the liquid metal motion. This fact, combined with the observation made by Rabkin (Ref. 10) that a strong current of molten metal flows across the surface and towards the back of the weld pool during the arc welding process, may be used to explain the non orthogonal growth mechanism.

Flow of molten metal near the surface towards the back of the weld pool and down past the rear fusion boundary and then forward along the bottom of the weld pool could cause columnar growth to deviate from the normal to the instantaneous freezing interface. This effect can be so pronounced that at high welding speeds, columnar growth can actually occur in a direction opposite to the welding direction. Figure 12 shows one of several cases found where this apparently reverse direction growth occurred.

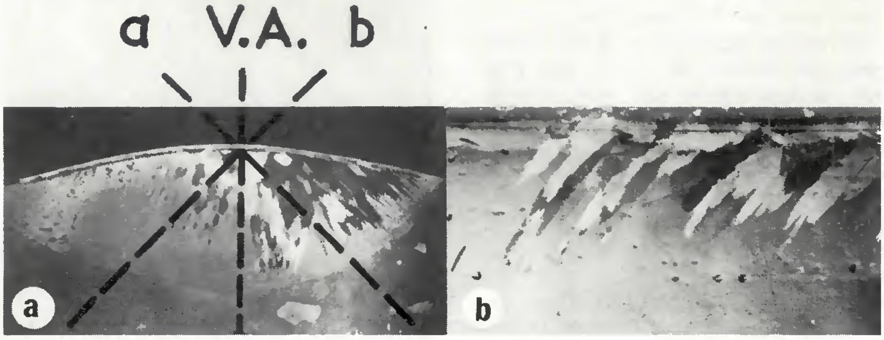

Fig. 9 — Weld made on large grain base metal. (a) Conventional transverse section (welding direction toward reader). (b) Longitudinal centerline-plane section, 48 ipm; welding direction left to right; anodized; polarized light. X 25, reduced 30%

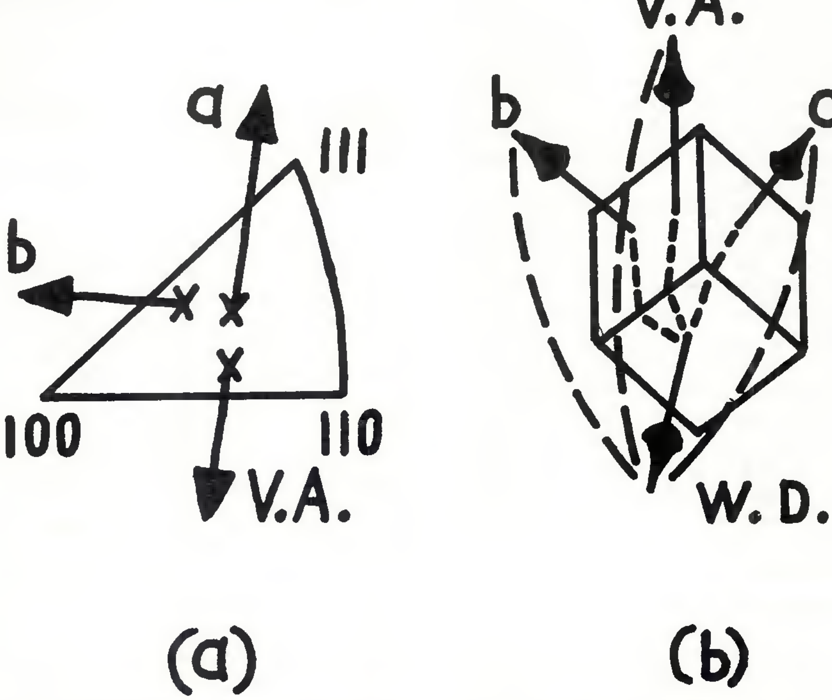

Fig. 10 — Crystallographic orientation representation of the three longitudinal planes of weld of Fig. 9. (a) Standard triangle; (b) Unit cell orientations

Absence of Preferred Orientation

Integrated structure, back reflection Laue x-ray diffraction patterns of the upper regions of the specimens of Figs. 5(c), 11(a) and 11(b) showed essentially uniform ring distributions of diffraction spots, indicating the absence of preferred orientation. Although the development of a preferred crystallographic orientation of columnar grains in fusion zones with distance from the fusion boundary has been reported for 0.012 in. sheet (0.3 mm) of alloy 3003 aluminum (Ref. 1), Walton and Chalmers (Ref. 11) present evidence to support an argument against significant preferred orientation developing in welds of purer metals.

In alloys, the presence of molten metal superheat and impurities provide two conflicting influences upon development of a preferred orientation in a freezing ingot. Impurities favor dendritic solidification by constitutionally supercooling the melt ahead of the freezing interface. Since dendrites may have strong lateral components of growth, favorably oriented dendrites may readily pinch off those less favorably oriented thereby developing a preferred orientation in the columnar zone.

On the other hand, compositional and thermal conditions may exist which inhibit dendritic growth and which result in columnar grains having a cellular substructure. In their work, Walton and Chalmers found that competitive growth mechanisms which produce a preferred orientation in a columnar zone, namely dendrite formation, may be suppressed by extensive superheating thereby creating steep thermal gradients directly ahead of the freezing interface. These steep thermal gradients favor cellular growth which has markedly weaker lateral growth components and which, therefore, does not readily pinch off neighboring grains.

All welds made in the present study not only experienced steep thermal gradients within the weld pool, as with all arc welding, but also solidified with cellular substructures. Combining the two effects of limited lateral columnar growth and limited columnar bending, a condition obtains wherein not only the development of preferred orientation is inhibited but the competitive growth

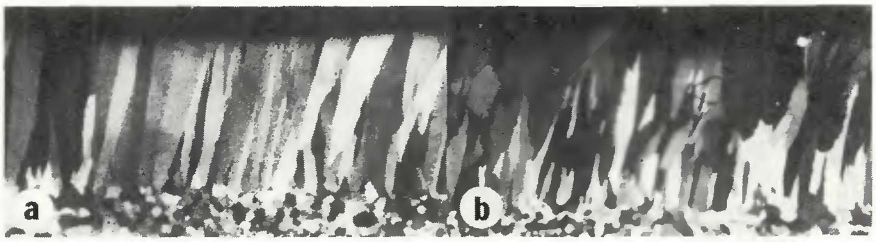

Fig. 11 — Longitudinal centerline plane section through weld made on conventional polycrystalline base metal. (a) Sectioned exactly on centerline. (b) Sectioned slightly off centerline plane. 300 ipm; welding direction left to right; anodized; polarized light. X 40, reduced 30%

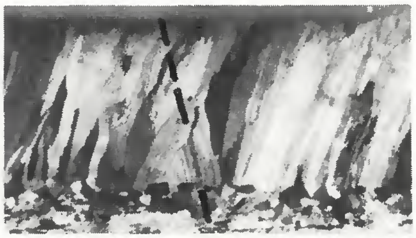

Fig. 12 — Longitudinal centerline plane section through weld made on conventional polycrystalline base metal showing columnar grains growing in direction opposite to welding, 426 ipm; welding direction left to right; anodized; polarized light. X40, reduced 34%

mechanism itself is severely limited if not made completely inoperative.

Considering the actual physical dimensions of the height and width of fusion zones studied herein, the actual point density of discrete nucleation events observed in fusion zones of several hundreds of specimens is quite low. When this statistical distribution factor is taken into account along with the following observed geometrical factors:

1. 30% of all columnar grains were nucleation free;
2. Nucleation was relatively widely spaced longitudinally;
3. Nucleation occurred only in the lower half of the fusion zone;
4. The extent of columnar grain bending was limited; and
5. The extent of competitive growth was limited;

it can be seen that the probability of discrete nucleation events occurring within the geometrically narrow columnar grains of fusion zones made on conventionally polycrystalline base metal is extremely low. Therefore, it is concluded that nucleation in the fusion zone is a relatively rare and insignificant event.

Conclusions

The following conclusions have been made on the basis of this investigation of welds on large grain aluminum base metal:

1. No mechanism of solidification at the fusion boundary other than epitaxial growth occur.
2. The <100> is the most favored growth direction in FCC aluminum weld metal.
3. Individual columnar grains do not change their crystallographic orientation with bending and with distance from the fusion boundary.
4. Nucleation events occur in the fusion zone of approximately 70% of all partially melted base metal grains while the remaining 30% are favorably oriented for nucleation free growth.
5. The closer the partially melted base metal grain is oriented to the ⟨111⟩ direction, the closer nucleation occurs to the fusion boundary.
6. Nucleation seldom occurs in the upper regions of the fusion zone in the centerline plane.
7. Nucleation in the fusion zone requires: (a) an unfavorable crystallographic growth orientation; (b) favorable thermal conditions; and (c) impurities in the weld metal.
8. Variations in welding speed do not appreciably affect fusion zone growth morphologies other than initial nucleated columnar grain growth directions.
9. Columnar grains on the centerline plane do not "bend" significantly but assume some degree of "tilt" initially which they maintain throughout their length.
10. A correlation exists between fusion zone nucleation morphologies on the centerline plane and parent base metal grain crystallographic orientation.
11. A feathery growth morphology believed to be twinned growth occasionally develops in columnar grains which deviate initially from the <100> growth direction by approximately 20 deg and which tend to grow towards the <100>.

From the work on large grain and polycrystalline aluminum, five major conclusions have been reached concerning weld fusion zones made on conventional polycrystalline aluminum base metal:

1. Columnar grains tend to remain straight by deviating from the normal to the instantaneous freezing interface in the upper regions of the fusion zone at the rear portion of the weld pool due to weld metal convection.
2. At high welding speeds, columnar grains occasionally appear to grow in the opposite direction of welding.
3. In the absence of columnar bending, competitive growth mechanisms operative on the centerline plane are almost negligible.
4. Preferred orientation does not develop on the centerline plane.
5. Nucleation events in the fusion zone are rare.

Acknowledgements

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References

1. Savage, W. F., and Aronson, A. H., "Preferred Orientation in the Weld Fusion Zone," *Welding Journal*, 45 (2), Feb. 1966, Research Suppl., 85-s to 89-s.
2. Savage, W. F., Lundin, C. D., and Chase, T. G., "Solidification of Fusion Welds in Face-Centered Cubic Metals," *Welding Journal*, 47 (11), Nov. 1968, Research Suppl., 522-s to 526-s.
3. Savage, W. F., Lundin, C.D., and Aronson, A.H., "Weld Metal Solidification Mechanics," *Welding Journal*, 44 (4), April 1965, Research Suppl., 175-s to 181-s.
4. Chalmers, B., *Principles of Solidification*, John Wiley and Sons, Inc., New York, 1964.
5. D'Annessa, A. T., "Sources and Effects of Growth Rate Fluctuations During Weld Metal Solidification," *Welding Journal*, 49 (2), Feb. 1970, Research Suppl., 41-s to 46-s.
6. Tiller, W. A., Jackson, K. A., Rutter, J. W., and Chalmers, B., "The Redistribution of Solute Atoms During the Solidification of Metals," *Acta Met*, 1 (7), 1953, 428 to 437.
7. Bayles, B. J., Ford, J. A., and Salkind, M. J., "The Effect of Elevated-Temperature Exposure on the Microstructure and Tensile Strength of Al_3Ni Whisker-Reinforced Aluminum," *Trans. AIME*, 239 (6), 1967, 844 to 849.
8. Lacombe, P., "Electrolytic Etching of Metals," *The Surface Chemistry of Metals and Semiconductors*, J. Wiley and Sons, Inc., New York, 1959.
9. Poppmeier, W., Tarmann, B., and Schaaber, O., "Application of Alternating Electromagnetic Fields in the Continuous Casting of Steel," *Journal of Metals*, 18 (10), 1966, 1109 to 1114.
10. Rabkin, D. M., "Temperature Distribution Throughout the Weld Pool in Automatic Welding of Aluminum," *British Welding Journal*, 6 (3), 1959, 132 to 137.
11. Walton, D., and Chalmers, B., "The Origin of the Preferred Orientation in the Columnar Zone of Ingots," *Trans. AIME*, 215 (6), 1959, 447 to 457.

WRC Bulletin
No. 184
June 1973

"Submerged-Arc-Weld Hardness and Cracking in Wet Sulfide Service"

by D. J. Kotecki and D. G. Howden

This study was undertaken to determine:

(1) The causes of higher-than-normal hardness in submerged-arc welds in plain-carbon steels

(2) The levels of strength or hardness which will not be susceptible to sulfide-corrosion cracking

(3) Welding procedures which will assure that nonsusceptible welds will be produced.

Concentration is primarily on weld metal, though some consideration to the weld heat-affected zone is given. The study covered a two-year period. The first year was concerned with a macroscopic view of the weldments. In that first-year study, some inhomogeneities were observed in weldments which are not obvious in a macroscopic view of the weldment. It appeared likely that these inhomogeneities could affect the behavior of the weldment in aqueous hydrogen-sulfide service. Accordingly, their presence and effects were investigated during the second year.

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WRC Bulletin
No. 185
July 1973

"Improved Discontinuity Detection Using Computer-Aided Ultrasonic Pulse-Echo Techniques"

by J. R. Frederick and J. A. Seydel

The purpose of this project, sponsored by the Pressure Vessel Research Committee of the Welding Research Council, was to investigate means for obtaining improved characterization of the size, shape and location of subsurface discontinuities in metals. This objective was met by applying computerized data-processing techniques to the signal obtained in conventional ultrasonic pulse-echo systems. The principal benefits were improved signal-to-noise ratio and resolution.

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