Fusion-Boundary Macrosegregation in Dissimilar-Filler Welds

Fundamental solidification and macrosegregation in welds made with filler metals different in composition from the workpiece are presented

BY S. KOU AND Y. K. YANG

ABSTRACT. More often than not, the filler metal in arc welding is different (dissimilar) in composition from the base metal. It can cause macrosegregation along the fusion boundary and degrade the weld quality, but the formation of such macrosegregation is still not well understood. In the present study, the liquidus temperature of the weld metal T_{LW} and that of the base metal T_{LB} were considered, in addition to the stagnant or laminar-flow layer of liquid base metal along the weld pool boundary suggested by Savage. The following solidification concepts were presented: 1) The melting front is at T_{LB} and not T_{LW}; 2) the solidification front is no longer isothermal at T_{LW} everywhere — only the homogeneous bulk weld pool begins to solidify at T_{LW}; 3) the liquid base metal can freeze quickly in a different liquid cooler than T_{LB} before much mixing occurs, so can the liquid weld metal freeze quickly in a different liquid cooler than T_{LW}, and macrosegregation is promoted either way; and 4) complete mixing throughout the weld pool is impossible with $T_{LW} > T_{LB}$. Even when the filler metal is mixed completely with the bulk weld pool, macrosegregation can still occur by the following two mechanisms. In Mechanism 1, for filler metals making $T_{LW} < T_{LB}$, the region of liquid weld metal immediately ahead of the bulk solidification front of T_{LW} is below T_{LB}. The liquid base metal swept by convection from the stagnant or laminar-flow layer into this cooler region can freeze quickly. In Mechanism 2, for filler metals making $T_{LW} >$ T_{LB}, the layer of liquid base metal is below T_{LW}. The liquid weld metal pushed by convection from the bulk weld pool into this cooler layer can freeze quickly. Filler-deficient features, including "beaches," "peninsulas," and "islands," formed by Mechanism 1 are distinctly different from those formed by Mechanism 2. Macrosegregation reported by previous investigators can be explained by Mechanism 1, but macrosegregation by Mechanism 2 has not been reported. The mechanisms were verified with gas metal arc welds of 1100 Al (pure Al) made with filler 4145 Al (Al-4Cu-10Si) and of Cu made with filler ERCuNi (Cu-30Ni).

S. KOU and Y. K. YANG are, respectively, professor and graduate student in the Department of Materials Science and Engineering, University of Wisconsin, Madison, Wis.

Introduction

In arc welding, the filler metal more often than not differs from the workpiece in composition. Such a filler metal, called a dissimilar filler metal, can help reduce weld cracking or develop desired weld properties. The present study deals with welding one workpiece material with a dissimilar filler metal, that is, dissimilar-filler welding and the resultant weld is called a dissimilar-filler weld. Welding two metals of different compositions together, that is, dissimilar-metal welding, is beyond the scope of this study.

The melted base metal and the droplets of the dissimilar filler metal mix with each other in the weld pool and solidify as the weld metal. Houldcroft (Ref. 1) showed that the bulk weld metal is essentially homogeneous; for instance, pure aluminum welded with an Al-5Cu filler metal and Al-l.0Si-l.0Mg with Al-4.9Si or Al-1.4Si (all compositions in weight-percent hereinafter).

KEYWORDS

Dissimilar Filler Metals
Gas Metal Arc Welding
Solidification
Macrosegregation
Unmixed Zone
Filler-Deficient Zone
Aluminum Alloys
Copper Alloys
Nickel Alloys

However, subsequent studies have shown that the weld metal near the fusion boundary can differ significantly from the bulk weld metal in composition and hence microstructure and properties. This composition variation is considered as macrosegregation instead of microsegregation. Microsegregation in welds occurs over the scale of dendrite arm or cell spacing, for instance, 10–20 μm in aluminum arc welds (Ref. 2). Macrosegregation in welds, on the other hand, can occur over a much larger scale, for instance, over a 100–200 μm layer along the fusion boundary or even a 1–2 mm nugget beyond the fusion boundary at the weld bottom (Refs. 3, 4).

Macrosegregation in dissimilar-filler welds was discovered 40 years ago. It has been observed in various welds including steels, aluminum alloys, and superalloys (for instance, Refs. 5–14). Different investigators have given this phenomenon different names and offered different explanations.

Savage et al. (Ref. 6) welded HY-80 steel (containing about 2.8% Ni, 1.6% Cr, and 0.3% Mn) with E11018G steel electrodes (containing about 1.5% Mn and negligible Cr). They observed an "unmixed zone" in the form of a thin layer (~75 μm thick) along the fusion boundary (which they called weld interface) but could extend into the weld metal (which they called composite region) as peninsulas (which they called folds). A composition gradient existed between the unmixed zone and the weld metal.

The unmixed zone was attributed to the existence of "either a stagnant layer or a laminar flow layer immediately adjacent to the solid base metal" because "even with the turbulent motion in a weld pool, the velocity of liquid motion must approach zero at the solid-liquid interface."

Duvall and Owczarski (Ref. 7) welded the Ni-based superalloy Udimet 700 with filler metals of Alloy 718 and Hastelloy X.

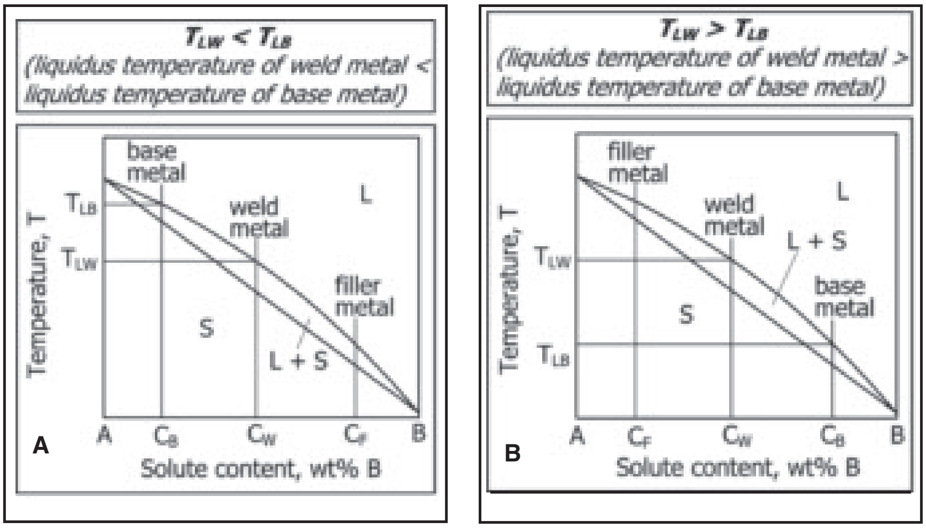

Fig. 1 — Schematic phase diagrams showing the following: A — filler metal that makes $T_{LW} < T_{LB}$; B — filler metal that makes $T_{LW} > T_{LB}$.

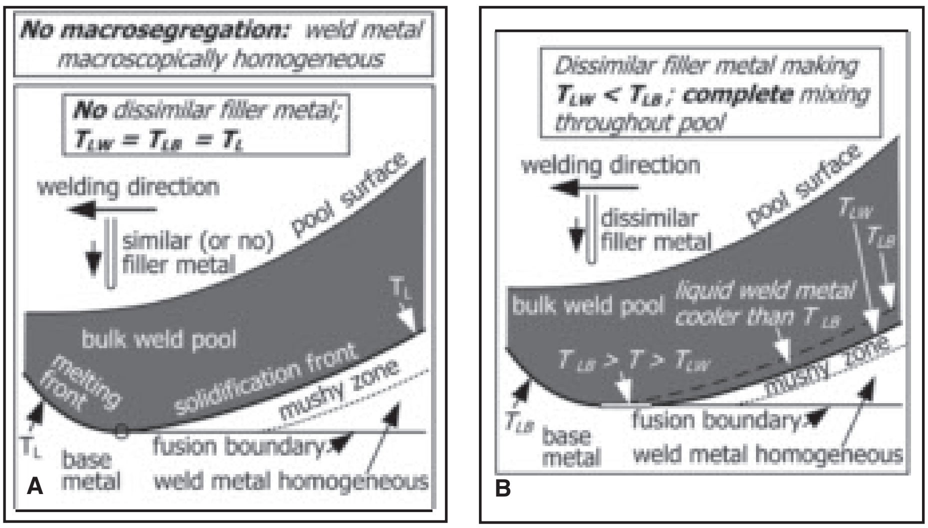

Fig. 2 — Absence of macrosegregation: A — No dissimilar filler metal; B — dissimilar filler metal makes $T_{LW} < T_{LB}$ but mixing is complete throughout the weld pool. Pool boundary is melting front before circle and solidification front after.

A "filler metal depleted area" in the form of a beach (~ 80–150 μm thick) was found between the fusion boundary and the bulk weld metal. A composition gradient existed across this area — from the composition of the base metal to that of the bulk weld metal. No evidence of the unmixed zone was found, that is, no region of a uniform composition close to the base metal composition. Liquid-metal diffusion was suggested as the most probable cause of the composition gradients.

Karjalainen (Ref. 8) welded a commercially pure aluminum (Al-0.3Fe) with an Al-4.4Mg filler metal by gas metal arc welding (GMAW). An unmixed zone in the form of a beach (~65 μm uniform thickness or 0–150 μm nonuniform thickness) identical to the base metal in composition was observed along the fusion boundary. In addition, a "pale band" (~25 μm uniform thickness) planar in microstructure (without any cells or dendrites) existed between the unmixed zone and the bulk weld metal. A composition gradient existed across the pale band, changing from the composition of the base metal in the unmixed zone to that of the bulk weld metal. It was implied that the composition gradient was due to partial mixing between the liquid base metal and the bulk weld pool, perhaps caused by convection or liquid diffusion or both.

Ornath et al. (Ref. 13) welded a low-alloy steel with a stainless steel filler of Fe-18Cr-8Ni-7Mn. No unmixed zone was observed, only a hard martensite layer in the form of a beach (~100–150 μm uniform thickness) along the fusion boundary. A composition gradient existed across the layer, called the "intermediate zone," from the base-metal composition to the bulk-weld-metal composition. Martensite formed upon nonequilibrium cooling because the composition in the layer fell in the martensite range of the constitutional diagram (Ref. 2). It was pointed out that the time required for liquid diffusion across the layer (~30 s) was much too long to be possible during GMAW. Solute segregation during solidification was suggested to be the cause for the composition gradient. Although not pointed out, this thus implied that planar solidification occurred across the layer and that solutes were redistributed along the solidification path.

Macrosegregation in welds made between dissimilar metals, i.e., between two different base metals, is beyond the scope of this study. However, for the purpose of discussion, it is worth mentioning that beaches, peninsulas, and islands were observed in dissimilar welds between steel and stainless steel.

Doody (Ref. 9) welded carbon steel to stainless steel with stainless steel and Ni-based filler metals. He observed on the carbon steel side an "intermediate mixed zone" of high hardness (martensite) in the forms of beaches (~10–60 μm) and islands with a composition intermediate between the compositions of the carbon steel and the bulk weld metal. It was suggested that liquid diffusion might be the best explanation for the intermediate mixed zone. The names "beaches" and "island" were used for the first time to describe macrosegregation in welds.

Omar (Ref. 10) also welded carbon steel to stainless steel with filler metals of stainless steel and Ni-based alloys, and observed beaches, peninsulas, and islands on the carbon-steel side. These included 1) beaches of martensite, and 2) islands and peninsulas exhibiting the base-metal structure (ferrite and pearlite) but with martensite at the interface between them and the bulk weld metal. The name "hard zone" was chosen instead of "unmixed zone" to emphasize that the martensite differed from the base metal in both microstructure and composition.

To summarize, various forms of macrosegregation near the fusion boundary of arc welds have been reported, such as the unmixed zone, filler metal depleted area, intermediate zone, intermediate mixed zone, and hard zone. According to the materials welded and the resultant microstructure and macrosegregation, these forms can be grouped into 1) beaches in aluminum welds made with dissimilar filler metals, 2) beaches and peninsulas in steel and Ni-based superalloy welds made

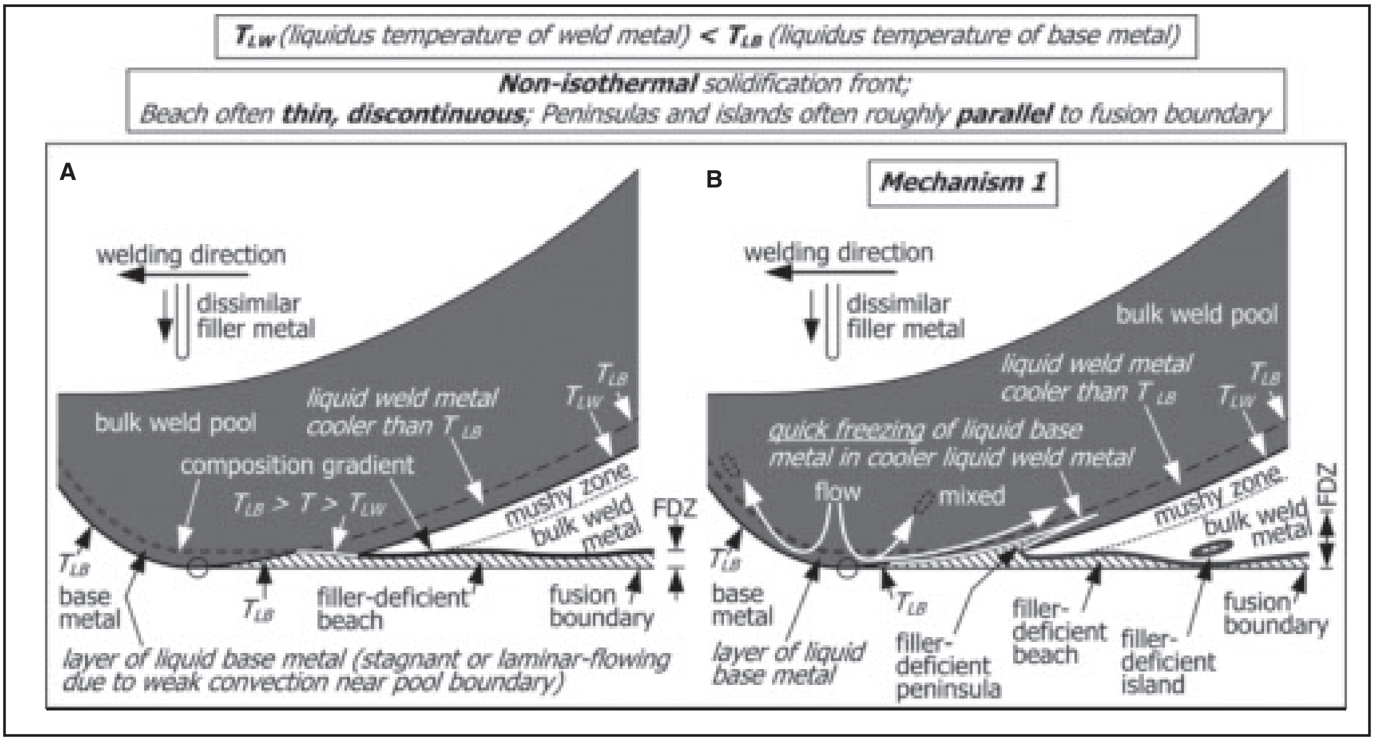

Fig. 3 — Formation of fusion-boundary macrosegregation (filler-deficient zone FDZ) when filler metal makes $T_{LW} < T_{LB}$: A — beach; B — beach, peninsula, and island by Mechanism 1. Pool boundary is melting front before circle and solidification front after.

with dissimilar filler metals, and 3) beaches, peninsulas, and islands in dissimilar-metal welds between steel and stainless steel.

Macrosegregation in arc welds made with dissimilar filler metals is still not well understood even though it has been 40 years since Savage et al. (Ref. 5) reported the "unmixed zone." Different explanations for macrosegregation have been given, including weak convection, liquid diffusion, partial mixing, and solute segregation during welding.

Fusion-boundary macrosegregation in dissimilar-filler welds has been reported to cause problems, including hydrogen cracking (Refs. 15–17), corrosion (Ref. 19), and stress corrosion cracking (Refs. 9, 12). It has been reported that dissimilar-filler welds of Al-Zn-Mg alloys are susceptible to stress corrosion cracking (Refs. 18, 19) and welding interface attack by corrosion (Ref. 20).

Regarding macrosegregation in arc welds made with dissimilar filler metals, the beaches, peninsulas, or islands are filler deficient because the layer of liquid base metal is either not or only partially mixed with the bulk weld pool, into which the filler metal is added and well mixed. Thus, the name "filler-deficient zone" (FDZ) will be used in the present study to indicate the region of the weld metal containing filler-deficient beaches, peninsulas, and islands. This name includes both the case of having no filler metal at all (that is, the unmixed zone) and the case of having less filler metal than in the bulk weld metal (that is, the filler metal depleted area, intermediate zone, intermediate mixed zone, and hard zone).

Experimental Procedure

Pure Cu 101 (also known as oxygen-free, electronic-grade Cu, 99.99% purity) was welded with Cu-30.40Ni welding wire. The former was 6.4 mm (¼ in.) thick, 51 mm (2 in.) wide, and 102 mm (4 in.) long, and the latter 1.1 mm in diameter. Bead-on-plate, gas metal arc welding (GMAW) was carried out under the following welding conditions: 6.4–8.5 mm/s (15–20 in./min) travel speed, 169 and 212 mm/s (400, 500 in./min) wire feeding rate, 30–37 V arc voltage, 300–350 A average current, and Ar shielding.

Likewise, 1100 Al (commercially pure aluminum) was welded with filler metal 4145 Al (essentially Al-4Cu-10Si). The former was 9.5 mm (⅜ in.) thick, 102 mm (4 in.) wide, and 203 mm (8 in.) long, and the latter 1.2 mm (3⁄64 in.) in diameter. The shielding gas was either Ar or He. With Ar shielding, the welding conditions were as follows: 28–30 V arc voltage, 186–191 mm/s (440–450 in./min) wire feeding speed, 5.1–7.4 mm/s (12–17.5 in./min) travel speed, and 250 A average current. With He, the welding conditions were as follows: 35 V arc voltage, 186 mm/s (440 in./min) wire feeding speed, 7.4 mm/s (17.5 in./min) travel speed, and 210 A average current.

The resultant welds were cut, polished, and etched. The Cu weld was first etched with an iron chloride solution consisting of 3 g of $FeCl_3$, 2 mL of 37% HCl, and 100 mL of methanol and then with an ammonium persulfate solution consisting of 10 g of $(NH_4)_2S_2O_8$ and 100 mL of distilled water. The Al welds were etched with a solution of 0.5 vol-% HF in water. Macrographs of cross sections of the welds were taken with a digital camera.

The concentration of any element, E, in a homogeneous weld metal can be calculated as follows (Ref. 2):

$$\%\text{ E in weld metal} = (\%\text{ E in base metal}) \times [A_b/(A_b + A_f)] + (\%\text{ E in filler metal}) \times [A_f/(A_b + A_f)] \qquad (1)$$

where A_b and A_f are the areas in the weld transverse cross section that are below and above the workpiece surface, respectively. Equation 1 is based on the assumption of uniform composition in the weld metal,

Fig. 4 — Filler-deficient beaches, islands, and peninsulas in gas metal arc welds of 1100 Al (pure Al) made with filler metal 4145 Al (Al-4Cu-10Si): A through C — Longitudinal micrographs (crosses indicate locations of composition measurements, which show neither Cu nor Si); D through F — transverse micrographs. (From Huang and Kou, Ref. 24.)

that is, no macrosegregation. However, macrosegregation was essentially limited to near the fusion boundary, Equation 1 was still used as an approximation for calculating the average composition of the weld metal.

In Equation 1, areas A_b and A_f represent contributions from the base metal and filler metal, respectively. The ratio $A_b/(A_b + A_f)$ is the so-called dilution ratio. Areas A_b and A_f were determined by enlarging the transverse macrograph on a computer monitor and by using commercial computer software.

Composition measurements were made by energy-dispersive spectroscopy (EDS).

Results and Discussion

Effect of Filler Metal on Weld-Metal Liquidus Temperature

A dissimilar filler metal can change the composition of the bulk weld metal and make the liquidus temperature of the weld metal (T_{LW}) significantly different from that of the base metal (T_{LB}). This important factor has not been considered so far. For convenience of discussion, a phase diagram similar to the Ni-Cu phase diagram is shown in Fig. 1 to show the compositions of the base metal (C_B), filler metal (C_F), and weld metal (C_W) relative to each other. The liquidus line slopes down from the melting point of the pure metal A. Figure 1A is for a filler metal that lowers the liquidus temperature of the weld metal, that is, $T_{LW} < T_{LB}$. Since the filler metal contains more solute than the base metal, the weld metal also contains more solute than the base metal. Thus, the liquidus temperature of the weld metal T_{LW} is below that of the base metal T_{LB}. Figure 1B, on the other hand, is for a filler metal that raises the liquidus temperature of the weld metal, that is, $T_{LW} > T_{LB}$. Since the filler metal contains less solute than the base metal, the weld metal also contains less solute than the base metal. Thus, the liquidus temperature of the weld metal T_{LW} is above that of the base metal T_{LB}.

Welding without a Dissimilar Filler Metal

Figure 2A shows a weld pool in arc welding without a dissimilar filler metal. If the workpiece is an alloy with a liquidus temperature T_L, it is welded either without a filler metal or with one made of the same alloy. Since the weld metal and the base metal are identical in composition, $T_{LW} = T_{LB} = T_L$. The melting front is the leading portion of the weld pool boundary where the base metal melts completely. The solidification front, on the other hand, is the trailing portion of the weld pool boundary where the liquid metal in the weld pool begins to solidify. The mushy zone is the region where solidification occurs, that is, the region of solid plus liquid. The solidified weld metal is macroscopically homogeneous though not microscopically.

Welding with $T_{LW} < T_{LB}$ and Complete Mixing throughout Weld Pool

Consider the idealized case where mixing between a dissimilar filler metal and the melted base metal is assumed complete throughout the weld pool. This case is shown in Fig. 2B for a filler metal that makes $T_{LW} < T_{LB}$. The filler metal causes the solidification front to shift backward (opposite to the welding direction) from T_{LB} to T_{LW}. Thus, the region of liquid weld metal immediately ahead of the solidification front (T_{LW}) is below T_{LB} simply because of $T_{LW} < T_{LB}$ and not any undercooling.

The weld metal of the resultant weld is homogeneous macroscopically though not microscopically. Theoretically, if solidification from the fusion boundary is by the planar mode initially (before switching to the cellular or dendritic mode), a composition gradient can still exist over a layer along the fusion boundary because of solute segregation during planar solidification. In reality, however, the layer can be very thin (e.g., 25 μm) even if it does exist. This layer is not shown in Fig. 2B.

Since the liquid weld metal is homogeneous at C_W throughout the weld pool, the entire pool boundary should be at T_{LW} according to the phase diagram — Fig. 1A. In reality, however, the melting front is still at T_{LB} because this is the temperature at which the base metal melts completely. Solid-state diffusion (on the order of 10^{-8} cm^2/s) is far too slow for the solute in the weld pool to diffuse into the solid base metal at the melting front to change its composition from C_B to C_W and make it melt completely at T_{LW}.

Macrosegregation Mechanism for $T_{LW} < T_{LB}$

Macrosegregation can occur in dissimilar-filler welding near the fusion boundary even when mixing between the liquid filler metal and the bulk weld pool is complete. Two mechanisms will be proposed as follows. They are verified with Al-Cu welds in a follow-up paper (Ref. 3). The more complicated case where the filler metal mixes only partially with the bulk weld pool will be dealt with in another follow-up paper (Ref. 4).

Figure 3 shows the longitudinal cross section of the weld pool in welding with a dissimilar filler metal that lowers the liquidus temperature of the weld metal, that is, $T_{LW} < T_{LB}$. Complete mixing in the weld pool all the way to the pool boundary (Fig. 2B) is very unlikely. According to fluid mechanics (Ref. 21), the velocity of a moving liquid is zero at a solid wall, that is, the so-called "no-slip" boundary condition for fluid flow. Thus, near the weld pool boundary convection is weakened, and a stagnant or laminar-flow layer of liquid base metal can exist as Savage suggested (Ref. 6). However, this layer can be very thin because convection in the weld pool is often strong. The layer can be discontinuous if washed away by convection. Driving forces for convection include, for instance, the electromagnetic force, surface-tension gradients, impingement of filler metal droplets, and arc shearing. Weld pool convection can become turbulent and unsteady (Ref. 2).

Figure 3A shows the formation of a filler-deficient beach along the fusion boundary. In the absence of significant undercooling, the bulk weld pool begins solidification at T_{LW}. However, the layer of liquid base metal begins solidification at its own liquidus temperature T_{LB}. Thus, the solidification front (the pool boundary behind the circle) is no longer isothermal at T_{LW} everywhere as in welding without a dissimilar filler metal — Fig. 2A.

Because $T_{LW} < T_{LB}$, the region of the liquid weld metal immediately ahead of the T_{LW} bulk solidification front is below T_{LB}. In other words, this region is cooler than the liquid base metal in the stagnant or laminar-flow layer, which by definition is above T_{LB}. The presence of this cooler region of liquid weld metal has an important implication as will be described later on.

The layer of liquid base metal near the pool boundary solidifies and forms along the fusion boundary a filler-deficient beach of the base-metal composition, that is, the so-called "unmixed zone" (Refs. 6, 8). The layer and hence the resultant beach can vary in thickness along the fusion boundary. This can occur if, for instance, the heat input fluctuates during welding or the temperature gradient normal to the pool boundary varies along the pool boundary.

As shown in Figure 3A, a composition gradient can exist between the layer of liquid base metal and the bulk weld pool, for instance, due to diffusion or partial mixing between the two liquids. This composition gradient can be further changed by solute segregation caused by solidification, and this change can vary with the solidification mode, with planar solidification causing a bigger change than cellular or dendritic solidification. Thus, the composition gradient between the beach and the bulk weld metal can exist because of the following reasons: 1) diffusion between the two liquids, 2) partial mixing between the two liquids, and 3) solute segregation during solidification. These reasons can explain the presence of the composition gradient between the unmixed zone and the bulk weld metal (Ref. 8), that is, the "pale band" associated with planar solidification.

However, if liquid diffusion penetrates all the way through the layer of liquid base metal near the pool boundary because the layer is thin or because diffusion of the solute species is fast or both, a composition gradient alone can exist, that is, without an "unmixed zone" in the beach. This may explain why in some welds a composition gradient alone was found, without any unmixed zone, such as the "filler depleted area" (Ref. 7), the "hard zone" (Ref. 10), or the "intermediate zone" (Ref. 13).

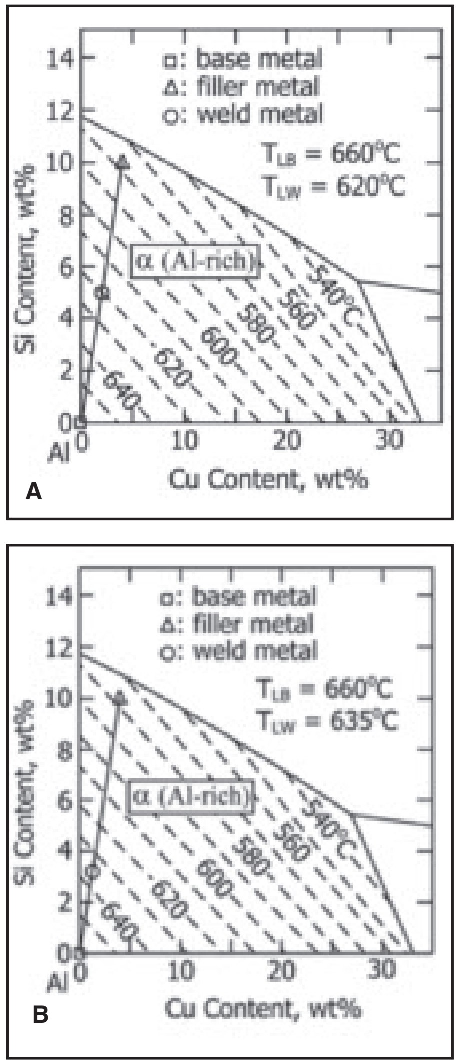

Fig. 5 — Liquidus projection of ternary Al-Cu-Si system showing liquidus temperatures of base metal T_{LB} and weld metal T_{LW} for welds of 1100 Al (pure Al) made with filler 4145 Al (Al-4Cu-10Si): A — welds shown in Fig. 4A–C (50% dilution); B — weld shown in Fig. 4D–F (68% dilution).

The mechanism for the formation of filler-deficient beaches, peninsulas, and islands along the fusion boundary when $T_{LW} < T_{LB}$, which will be called Mechanism 1 hereinafter, is shown in Fig. 3B. As mentioned previously, the liquid weld metal in the region immediately ahead of the mushy zone is below T_{LB}. Thus, if the liquid base metal in the layer nearby is swept into this cooler region by convection, it can begin to freeze quickly without much mixing with the liquid weld metal. As for the liquid base metal carried into the warmer bulk weld pool, it can mix with the liquid weld metal and be dispersed quickly by convection before the cooler region catches up with it, that is, no contribution to macrosegregation in the resultant weld.

Depending on the strength of convec-

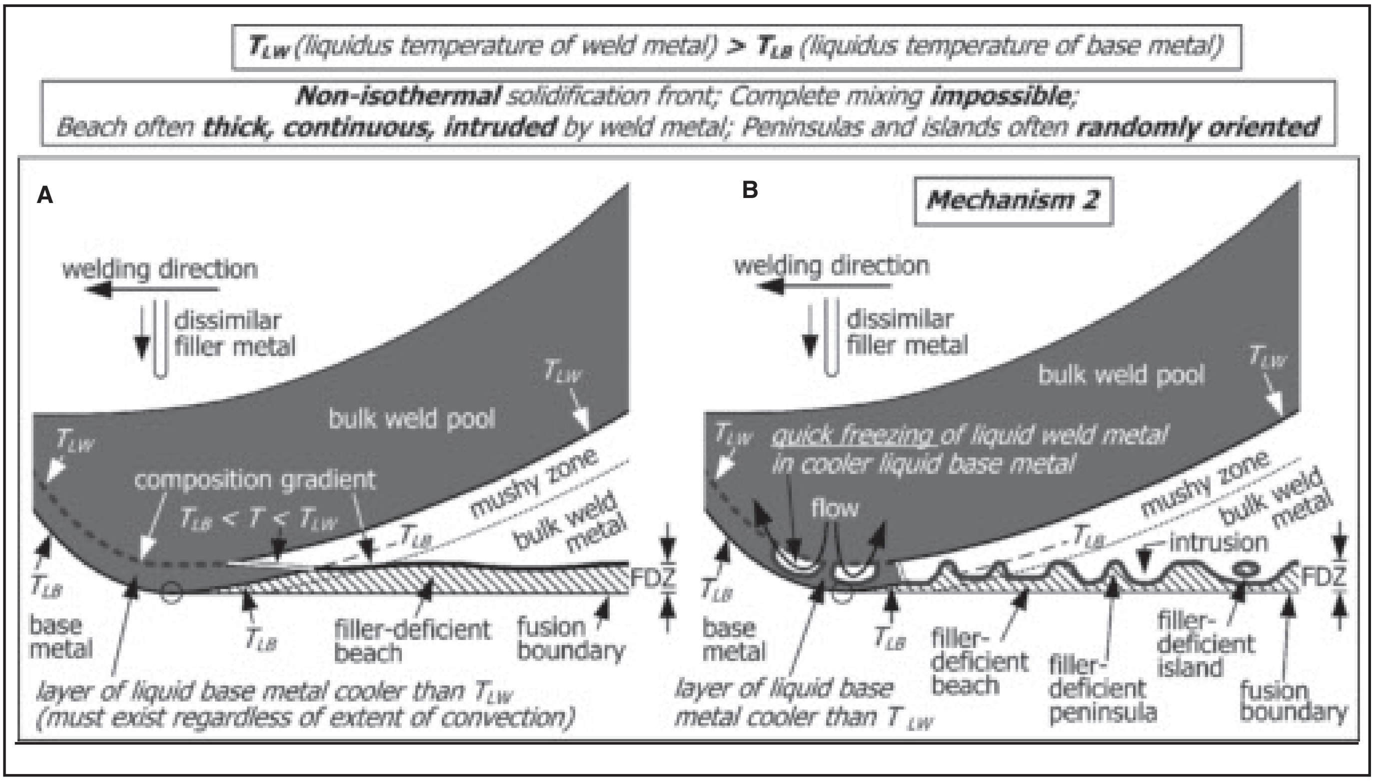

Fig. 6 — Formation of fusion-boundary macrosegregation (filler-deficient zone FDZ) when filler metal makes $T_{LW} > T_{LB}$: A — beach; B — weld-metal intrusions, beach, peninsulas, and islands by Mechanism 2. Pool boundary is melting front before circle and solidification front after.

tion and the width of the cooler region, filler-deficient peninsulas or even islands can form. These peninsulas or islands often appear roughly parallel to the fusion boundary in a weld transverse or longitudinal micrograph. However, a feature appearing as an island in the micrograph can be either a real island completely surrounded by the weld metal or just the cross section of a peninsula. Also, at locations where the liquid base metal is completely washed off by convection jets impinging on the pool boundary, a filler-deficient beach will not exist. This may explain why the filler-deficient beach is often discontinuous along the fusion boundary (Ref. 9). Again, a composition gradient can exist at the interface between the bulk weld metal and the filler-deficient features because of the three reasons mentioned previously. These reasons can explain the "intermediate mixed zone" due to liquid diffusion (Ref. 9).

Before proceeding further, it should be noted that formation of peninsulas in the absence of a cooler region of liquid weld metal ahead of the mushy zone is difficult but not impossible under some welding conditions and in some special materials. If the liquid base metal is carried immediately ahead of the solidification front and if the front advances fast enough to swallow it before it disappears due to liquid diffusion or mixing, it is still possible for peninsulas to form even without the cooler region. This may explain the existence of peninsulas of nondendritic equiaxed grains in autogenous gas tungsten arc welds of 2195 Al (Ref. 22). It has been suggested that heterogeneous nuclei Al_3Zr and $Al_3(Li_xZr_{1-x})$ survive in a narrow region of cooler liquid near the pool boundary but dissolve (or become ineffective nucleation sites for equiaxed grains) in the warmer bulk weld pool.

However, it should be pointed out that formation of nondendritic equiaxed grains in 2195 Al welds is likely to be easier in autogenous gas tungsten arc welding than in dissimilar-filler gas metal arc welding. This is because convection in the weld pool can be much weaker in gas tungsten arc welding than in gas metal arc welding because of the higher welding current and the spray mode of filler metal transfer in typical gas metal arc welding. Also, there is no composition difference between the liquid base metal and the liquid weld metal to cause diffusion. Strong convection and liquid diffusion can reduce the chance for the liquid base metal to stay unmixed before it reaches the solidification front and freezes.

Figure 4A–C shows longitudinal micrographs of gas metal arc welds of 1100 Al made with filler metal 4145 Al. The base metal 1100 Al is essentially pure Al, and T_{LB} is thus the melting point of pure Al (660°C). Filler 4145 is essentially Al-4Cu-10Si. The weld in Fig. 4A had a dilution of about 50%, that is, the base metal contributed to 50% of the volume of the weld metal. Thus, the weld metal composition was Al-2Cu-5Si, and T_{LW} is 620°C as shown by the liquidus projection of the ternary Al-Cu-Si system in Fig. 5A (Ref. 23). The weld in Fig. 4B and C had a similar dilution, weld metal composition, and, thus, T_{LW}. Thus, the condition $T_{LW} < T_{LB}$ existed in the welds.

Figure 4A is a longitudinal micrograph showing part of the melting front of the weld pool at the end of welding. A beach and a peninsula extending from it are visible. The peninsula is essentially parallel to the fusion boundary. Composition measurements at the locations indicated by crosses show that the beach and peninsula are both identical to the base metal in composition, that is, essentially pure Al with no Cu or Si from the filler metal. Thus, the beach and peninsular are filler-deficient features that originated from the melted but unmixed base metal as proposed by Mechanism 1. The fusion boundary is at the interface between the base-metal-like beach and the unmelted base metal and this confirms that the melting front is at the liquidus temperature of the

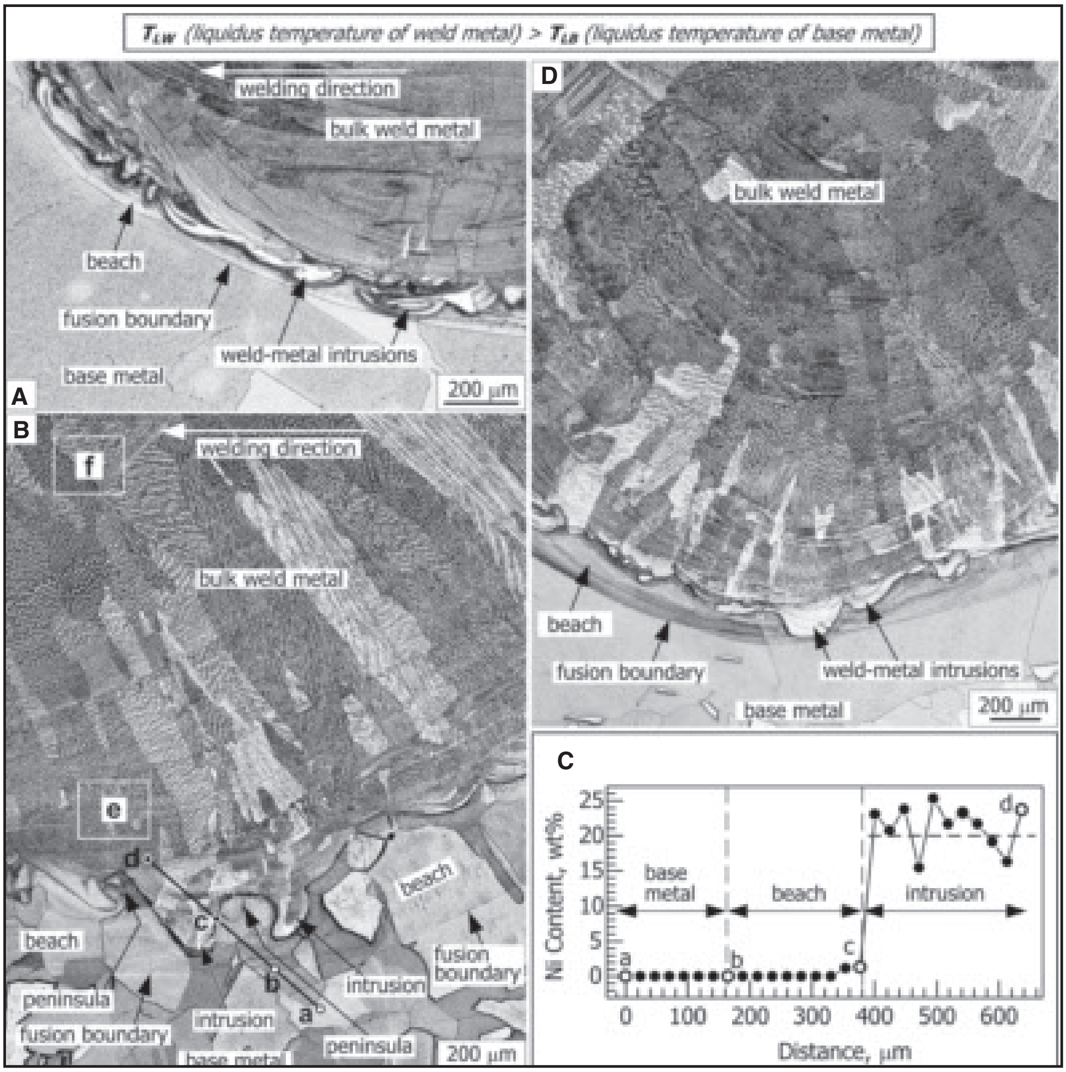

Fig. 7 — A new type of macrosegregation discovered in the present study, that is, filler-deficient beach along fusion boundary with weld metal intruding into the beach: A, B — longitudinal micrographs; C — composition profile along ad in B; D — transverse micrograph. Compositions in area e, in area f, and along cd all about Cu-20Ni. Base metal: pure Cu; filler metal: Cu-30Ni.

base metal T_{LB} (not T_{LW}) as mentioned previously.

Figure 4B is a longitudinal micrograph taken far behind the end of a similar weld. It shows two peninsulas and one island, and they are essentially parallel to the fusion boundary. The peninsula on the right and its surrounding area are enlarged in Fig. 4C. It extends from the beach to its left, suggesting convection caused the melted base metal along the fusion boundary to form a beach and a peninsula further downstream. Again, composition measurements at the locations indicated by crosses show that the peninsula and island are both identical to the base metal in composition, thus confirming that they originated from the liquid base metal.

Figure 4D–F show transverse micrographs of a gas metal arc weld of 1100 Al made with filler 4145. The dilution was about 68%. Thus, the weld metal composition was Al-1.3Cu-3.3Si and T_{LW} is 635°C as shown by the liquidus projection of the ternary Al-Cu-Si system in Fig. 5B. Thus, the condition $T_{LW} < T_{LB}$ also existed in the weld.

Figure 4D is a transverse micrograph showing an island parallel to the fusion boundary. As shown in the enlarged micrograph in Fig. 4E, the microstructure in the island is very different from that of the surrounding weld metal but similar to the base metal except for the redistribution of the intermetallic compound Al_xFe_y (dark etching particles). The same is true for the beach and peninsula shown in the transverse micrograph in Fig. 4F. Thus, these islands, beaches, and peninsulas are filler-deficient features that originated from the liquid base metal.

Macrosegregation Mechanism for $T_{LW} > T_{LB}$

Unlike the case of $T_{LW} < T_{LB}$, complete mixing throughout the entire weld pool is impossible with $T_{LW} > T_{LB}$. This will be explained as follows.

Figure 6 shows the longitudinal cross-section of the weld pool in welding with a filler metal that makes $T_{LW} > T_{LB}$. Figure 6A shows the formation of the filler-deficient beach along the fusion boundary. Since the liquid weld metal is homogeneous at C_W in the bulk weld pool, the boundary of the bulk weld pool should be at T_{LW}, according to the phase diagram. However, since $T_{LW} > T_{LB}$, the base metal between T_{LW} and T_{LB} is above its liquidus temperature T_{LB} and thus must melt completely. Consequently, immediately outside the bulk weld pool, a stagnant or laminar-flow layer of liquid base metal must exist regardless of weld pool convection. This layer of liquid base metal begins solidification at T_{LB} into a filler-deficient beach along the fusion boundary. Thus, the solidification front is again no longer isothermal as in welding without a dissimilar filler metal. Instead, it switches from T_{LW} in the bulk weld pool to T_{LB} near the fusion boundary. Again, a composition gradient can exist at the interface between the bulk weld metal and the filler-deficient because of the three reasons mentioned previously.

The presence of the layer of liquid base metal is also consistent with the aforementioned fact that the melting front should be at T_{LB} because solid diffusion is too slow to change the melting front composition to make it melt at T_{LW}. The thickness of the layer increases with increasing temperature difference ($T_{LW} - T_{LB}$).

The mechanism for the formation of the filler-deficient beaches, peninsulas, and islands along the fusion boundary when the filler metal makes $T_{LW} > T_{LB}$, which will be called Mechanism 2 hereinafter, is shown in Fig. 6B. The layer of the liquid base metal immediately outside the bulk weld pool boundary (T_{LW}) is below T_{LW}. Consequently, if the liquid weld metal nearby is pushed by convection toward the pool boundary, it can immediately enter this cooler region and begin to freeze quickly as weld-metal intrusions without much mixing with the liquid base

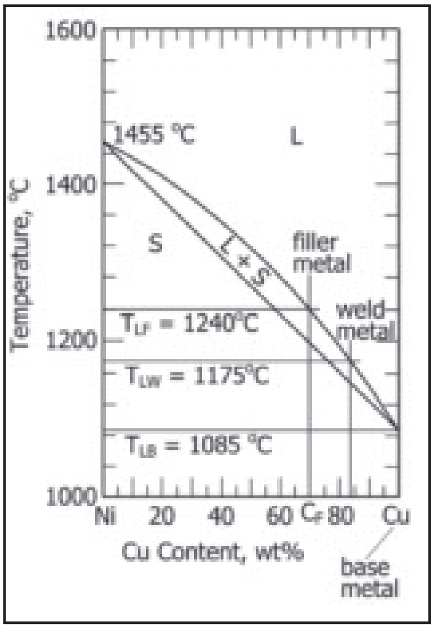

Fig. 8 — Ni-Cu phase diagram (Ref. 25) showing the liquidus temperatures of base metal T_{LB}, weld metal T_{LW}, and filler metal T_{LF} of the Cu weld made with filler metal Cu-30Ni shown in Fig. 7B.

metal. This also means that the liquid base metal in the cooler region can solidify without much mixing with the liquid weld metal. Again, a composition gradient can exist at the interface between the bulk weld metal and the filler-deficient feature.

Figure 7 shows a gas metal arc weld of pure Cu made with a filler metal of Cu-30Ni alloy. The dilution was about 45% and the weld metal is thus Cu-16.5Ni. The Ni-Cu phase diagram (Ref. 25) in Fig. 8 shows that T_{LB} is 1085°C (the melting point of pure Cu) and that T_{LW} is 1175°C and thus $T_{LW} > T_{LB}$.

Figure 7A is a longitudinal micrograph showing part of the melting front of the weld pool at the end of welding. A layer of melted and resolidified pure Cu is present along the fusion boundary. Several intrusions of the weld metal into the base metal layer are visible. The fusion boundary here is the melting front and it is located at the interface between the melted and unmelted base metal, that is, T_{LB} (the melting point of pure Cu in the present case), and not T_{LW}. Figure 7B is a longitudinal micrograph taken far behind the weld end. Again, a layer of melted and resolidified pure Cu is present along the fusion boundary, with intrusions of the weld metal into the layer. The composition profile across the fusion boundary taken along line ad is shown in Fig. 7C. As shown, the beach bc is identical to the base metal ab in composition, that is, pure Cu, thus confirming that it originated from a melted but unmixed base metal as proposed by Mechanism 2. The intrusion cd has an average composition of about Cu-20Ni and it fluctuates because of microsegregation across the cellular solidification structure. The compositions measured over rectangular areas "e" and "f" were Cu-19Ni and Cu-21Ni, respectively, thus indicating that the compositions along cd and in areas "e" and "f" were all about Cu-20Ni. This Ni content is higher than the Cu-16.5Ni composition of the bulk weld metal calculated based on the dilution ratio. The composition measured far away in the bulk weld metal was about Cu-16Ni. This is close to but slightly below Cu-16.5Ni. Thus, the Ni content was somewhat higher near the weld bottom but decreased slightly away from the bottom, that is, mixing of the filler metal was nearly though not exactly complete.

Figure 7D is a transverse micrograph of a similar weld showing a similar microstructure. All three micrographs in Fig. 7 show that a filler-deficient beach exists and is continuous along the fusion boundary. The weld metal intrudes into the beach but does not mix with it. The morphology of macrosegregation has not been reported so far.

Figure 9 is a scanning electron microscopy (SEM) image of the area around the intrusion intersected by cd in Fig. 7B. The cellular structure is much finer in the intrusion than in the nearby bulk weld metal of the same composition (about Cu-20Ni, as mentioned previously), thus suggesting that the cooling rate was much higher in the intrusion than in the bulk weld metal. This confirms the quick freezing of the liquid weld metal in the cool layer of liquid base metal to form intrusions, as suggested by Mechanism 2.

Comparing Macrosegregation Formed by Two Mechanisms

It is easier for a beach to be continuous along the fusion boundary and for peninsulas or islands to form near the fusion boundary when $T_{LW} > T_{LB}$ (Fig. 6B) than when $T_{LW} < T_{LB}$ (Fig. 3B). With $T_{LW} < T_{LB}$, the stagnant or laminar-flow layer of liquid base metal along the pool boundary can be very thin and discontinuous due to weld pool convection. Furthermore, the cooler region of liquid weld metal ahead of the bulk solidification front is away from the layer. Thus, convection will have to be able to carry the liquid base metal from the layer into the region in order to form peninsulas or islands. However, it should be pointed out that convection does not have to be two-dimensional, that is, in the longitudinal cross section of the weld pool, in order to cause macrosegregation. It can be three-dimensional as long as it can carry the liquid base metal into the cooler region, which is also three-dimensional.

With $T_{LW} > T_{LB}$, on the other hand, a continuous layer of liquid base metal exists along the outside of the bulk weld pool regardless of weld pool convection. Furthermore, the cooler layer of liquid base metal along the pool boundary is immediately next to the liquid weld metal. Thus, almost any convection next to the layer can push the liquid weld metal into the layer and form intrusions, and the liquid base metal left in the space between the intrusions can solidify into peninsulas or islands of random orientations.

With $T_{LW} < T_{LB}$, the more a filler metal lowers T_{LW}, the wider the cooler region of liquid weld metal ahead of the bulk solidification front becomes and thus the more room is available for the liquid base metal to enter and solidify quickly without much mixing with the liquid weld metal. Thus, the larger the temperature difference ($T_{LB} - T_{LW}$) is, the greater the chance for a thicker filler-deficient zone (FDZ) to form. However, the actual thickness of the FDZ also depends on the direction and strength of weld pool convection.

With $T_{LW} > T_{LB}$, the situation is similar. The more a filler metal raises T_{LW} above T_{LB}, the thicker the cooler layer of the liquid base metal near the pool boundary becomes, and thus the greater the chance is for the liquid weld metal to enter the layer and freeze quickly without much mixing with the liquid base metal. Thus, with a large temperature difference ($T_{LW} - T_{LB}$), a thicker FDZ is likely to exist. As in the case of $T_{LW} < T_{LB}$, the actual thickness of the FDZ can be affected significantly by weld pool convection during welding.

Conclusions

In the present study, fundamentals of solidification and macrosegregation in arc welding with a filler metal different in composition from the workpiece have been presented, including four solidification concepts, two macrosegregation mechanisms, and two distinctively different morphologies of macrosegregation — one of them discovered in the present study. Macrosegregation in such welds is important because dissimilar filler metals are routinely used in arc welding and because macrosegregation can cause hydrogen and stress-corrosion cracking. Until now, it has not been understood how the liquid base metal can solidify as base-metal-like peninsulas or islands within the weld metal without much mixing with it. The conclusions are as follows:

1. Four fundamental concepts of weld-metal solidification in dissimilar-filler welding have been presented. First, the melting front of the weld pool is not at the

liquidus temperature of the weld metal T_{LW} but at the liquidus temperature of the base metal T_{LB} because solid-state diffusion is far too slow to change the base metal composition to cause melting at T_{LW}. Second, the solidification front is no longer isothermal at T_{LW} everywhere as in welding without a dissimilar filler metal even in the absence of undercooling (which is negligible in most arc welding). The temperature at the solidification front, that is, the liquidus temperature, is at T_{LW} only for the homogeneous bulk weld pool. Elsewhere it is at a liquidus temperature that depends on the local composition of the liquid. For instance, if a stagnant or laminar-flow layer of liquid base metal exists along the pool boundary, the solidification front near the fusion boundary is at T_{LB}. Third, if the liquid base metal is carried into a different liquid cooler than its own liquidus temperature T_{LB}, it can start freezing quickly before much mixing occurs. Similarly, if the liquid weld metal is carried into a different liquid cooler than its own liquidus temperature T_{LW}, it can start freezing quickly before much mixing occurs. Either way promotes macrosegregation. Fourth, if the filler metal makes $T_{LW} < T_{LB}$, complete mixing throughout the weld pool may be possible under ideal conditions but if the filler metal makes $T_{LW} > T_{LB}$, complete mixing is impossible because the base metal right next to the boundary of the homogeneous bulk weld pool (that is, T_{LW}) is still above T_{LB} and thus must melt and form a layer of liquid base metal.

2. According to the above concepts, macrosegregation can occur in dissimilar-filler welding by the following two mechanisms even when the filler metal mixes completely with the bulk weld pool. Mechanism 1 is for filler metals that lower the liquidus temperature of the weld metal, that is, $T_{LW} < T_{LB}$. The region of liquid weld metal immediately ahead of the bulk solidification front of T_{LW} is below T_{LB}. The liquid base metal swept into this cooler region from the stagnant or laminar-flow layer by convection can begin to freeze quickly into filler-deficient peninsulas or islands, which often appear roughly parallel to the fusion boundary in a transverse or longitudinal micrograph. A feature appearing as an island in the micrograph can be either a real island completely surrounded by the weld metal or just the cross section of a peninsula. The liquid base metal remaining in the layer solidifies as an often discontinuous filler-deficient beach. To form peninsulas or islands, convection needs to be able to carry the liquid base metal into the cooler region. This convection can be three-dimensional because the region is also three-dimensional. Macrosegregation in 1100 Al (pure Al) welds made with filler metal 4145 Al (Al-4Cu-10Si) has confirmed this mechanism.

3. Mechanism 2 is for filler metals that raise the liquidus temperature of the weld metal, that is, $T_{LW} > T_{LB}$. The stagnant or laminar-flow layer of liquid base metal immediately outside the boundary of the homogeneous bulk weld pool (that is, T_{LW}) is below T_{LW} and the liquid weld metal pushed into this cooler layer from the bulk weld pool by convection can begin to freeze quickly as weld-metal intrusions into an often continuous filler-deficient beach. The liquid base metal left in the space between the intrusions can solidify into filler-deficient peninsulas or islands of random orientations. These filler-deficient features are distinctly different from those formed by Mechanism 1. This is a new kind of macrosegregation that has not been reported so far. To cause macrosegregation, convection can almost be in any direction because the bulk weld metal can be easily pushed into the cooler layer anyway. Macrosegregation in Cu welds made with filler metal Cu-30Ni has confirmed this mechanism. The much finer cell spacing in the weld-metal intrusion than in the bulk weld metal nearby has confirmed the quick freezing of the liquid weld metal in the cool layer of liquid base metal into intrusions, as suggested by Mechanism 2.

4. With the same difference between T_{LW} and T_{LB}, significant fusion-boundary macrosegregation can be much easier to form when $T_{LW} > T_{LB}$ than when $T_{LW} < T_{LB}$. This is mainly because, when $T_{LW} > T_{LB}$, the layer of liquid base metal along the bulk weld pool boundary and hence the resultant filler-deficient beach always exist and are often continuous regardless of weld pool convection. Weld-metal intrusions in the beach and filler-deficient peninsulas or islands between the intrusions can form easily because almost any convection can easily push the bulk liquid weld metal into the layer to freeze quickly. When $T_{LW} < T_{LB}$, however, the layer of liquid base metal and hence the resultant filler-deficient beaches are often very thin and discontinuous due to convection. To form peninsulas or islands, convection needs to be able to carry the liquid base metal from the layer into the cooler region of liquid weld metal ahead of the T_{LW} solidification front.

5. Mechanism 1 can explain the various forms of macrosegregation that have been reported in dissimilar-filler welding involving a single workpiece material, including the "unmixed zone," "filler metal depleted area," and "intermediate zone." Mechanism 2 can explain the new form of macrosegregation observed in this study, that is, a filler-deficient beach intruded by the weld metal.

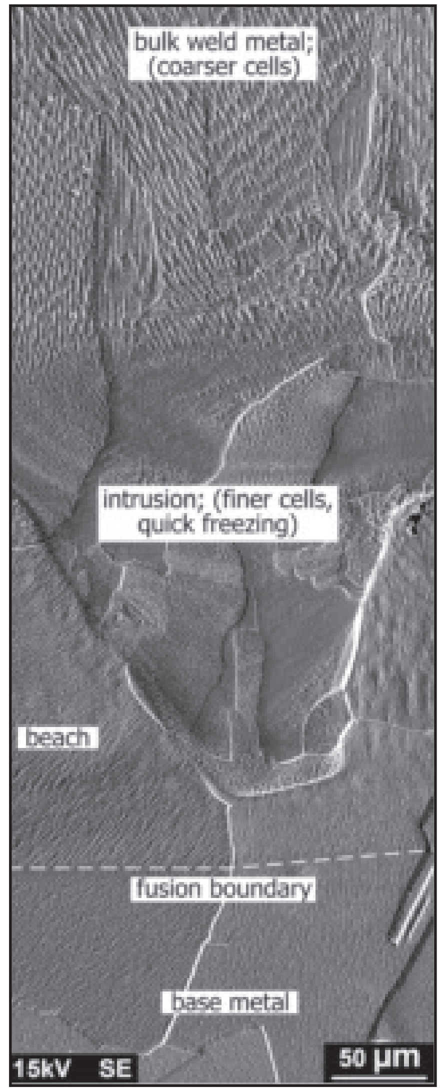

Fig. 9 — Evidence of quick freezing of intrusion in cooler layer of liquid base metal suggested by Mechanism 2. SEM image (of intrusion intersected by cd in Fig. 7B) shows much finer cells in intrusion than in nearby bulk weld metal of same composition. Base metal: pure Cu; filler metal: Cu-30Ni.

Acknowledgments

This work was supported by National Science Foundation under grant no. DMR-0455484. The authors are grateful to Bruce Albrecht and Todd Holverson of Miller Electric Mfg. Co., Appleton, Wis., for donating the welding equipment (including Invision 456P power source, and XR-M wire feeder and gun).

References

1. Houldcroft, R. T. 1954. Dilution and uniformity in aluminum alloy weld beads. *British Welding Journal* 1: 468–472.

2. Kou, S. 2003. *Welding Metallurgy*, 2nd ed. New York, N.Y.: John Wiley & Sons, Inc. pp. 114, 180, 206, 208, and 306.

3. Yang, Y. K., and Kou, S. 2007. Fusion-

boundary macrosegregation in dissimilar-filler Al-Cu welds. Accepted for publication in *Welding Journal*.

4. Yang, Y. K., and Kou, S. 2007. Weld-bottom macrosegregation in dissimilar-filler welds. Accepted for publication in *Welding Journal*.

5. Savage, W. F., and Szekeres, E. S. 1967. A mechanism for crack formation in HY-80 steel weldments. *Welding Journal* 46(2): 94-s to 96-s.

6. Savage, W. F., Nippes, E. F., and Szekeres, E. S. 1976. A study of fusion boundary phenomena in a low alloy steel. *Welding Journal* 55(9): 260-s to 268-s.

7. Duvall, D. S., and Owczarski, W. A. 1968. Fusion-line composition gradients in an arc-welded alloy. *Welding Journal* 47(3): 115-s to 120-s.

8. Karjalainen, L. P. 1979. Weld fusion boundary structures in aluminum and Al-Zn-Mg alloy. *Z. Metallkde.* 70: 686–689.

9. Doody, T. 1992. Intermediate mixed zones in dissimilar metal welds for sour service. *Welding Journal* 71(3): 55–60.

10. Omar, A. A. 1998. Effects of welding parameters on hard zone formation at dissimilar metal welds. *Welding Journal* 77(2): 86-s to 93-s.

11. Lippold, J. C., and Savage, W. F. 1980. Solidification of austenitic stainless steel weldments: Part 2 — The effect of alloy composition on ferrite morphology. *Welding Journal* 59(2): 48-s to 58-s.

12. Baeslack III, W. A., Lippold, J. C., and Savage, W. F. 1979. Unmixed zone formation in austenitic stainless steel weldments. *Welding Journal* 58(6): 168-s to 176-s.

13. Ornath, F., Soudry, J., Weiss, B. Z., and Minkoff, I. 1991. Weld pool segregation during the welding of low alloy steels with austenitic electrodes. *Welding Journal* 60: 227-s to 230-s.

14. Albert, S. K., Gills, T. P. S., Tyagi, A. K., Mannan, S. L., Kulkarni, S. D., and Rodriguez, P. 1997. Soft zone formation in dissimilar welds between two Cr-Mo steels. *Welding Journal* 76(3): 135-s to 142-s.

15. Linnert, G. E. 1967. *Welding Metallurgy*, Vol. 2. Miami, Fla.: American Welding Society.

16. Savage, W. F., Nippes, E. F., and Szekeres, E. S. 1976. Hydrogen induced cold cracking in a low alloy steel. *Welding Journal* 55(9): 276-s to 283-s.

17. Rowe, M. D., Nelson, T. W., and Lippold, J. C. 1999. Hydrogen-induced cracking along the fusion boundary of dissimilar metal welds. *Welding Journal* 78(2): 31-s to 37-s.

18. Kent, K. G. 1970. *Metals and Materials*, Weldable Al-Zn-Mg alloys. 4: 429–440.

19. Cordier, H., Schippers, M., and Polmear, I. 1977. Microstructure and intercrystalline fracture in a weldable aluminum-zinc-magnesium alloy. *Z. Metallkde.* 68: 280–284.

20. Pirner, M., and Bichsel, H. 1975. Corrosion resistance of welded joints in AlZnMg. *Metall*, 29: 275–280.

21. Kou, S. 1996. *Transport Phenomena and Materials Processing*. New York, N.Y.: John Wiley & Sons. pp. 57–60.

22. Gutierrez, A., and Lippold, J. C. 2004. A proposed mechanism for equiaxed grain formation along the fusion boundary in aluminum-copper-lithium alloys. *Welding Journal* 83: 169-s.

23. Phillips, H. W. L. 1959. *Annotated Equilibrium Diagrams of Some Aluminum Alloy Systems*. The Institute of Metals, London, UK, p. 41.

24. Huang, C., and Kou, S. 2001. Unpublished research at University of Wisconsin, Madison, Wis.

25. American Society for Metals. 1986. *Binary Alloy Phase Diagrams*, Vol. 1: pp. 106, 112, 165, and 942, Metals Park, Ohio: American Society for Metals.

Preparation of Manuscripts for Submission to the *Welding Journal* Research Supplement

Authors should address the following questions when writing papers for submission to the Welding Research Supplement:

- Why was the work done?
- What was done?
- What was found?
- What is the significance of your results?
- What are your most important conclusions?

With those questions in mind, most authors can logically organize their material along the following lines, using suitable headings and subheadings to divide the paper.

1) **Abstract.** A concise summary of the major elements of the presentation, not exceeding 200 words, to help the reader decide if the information is for him or her.

2) **Introduction.** A short statement giving relevant background, purpose, and scope to help orient the reader. Do not duplicate the abstract.

3) **Experimental Procedure, Materials, Equipment.**

4) **Results, Discussion.** The facts or data obtained and their evaluation.

5) **Conclusion.** An evaluation and interpretation of your results. Most often, this is what the readers remember.

6) **Acknowledgment, References, and Appendix.**

Keep in mind that proper use of terms, abbreviations, and symbols are important considerations in processing a manuscript for publication. For welding terminology, the *Welding Journal* adheres to AWS A3.0:2001, *Standard Welding Terms and Definitions.*

Papers submitted for consideration in the Welding Research Supplement are required to undergo Peer Review before acceptance for publication. Submit an original and one copy (double-spaced, with 1-in. margins on 8 ½ x 11-in. or A4 paper) of the manuscript. A manuscript submission form should accompany the manuscript.

Tables and figures should be separate from the manuscript copy and only high-quality figures will be published. Figures should be original line art or glossy photos. Special instructions are required if figures are submitted by electronic means. To receive complete instructions and the manuscript submission form, please contact the Peer Review Coordinator, Erin Adams, at (305) 443-9353, ext. 275; FAX 305-443-7404; or write to the American Welding Society, 550 NW LeJeune Rd., Miami, FL 33126.