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'Kissing Bond' Phenomena in Solid-State Welds of Aluminum Alloys

Discontinuities in extrusion welds are a model for friction stir welding defects

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ABSTRACT. The occurrence and nature of "kissing bonds" have been studied in three solid-state welding processes: friction stir welding, extrusion charge welding, and extrusion seam welding. A kissing bond is the descriptive term for two surfaces lying extremely close together, but not close enough for the majority of the original surface asperities to have deformed sufficiently in contact for atomic bonds to be created. Depending on their location and extent, they may have detrimental effects on the fatigue life and through-thickness load-bearing capacity of the component.

This paper presents analogies between kissing bonds in the above-mentioned joining methods using fractographic evidence and phenomenological hypotheses. The effects of these discontinuities on the mechanical properties of these joints produced in 6xxx-Series aluminum alloys used in automotive and marine structural applications are discussed.

Introduction

In the past few years, extrusion welds have become an increasingly important issue in modern billet-to-billet extrusion processing. In billet-to-billet processing of extruded sections, two types of welds are created: longitudinal, or seam, welds and transverse, or charge, welds. Seam welds originate from splitting and subsequent rejoining of the extruded metal around mandrel supports in bridge or porthole dies during the production of hollow extrusions. Charge welds result from the joint between two subsequently extruded billets (Refs. 1, 2). Both types of extrusion welding, as well as friction stir welding (FSW), are solid-state welding processes. Their formation in wrought aluminum alloys occurs due to matching of two surfaces under pressure and deformation at elevated temperatures (typically between 500° and 600°C, but under the melting temperature) where a metallic bond between the individual atoms in the matching surfaces takes place.

Testing and experience have shown that the overall mechanical properties are not affected by the presence of defect-free seam welds and, therefore, the properties of the bulk material can be used for design purposes. Regarding charge welds, it is a different matter; due to the discontinuous nature of this solid-state weld formation process, a part of the extruded profile length might have elongation and fracture toughness properties lower than the bulk.

Our experience shows that defect-free friction stir welds possess properties of seam welds. Ductility and strength of defect-free friction stir welds in 6xxx-Series aluminum alloys are dependent only on the thermal history of the material.

The paper attempts to convey the message that design criteria of extrusion welds, rather than conventional fusion welds, are applicable to the FSW process. This would result in application of lighter-weight design in aluminum. Three solid-state welding processes and their analogously occurring quality problems, specifically kissing bonds, are described. Mechanisms for kissing bond formation are proposed.

The Solid-State Welding Process

The solid-state welding processes are probably the oldest welding methods known to man. Archaeological findings in Ireland (Ref. 3) dated from the middle Bronze Age show its use in hammer welding of gold.

The mechanisms of solid-state welding vary. Welding can be carried out over a large range of temperatures, pressures, and deformation, so it is difficult to propose a single theory. We can, however, look at the basic factors in play and their effects upon weld formation as described by Tylecote (Ref. 3).

Attractive forces. Two surfaces must be brought close together to be within the range of interatomic attractive forces. For a metal, the atoms are held together by a so-called metallic bond. The bond can best be described as a cloud of free negatively charged electrons enveloping ionized positively charged atoms and forming one unit due to the resulting attractive forces. Other forces also contribute to a much lesser or even negligible extent, e.g., the van der Waals force and the electrostatic attraction between dipoles. The accepted conclusion is that the forces used in solid-state welding are mainly those arising from interatomic attractive forces. That means in practice that the surfaces must be brought in contact within atomic distances, which for most metals is less than 1 nm (Ref. 3).

Deformation process. To utilize the above-mentioned attractive forces for weld formation, intimate contact must be established between the two surfaces. Obviously, the yield stress must be exceeded in order to match surface asperities closely enough. For clean metal surfaces, 10% deformation might already be sufficient. In metals like aluminum, with naturally forming oxide layers, necessary levels of deformation and pressure to form a good weld are much higher. This is because the surface asperities not only need to be matched but also the (brittle) oxide layer must be broken up and "fresh" metal must be extruded through the formed gaps. For aluminum, it is reported that at least 40% of deformation at room temperature is

KEY WORDS

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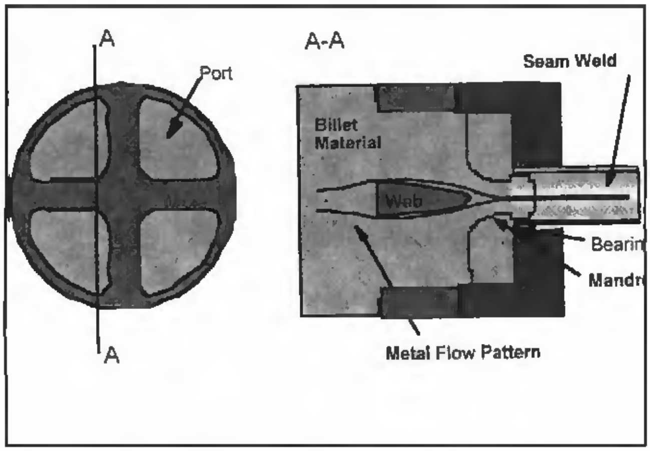

Fig. 1 — Schematic representation of longitudinal weld formation.

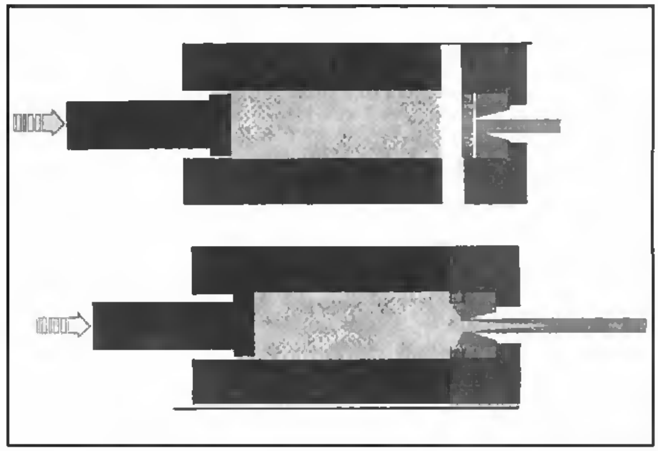

Fig. 2 — Schematic representation of transverse weld formation.

needed to achieve a full-strength weld when oxide layers are present on the contacting surfaces. When two surfaces experience a relative tangential movement, more efficient oxide film breakup is brought about. This results in a large reduction of overall deformation needed for proper welding. During hot deformation, weld formation is aided by grain rotation in the surface-at-large deformation, increasing the metal-to-metal contact area significantly (Ref. 3).

Surface films and contaminants. Several types of surface films and contaminants are present on the surfaces to be solid-state joined.

- Natural oxide films that are normally brittle, which form instantly at atmospheric conditions and are in the order of magnitude of 5 nm. The breakdown of such thin films takes place at a very early stage in the deformation process.
- Absorbed surface films of water vapor or organic instances.
- Lubricants used in industrial applications, either intentionally or unintentionally present on the contacting surfaces.

The ease of oxide film breakup is governed by the relative hardness between oxide film and the base metal. The higher this ratio, and the lower the hardness of the base metal, the easier joining takes place. It can be noted that aluminum oxide has a very high hardness compared to the metal itself. Some oxides formed by alloying elements, particularly magnesium oxide, are quite soft, however.

Studies undertaken by Semanov (Ref. 4) report the effect of lubricants upon cold welding of aluminum. In the case of polar lubricants, the level of deformation required for solid-state welding is more than double, compared to the deformation level required for a clean surface.

Pressure and diffusion. In pressure welding of similar metals, the diffusion processes leading to improvement of the intimacy of contact at the interface are of the highest interest. Mainly surface diffusion plays a role here (Ref. 3). At elevated temperatures, diffusion occurs more readily as the migration of atoms from one interface to another is easier. Diffusion can be related to the site-to-site movements of atoms in the lattice. Each atom is continuously oscillating about a site and occasionally this oscillation is violent enough to make it jump to a neighboring site. Thus, surface diffusion can aid in increasing the intimacy of contact at the interface. Tylecote (Ref. 3) considers that diffusion leads to improved matching of the interface and formation of small metallic bridges when film breakdown occurs under small increments of surface elongation. High local strains and strain rates enhance the diffusion further. When large hydrostatic pressure is present, combined with high levels of surface elongation and deformation, the degree of mismatch at the interface becomes so small that diffusion processes no longer affect the weld quality. It must also be mentioned that for some metals, diffusion can enhance the absorption of surface oxides. For aluminum alloys, however, this is not a major contributor to the weld quality, due to the low solubility of oxygen in the matrix. In the case of dissimilar alloys or metals, mutual solubility and the effect of new phases must also be considered.

Seam Weld Formation

Conventional extrusion of commercial aluminum alloys involves "squeezing" a preheated aluminum billet through a steel die. For solid sections, the construction of the die is quite straightforward, being a circular disk with or without prechambers and openings (or bearing channels) matching the desired profile shape. Dies for making hollow sections are more complicated. It is conventional in the industry to use dies with mandrels (forming the inner surface of the hollow part of a profile) suspended by webs or bridges.

Seam welds only occur in hollow extruded sections when bridge or porthole dies are used. The seam weld is the heavily shear-deformed band of metal separated around the web and joined together at the rear end of each web of a hollow die. Joining takes place through a shear- and pressure-driven solid-state welding mechanism in, subsequently, the weld chamber and bearing channel, with the metal flowing from this position into the extruded profile — Fig. 1. One cannot really distinguish between two separate surfaces. Because of the high adhesive forces between hot aluminum and the tool steel of the die, the aluminum is considered to be stationary at the internal tool surfaces (pure sticking friction), including at the steel surfaces of the webs. A heavily sheared layer is present during extrusion in the aluminum just above the stationary tool/aluminum interface. It is the metal of this heavily sheared layer that forms the seam weld. Both in front and behind the web a pocket of stationary aluminum is present, called a dead metal zone — Fig. 1. This metal is outside the metal flow field and thus remains in the die during the production run at the press.

The dead metal zone in front of the web borders the two split, heavily shearing metal streams out of the billet into the adjacent ports of the web in question. As this is occurring inside the billet, no oxygen is available. No free surfaces are created; the assumed mechanism lets two streams of heavily deformed material come in contact after shearing over the web and the dead metal zone behind the web (Ref. 5). Both hydrostatic pressure and high shear

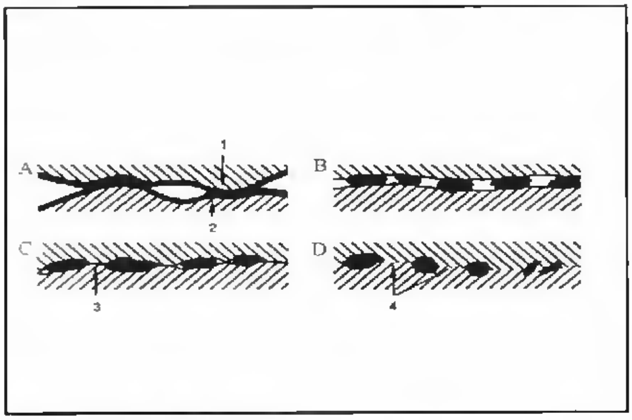

Fig. 3 — Four stages of transverse welding by Akeret.

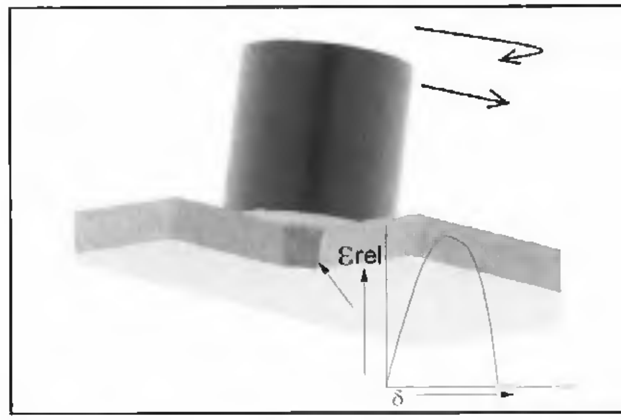

Fig. 4 — Shear zone around the pin in FSW.

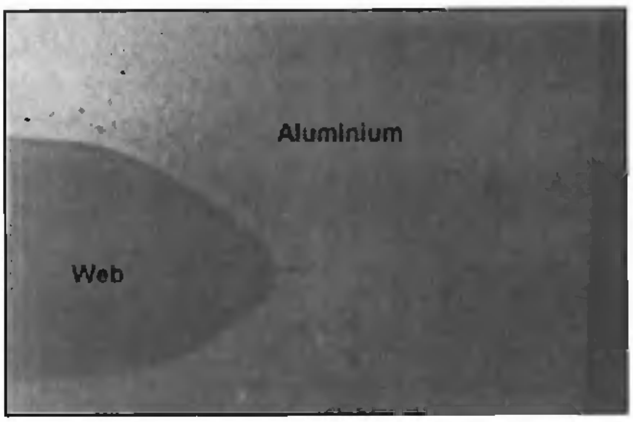

Fig. 5 — Split metal in the welding chamber, right behind the web; extrusion direction is from the left to the right. The dark gray body to the left is the web.

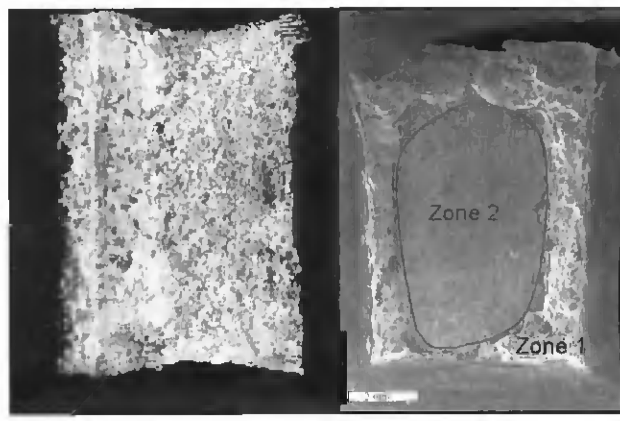

Fig. 6 — A — The fracture surface of a tensile tested transverse weld specimen in AA6060 aluminum alloy (by stereo microscope). B — The fracture surface (by SEM) of a Charpy-tested specimen of the same transverse weld at the same position along the extruded length

deformation are present and, therefore, conditions for solid-state welding are met everywhere in the shear zone. Continuous shearing and joining are assumed to take place in the shear zone. There is, therefore, no resulting joint line; the weld only shows up in the cross section as an area with a differing structure due to the high shear strain rates it has undergone. This results in either more heavily deformed grains, or, with a recrystalizing alloy, a finer recrystalized structure (in some alloys extensive grain growth can be witnessed after recrystalization). Some degree of lineup of primary and secondary particles and increased dislocation density can be witnessed. The texture itself can also be different compared to the rest of the profile, with grains having a different rotation in relation to the structure of the rest of the material.

Charge Weld Formation

The charge weld is the solid-state pressure weld created between the surface of the extrusion residue left in the die cavities after shearing of the press-rest (butt end) and the front surface of the subsequent billet being extruded. The charge weld represents the plane between two successive billets as it occurs inside the profile after extrusion. It is worth noting here that a charge weld also will occur at the interface between two smaller billets extruded together as one single billet (split billet).

Rests (ends) of previous extruded billets remain partly in the dead metal zones, with material of these zones flowing/leaking slowly into the profile surface. The charge weld never totally emerges through the outer surface of the profile, but stretches out up to the dead metal zone at the end of the billet. When more billets are extruded, rests of each billet will remain on top each of other in the dead metal zone and all will flow/leak into the profile surface as thin layers. As the extrusion billets are preheated to typically 450°C in ovens open to the atmosphere, the two contacting surfaces are heavily oxidized. The thickness of the oxide layer is an order of magnitude larger than that of the saw-cut material. The front surface of the new billet will first start to move into the center of the deformation zone, giving that point of initial contact between the two surfaces zero stretch. Although pressure would have been more than adequate for solid-state welding to occur, complete breakdown of the oxide layer does not occur and, therefore, solid-state welding does not take place at the apex of the weld. The farther the new billet is pushed into the die opening, thereby forcing out more and more of the material of the previous billet, the more the interface is stretched out. Mechanical properties of the charge weld vary, therefore, over the length of the profile, with almost zero at the apex and 100% base properties toward the end of the extruded length.

Akeret (Ref. 6) proposed the following mechanism for charge weld formation:

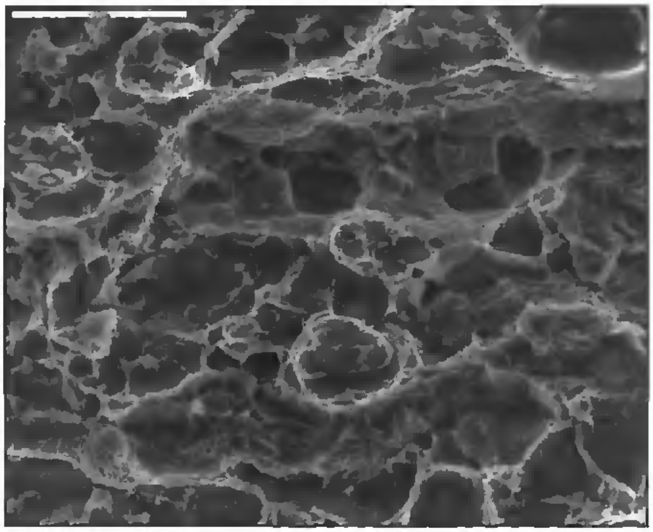

Fig. 7 — Dimples in a AA6082 base material specimen

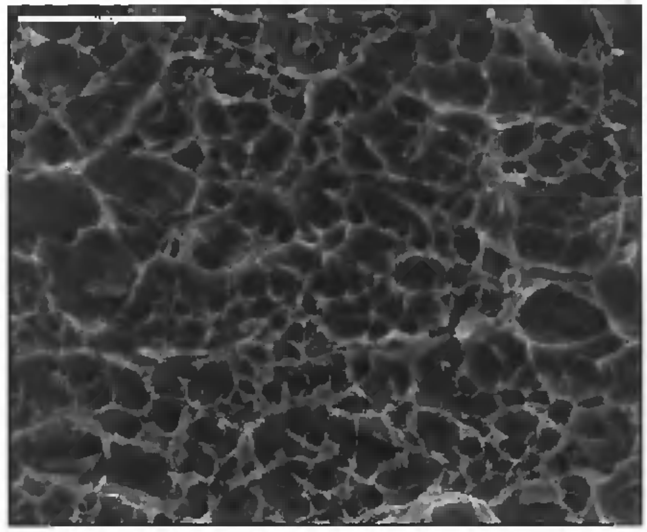

Fig. 8 — Dimples in a transverse weld specimen in AA6082

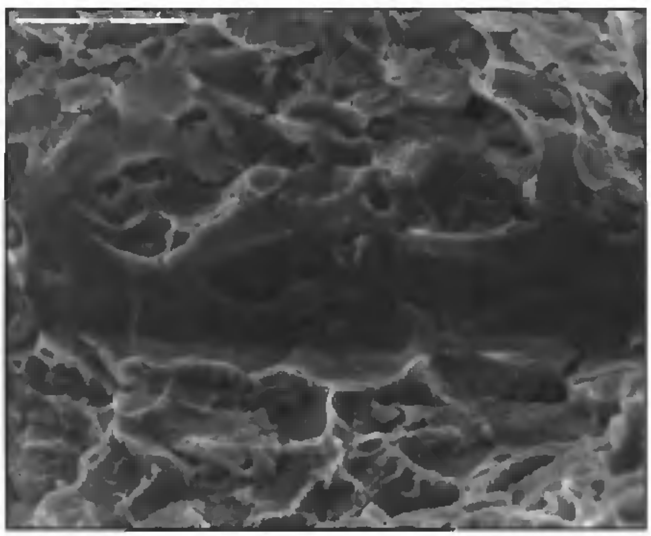

Fig. 9 — Fracture surface showing a kissing bond in a transverse weld in AA6082 (at higher magnification). The kissing bond is in the plane of the picture.

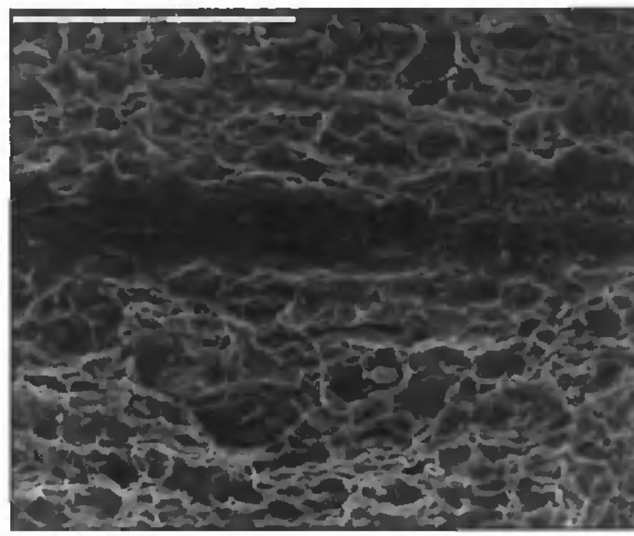

Fig. 10 — Overview of the fracture surface of a longitudinal weld in AA6082 with kissing bond showing in the center.

The transverse weld forms between two mating oxidized surfaces, on top of which, eventually, chemically absorbed or physically absorbed surface films can occur, e.g., oil.

These surfaces are compressed together at high temperatures, simultaneously being plastically deformed as they flow from their original location inside the container, through the deformation zone ahead of the die, out into the resulting extruded profile.

Four stages can be distinguished as shown in Fig. 3.

Matching of surface asperities. As the roughness of the two mating surfaces are pressed tightly together, small amounts of air may be trapped in small pockets in the interface between the extrusion residue and the billet. As the pressure between the two mating surfaces increases, high asperities of the surface (labeled 1 and 2 in Fig. 3A) come in contact and get crushed, the surface layers being broken apart, exposing areas of clean metal. Eventually, oxygen contained in local pockets of air will react with the newly generated surfaces, forming a thin oxide film, until no more oxygen is present.

Cracking of the surface layer. The oxide film is less ductile than the aluminum bulk material. Therefore, during plastic deformation, the oxide film of the interface will break up into island-shaped flakes.

Extrusion of base material in the gaps. When the surface oxide film has broken up — as is always present at the aluminum surface, since aluminum easily reacts with atmospheric oxygen — the underlying aluminum base material will extrude through the holes between the oxide flakes (labeled as 3 in Fig. 3C), because of high pressure inside the deformation zone.

Formation of ligaments. When the base material extruding through the holes between the oxide flakes comes in contact under pressure, the surfaces will locally be welded firmly together (labeled as 4 in Fig. 3D).

As in all solid-state welding, the intermetallic bindings are in reality "synthetic" grain boundaries. These boundaries can be produced when completely smooth and clean surfaces are brought together within an atom distance (which is pretty close — about 1 nm). Binding occurs when free electrons from one of the bodies transfers to the other.

This proposed mechanism will certainly be valid for the beginning of the charge weld. With further progressing of the charge weld, the contacting surfaces

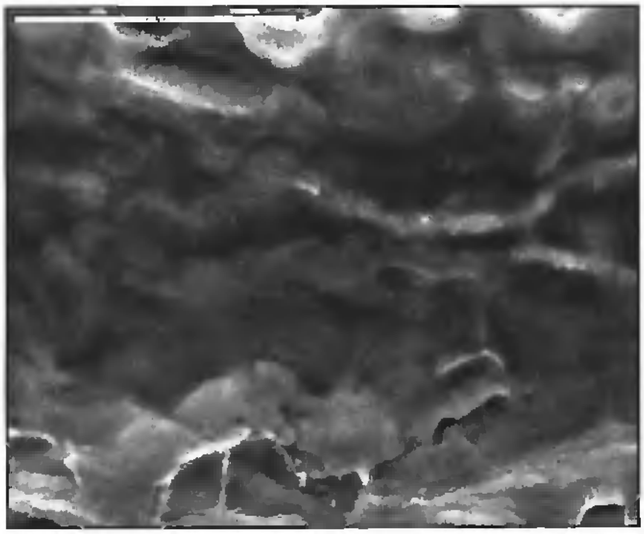

Fig. 11 — Close-up of the kissing bond in a longitudinal weld specimen in AA6082.

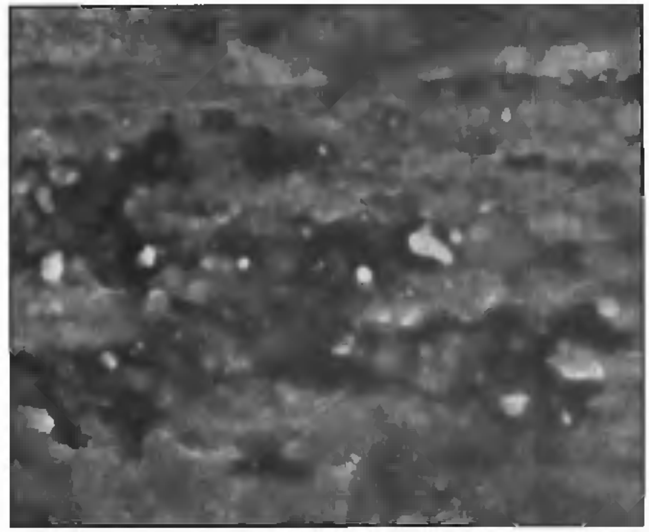

Fig. 12 — Extruded surface of a base material specimen of AA6082.

will be subjected to an ever-increasing shear strain, as the material from the previous billet gets pushed out of the die by the new billet. The effect of the oxide layer will therefore diminish equally with respect to the charge weld formation mechanism, because the contact surfaces are stretched out more extensively as more of the old billet material is moved out of the die. Shear-based solid-state welding is then likely to become the major mechanism, making the charge weld less of a pressure weld with increasing amount of the new billet being extruded

Friction Stir Welding

During friction stir welding in butt configuration, the surfaces of two to-be-joined workpieces are brought into contact (Ref. 7). The rotating shoulder of the welding tool heats up the material to the plasticized state. Accepted theory of the FSW process says that the role of the tool pin is to shear the material to its back during translation of the tool. But this is not the only mechanism. The inserted rotating pin brings the material at both sides of the joint line to the plastic state, aided by the frictional heat input of the shoulder. At the surface of the pin, the relative movement of the aluminum is almost zero. The shear-strain rate increases to a certain maximum in the layer adjacent to the pin surface. The viscosity of the material at elevated temperature governs the position of this peak and the intensity. Similarly to the extrusion process, we may refer to this region with a large shear-strain rate gradient as the shear zone. This is schematically shown in Fig. 4. The plasticized material around the pin is depicted in red. In the shear zone, a large shear-strain gradient can be expected, as shown in the graph, starting at near zero at the pin surface and peaking some radial distance δ into the shear zone, and then dropping down to zero again at the transition from shear zone to "unaffected material." When the rotating pin progresses along the joint line, the surfaces of the two workpieces are dragged into this shear zone, thus breaking up the brittle surface oxides. The combination of pressure and extensive shear present in the shear zone is adequate for the surface layers to stretch in contact. Solid-state welding occurs in the whole shear zone region, but the extent of joining is nonuniform. With subsequent revolution and translation of the pin, some of the metal in the shear zone, together with the solid-state welded surfaces, is moved and deposited behind the pin into the joint area. The proposed mechanism is therefore quite similar to the one for seam weld formation. There is not so much a situation of a pressure weld being generated between two contacting surfaces; rather, the contacting surfaces are stretched out and subjected to plastic shear in the shear zone around the pin. This is well supported by microstructures of friction stir welds. Work carried out by Midling (Ref. 7) shows that a distinct joint line could be seen when two different materials are welded. However, detailed examination of the friction stir welds of cast-to-wrought aluminum alloys (Ref. 8) indicates that a narrow interface occurs, here referred to as shear zone. In any case, a joint area having a different deformation structure compared to the rest of the material is present in the material after the pin has passed.

Typical friction stir welding pins feature a thread or fins (Refs. 9, 10). These features on the pin profile are comparable to the welding chambers of the porthole extrusion die. However, because surfaces of two to-be-joined members are oxidized and possibly contaminated, elements of the charge weld formation are also present. It is quite likely that after breaking up of the brittle surface oxides, the hydrostatic pressure in the shear zone around the pin causes subsequent extrusion of "fresh" metal through the gaps, as in Akeret's charge weld mechanism, forming new ligaments when coming in contact. It is our opinion that the seam weld formation mechanism plays the larger role, as is the case with the charge weld formation beyond the apex.

Kissing Bond Formation

A typical weld defect occurring with all three solid-state welding methods mentioned is the kissing bond. A kissing bond is a specific type of solid-state bonding defect, where two previously separate or separated regions of the material are in contact with little or no metallic bond present. The kissing bond usually has slightly reduced static load-carrying capacity, but impact strength, and possibly fatigue life, can be significantly impaired.

In seam welds, experimental work at Hydro Aluminium and NTNU (Ref. 5) has shown that with an unfavorable design of web and weld chamber, a gas pocket can be formed behind the dead metal zone at the end of the bridge. An explanation is that the aluminum layer in direct contact with the steel surface at the end of the web has a relative movement — in other words, it is sliding over the web. The split surfaces can be oxidized before meeting each other, and subsequent pressure and shear might be inadequate to break up the oxide film and bring fresh metal in close contact. In that case, not all of the generated surface will create metal bonds. The result is

Fig. 13 — Fracture surface of a friction stir weld in AA6082 showing vertically lined-up, tear-shaped kissing bonds.

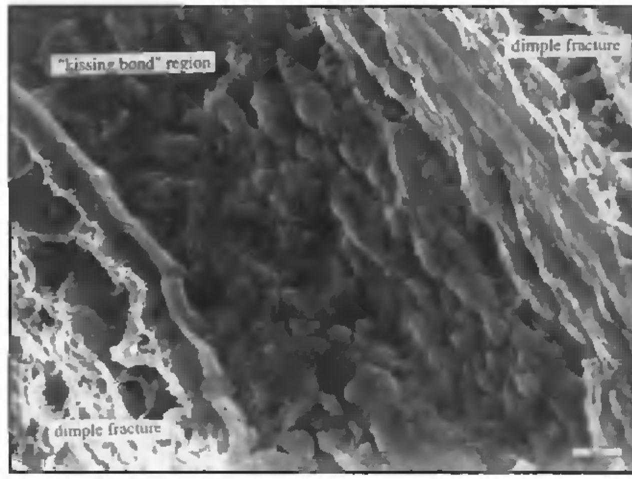

Fig. 14 — Close-up of the center kissing bond region of the specimen in Fig. 13.

the formation of a kissing bond. The picture in Fig. 5 shows a cross section of the end of a web and the welding chamber of a hollow die (sectioning being made after extrusion), showing a split between the two streams of metal. The reason is that the hydrostatic pressure is not high enough to make the metal meet directly behind the web. It must be stressed here that even without a gas pocket being present, it can be expected that under sliding conditions, the maximum shear strain in the shear zone will be significantly lower. Even though the surfaces will not oxidize, and are therefore fresh metal surfaces when they come in contact, the level of shear necessary for 100% metallic bonding might not be reached. This also results in a kissing bond.

In charge welds, as mentioned, the kissing bond formation takes place in the apex of the weld. The accepted reason for this is that between the contacting surfaces of the new billet and the metal left in the die, neither stretch nor shear is present at the beginning. No metal bond occurs, although the matching surfaces are in a real contact. With progression of the charge weld, the amount of stretch and shear of the contacting surfaces increases rapidly, leading to kissing-bond-defect-free material. Farther away from the apex, the kissing bond type of defect can still be present when very ductile surface contaminants, e.g., oil, are present.

With friction stir welding, insufficient stretch of the material caused by sliding, rather than sticking friction on the pin, is the major cause of the kissing bond defect. Analogously to the web and weld chamber in seam welds, unfavorable design of the pin contributes to this. The pin is profiled and its cross section is nonuniform. Consequently, the shear-strain rate distribution in the shear zone is more complex than shown schematically in Fig. 4. At the places where the material is subjected to high strain rates, usually at the outside for the screw thread pin, or at the fins for the fin-concept pin, sliding friction can occur. The experimental work carried out by Colligan (Ref. 11) supports this.

Fracture Surface of the Kissing Bond

To describe the appearance of the kissing bond failure, a constrained Charpy impact test was used on modified Charpy samples (Refs. 12, 13). Testing on charge welds has shown that when kissing bonds are present, the fracture surface of a broken conventional (unnotched) tensile specimen hardly indicates a presence of the defects. On the contrary, a constrained Charpy impact test shows kissing bonds very clearly in the fracture surface — Fig. 6.

Scanning electron microscope (SEM) fractography was performed on the Charpy samples. The direction of impact was chosen parallel to the joint line in each of the cases. Side grooves were applied in line with the joint line to ensure crack propagation through the solid-state welds rather than through the base material. The fracture surface of a specimen containing a kissing bond can roughly be divided into two zones: a rough surface with a lot of large, deep dimples (labeled in Fig. 6 as zone 1), and a smooth surface without them, or with very shallow dimples (labeled in Fig. 6 as zone 2). The former (zone 1) is the good part of the joint, absorbing a lot of energy during the impact test. The latter (zone 2) is the kissing bond area, absorbing little energy in the impact test. Higher magnification of the kissing bond area (zone 2 in Fig. 6) reveals two features: fine lines forming the edge/borders of very shallow dimples, and a surface exposing an orange peel effect caused by the subgrains rotating during the deformation of the solid-state welding process. The former is a result of a weak bond. If complete bonding had taken place, normal size dimples would have been seen in this part of the fracture surface. The latter kissing bond feature occurs where there is hardly any bond at all. Two originally free surfaces are only slightly deformed and squeezed together without the necessary surface stretch and shear that can result in formation of a full solid-state weld. The areas in zone 2 on Fig. 6, with absence of dimples, are characteristic for the kissing bond, as being two partially free surfaces lying extremely close together in the plane of the charge weld.

A base material specimen of AA6082 is shown in Fig. 7. The fracture surface displays dimples as expected. The structure shows relatively large, deep dimples with smaller dimples inside them, most likely originating from precipitation-free zones. Figure 8 shows the fracture surface of a charge weld. The dimple structure is relatively fine and can result in a relatively lower ductility compared with the structure as shown in Fig. 7 (Ref. 14). Material properties such as tensile strength and energy absorption are still expected to be on a level with the base material. Notice that there are still smaller dimples present inside the larger dimples.

A kissing bond defect formed in the same charge weld specimen is shown in Fig. 9 at higher magnification. The kissing bond itself can be seen in the middle of the picture, as a more or less free surface, with an almost entire absence of dimples. Notice that around the kissing bond, the dimple structure is similar to that shown in the base material of Fig. 7.

Apart from charge welds, seam welds

in the same alloy were also investigated. In Fig. 10, we see an overview of the fracture surface of a seam weld, containing a kissing bond in the center. There is a marked transition from a dimple structure to what appears to be a free surface in the kissing bond. Notice the abrupt transition from dimple structure to kissing bond at the right-hand side of the picture.

Figure 11 shows a close-up of the kissing bond of the seam weld shown in Fig. 10. No dimples are present at all; the surface has the characteristics of a free surface. The appearance of the grains are like those found in the surface of an extruded profile. Surface formation in aluminum extrusion takes place on the bearing surface, toward the exit side of the bearing channel. Grains forming the surface are first subjected to shear in the shear zone that has formed on the bearing from the entrance of the bearing channel and onward. This is due to sticking friction between the steel surface of the bearing and the aluminum in the bearing channel. At some distance from the entrance in the bearing channel, there is a transition point/region from sticking to sliding friction. After this point, the surface grains slide over the steel surface toward the exit of the bearing channel. The similarities between the surface of the kissing bond and the surface of an extruded aluminum section strongly indicate that the kissing bond has the same formation history as the extruded surface: first subjected to shear deformation in a shear zone, and then sliding over a steel surface. Figure 12 shows the surface of the extruded profile in AA6082 of the base material specimen. Apart from signs of damage due to handling of the profile after surface generation, the similarity is striking.

The fracture surface of an FSW Charpy specimen in 6082 with kissing bonds in the center is shown in Fig. 13. A row of tear-shaped kissing bond defects can be seen lined up in vertical direction slightly to the right of the center. The Charpy sample has the notch placed at the centerline of the weld. The orientation of the picture is such that the root of the weld is at the left side of the picture. The kissing bonds coincide exactly with the position of the second fin of the FSW pin used to make the weld. The high magnification image shown in Fig. 14 is of the area around the kissing bond seen in the middle of Fig. 13. There is an obvious difference between the appearance of the dimple fracture surface sideways and the region between them, which did not experience the fracture at all. This region is the free surface of the kissing bond, showing orange skin appearance similar to the kissing bond in the seam weld fracture of Fig. 11. The orange skin appearance is attributed to the free rotation of subgrains during the deformation process. The surface, again, is similar to that of an extruded aluminum profile — Fig. 12.

Conclusions

Three solid-state joining processes in aluminum alloys have been discussed: the seam weld and charge weld formation in extrusion, and friction stir welding.

The remarkable similarities and relatively minor differences between the mechanisms of these three processes have been discussed. Presented here is the concept that friction stir welding contains the governing mechanisms of both seam weld and charge weld formation as present in hot aluminum extrusion, based on the fractographic evidence.

All three processes can give rise to a specific type of defect — the kissing bond — and feasible governing mechanisms have been presented. For kissing bonds in charge welds, the lack of deformation of the initial contacting surfaces is seen as the main cause, resulting in insufficient oxide layer breakup, prohibiting metallic bonds from forming between the metal of both contacting surfaces. For both seam weld formation and friction stir welding, a mechanism based upon slipping friction conditions between tool surfaces and the aluminum in the adjacent shear zone has been seen to be viable for kissing bond generation.

The work carried out supports the hypothesis that a kissing bond originates from two free surfaces that have been brought together very closely, but without sufficient shear deformation for solid-state welding to take place. Insufficient shear deformation is usually the consequence of sliding friction conditions instead of sticking friction conditions being present at the aluminum-steel interface. For seam weld formation, this sliding friction results in a kissing bond when it is present at the end of the web. For FSW, a kissing bond occurs when the aluminum in the shear zone is sliding over the pin surface. The appearance of the kissing bond is similar to that of the extruded surface, indicating that its formation might be similar to that of surface formation of an aluminum-extruded profile in the bearing channel.

The implications of the proposed mechanism are that kissing bond formation in both seam welds and friction stir welds can be avoided by controlling the friction condition between the plasticized metal at elevated temperatures and the tool surface.

A new theory concerning kissing bond formation in friction stir welds can be proposed based upon the work presented, but more experimental work has to be carried out for validation.

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