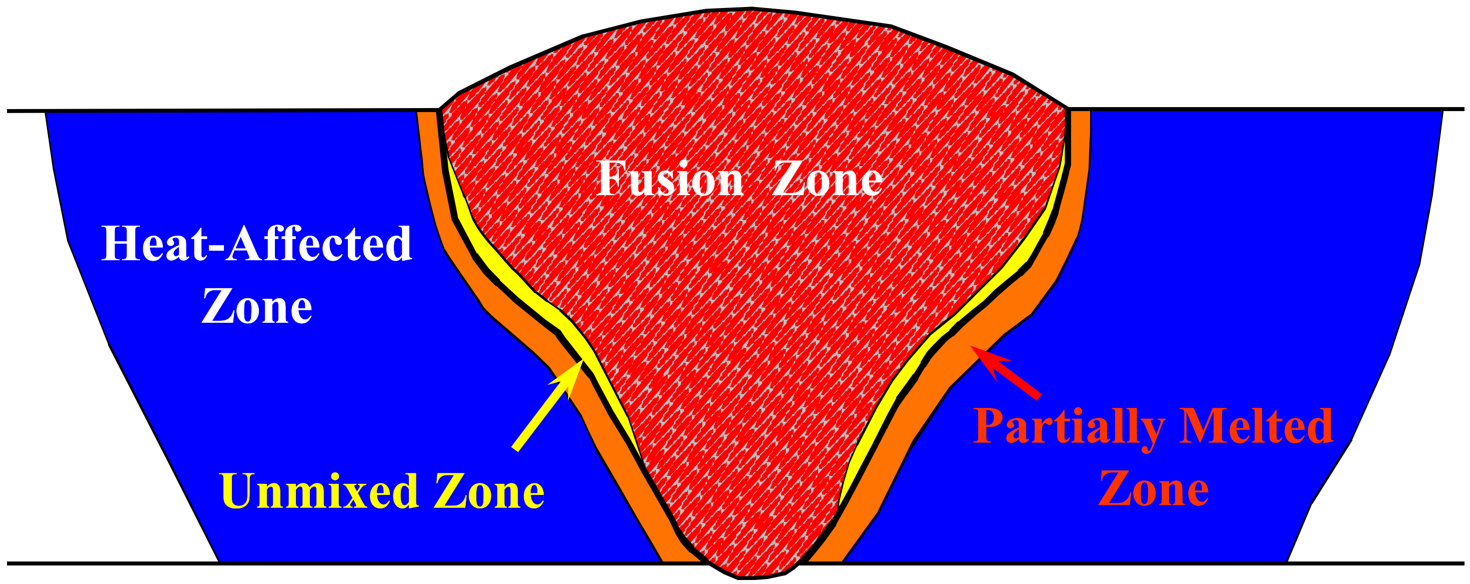
Regions of Fusion zone

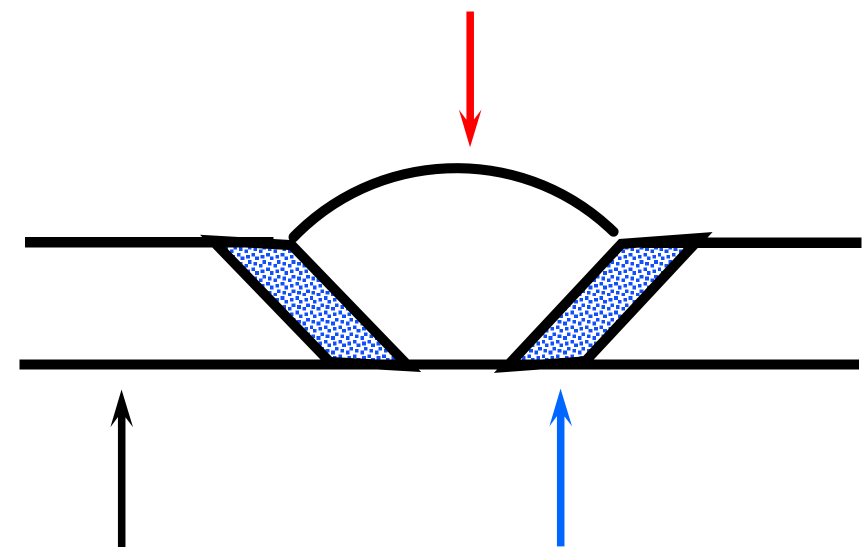


- Fusion zone
  - Composite zone
  - Unmixed zone (UMZ)
- Heat-Affected Zone (HAZ)
  - Partially-melted zone (PMZ)
  - True heat-affected zone (T-HAZ)

The Fusion Zone

- Region of the weld that is completely melted and resolidified
- Microstructure dependent on composition and solidification conditions
- Local variations in composition
- Distinct from other regions of the weld
- May exhibit three regions
  - Composite zone
  - Transition zone
  - Unmixed zone

Regions of Fusion Weld



2.2 REGIONS OF A FUSION WELD

Examination of a welded joint reveals distinct microstructural regions. The fusion zone is associated with melting. The HAZ, though not melted, is affected by the heat from the joining process. Beyond the HAZ is the unaffected base metal. The fusion zone and HAZ can be further subdivided, as described in this section.

The fusion zone is described as such because it is the region where melting and solidification occur to form the joint, or weld. Since all metals are crystalline in nature, many possessing cubic crystal lattices, there are general solidification phenomena common to all metals. In many materials, solidification behavior is very sensitive to composition. For example, the addition of small amounts of carbon and nitrogen to some steels can change their solidification behavior from ferritic (bcc) to austenitic (fcc). Minute additions of sulfur to steels can promote severe solidification cracking in the fusion zone. Aluminum alloys that are otherwise crack susceptible can be welded with a filler material containing more than 6% of silicon in order to avoid cracking.

The microstructure and properties of the HAZ are solely controlled by the thermal conditions experienced during welding and postweld heat treatment (PWHT). Aluminum alloys are routinely precipitation hardened or work hardened to increase strength; welding can completely eliminate these strengthening effects in the HAZ. Steel undergoes a phase transformation, which can result in a HAZ that has a radically different microstructure and properties than either the base metal or the fusion zone.

The understanding of regions of a weld has evolved tremendously since the 1960s. Prior to that time, a fusion weld was thought to consist of only two regions, the fusion zone and a surrounding HAZ, as shown in Figure 2.2 from a lecture by E.F. Nippes in 1959 [3]. Considerable research conducted by W.F. Savage and his students at RPI in the 1960s and 1970s revealed that other distinct regions of a fusion weld existed [4, 5].

In 1976, Savage *et al*. [4] proposed several changes to the terminology used to describe fusion weld microstructure regions, as shown in Figure 2.3. The fusion zone was considered to consist of two regions. The composite region represented the portion of the fusion zone where base metal and filler metal were mixed in a "composite" composition. Surrounding this region along the fusion boundary, they defined a region called the unmixed zone (UMZ). The UMZ consists of melted and resolidified base metal that does not mix with the filler metal. In some alloy systems, the UMZ can exhibit microstructures and properties very different from those of the composite region, particularly when dissimilar filler metals are used.

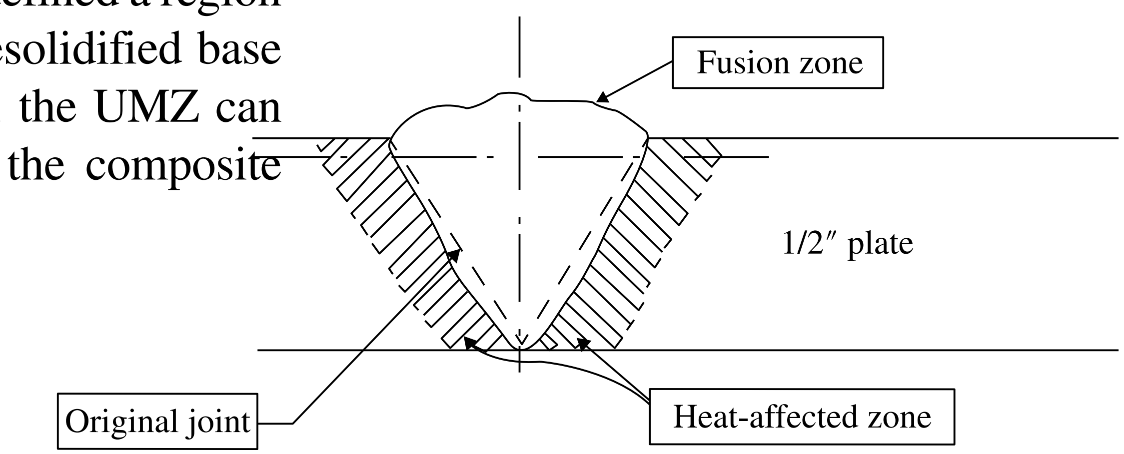


FIGURE 2.2 Early schematic of regions of a fusion weld (From Ref. [3]. © AWS).

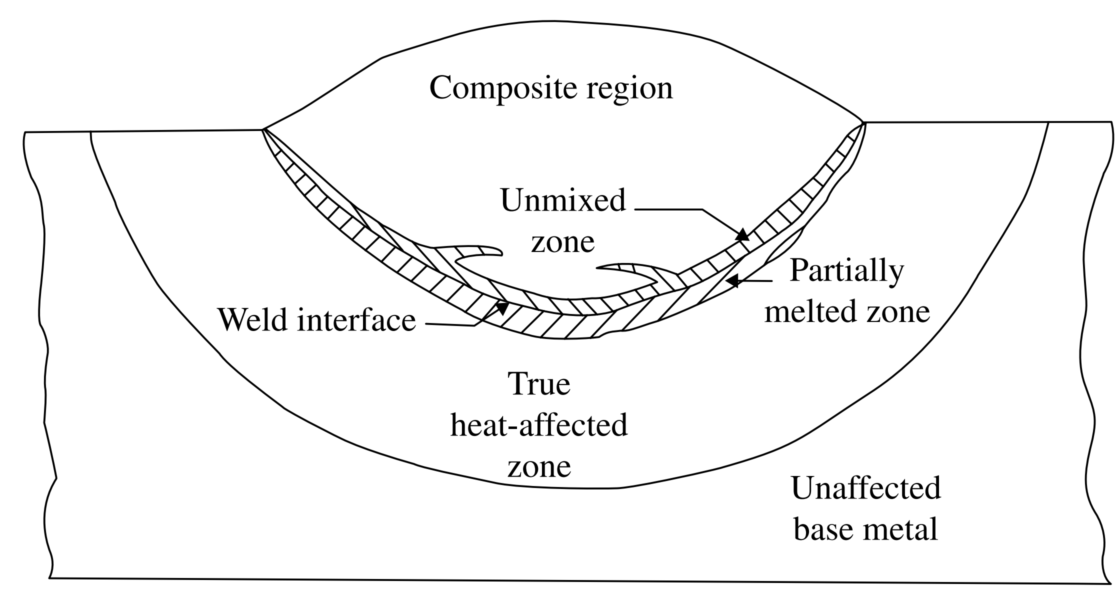


FIGURE 2.3 Regions of a fusion weld (From Ref. [4]. © AWS).

The HAZ was subdivided into two regions, the partially melted zone (PMZ) and the "true" heat-affected zone (T-HAZ). The PMZ exists in all fusion welds made in alloys since a transition from 100% liquid to 100% solid must occur across the fusion boundary. In addition, other mechanisms were identified that resulted in local melting (or liquation) in a narrow region surrounding the fusion zone. These include grain boundary melting due to segregation and a phenomenon described as "constitutional liquation" that results from local melting associated with a constituent particle. The designation of a T-HAZ was used to differentiate that region of the HAZ within which all metallurgical reactions occur in the solid state, that is, no melting, or liquation, occurs.

Little has changed since 1976 regarding terminology for describing regions of a fusion weld, although considerable research has been conducted on a variety of alloy systems to verify that these regions actually exist in these material systems. Additional refinements have been made to this original terminology. For example, the T-HAZ in steels has been subdivided into various subregions, such as the coarse-grained HAZ (CGHAZ), the fine-grained HAZ (FGHAZ), and the intercritical HAZ (ICHAZ) regions.

The only potential addition to the terminology in Figure 2.3 is a transition region within the fusion zone. In heterogeneous welds, where the filler metal is of different composition from the base metal, this would represent a composition transition from the composite region to the UMZ. In some alloy systems, this transition zone (TZ) can exhibit a microstructure distinctly different from the surrounding regions. For example, in welds between stainless steels and low-alloy steels, a martensitic structure may form in the transition region that does not occur elsewhere in the weld.

A new schematic of the regions of a fusion weld is provided in Figure 2.4 for a heterogeneous weld. It is similar to the illustration in Figure 2.3 but contains a composition TZ that may be present in some systems. The following sections will review the various regions defined earlier in considerable detail and will describe the mechanisms involved in their formation.

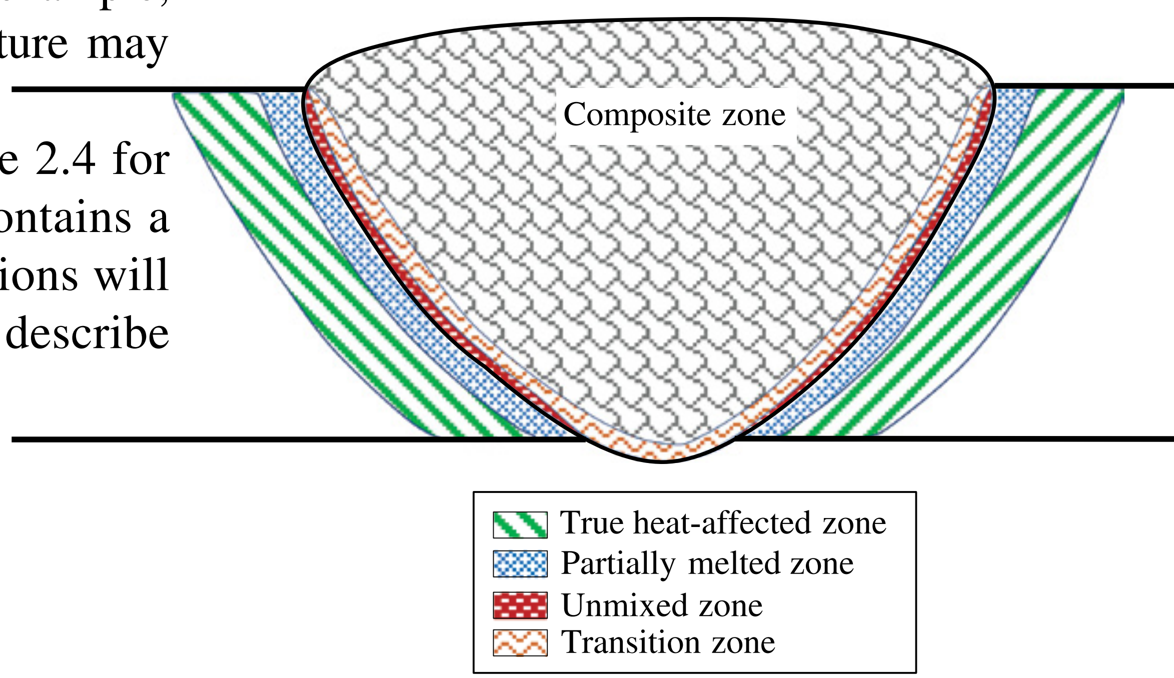


FIGURE 2.4 Modern schematic showing regions of a fusion weld.

Types of Fusion Zones

- Autogenous
  - No filler metal addition
  - GTAW on thin sheet, EBW of square butt joint
- Homogeneous
  - Addition of filler metal of matching composition
  - 4130 filler used to join 4130 Cr-Mo steel
- Heterogeneous
  - Addition of filler metal with dissimilar composition to the base material
  - 4043 filler used to join 6061 aluminum
  - Ni-based alloys for joining stainless steels

Fusion Zones

2.3 FUSION ZONE

The fusion zone represents that region of a fusion weld where there are complete melting and resolidification during the welding process. The microstructure in the fusion zone is a function of composition and solidification conditions. Small differences in composition often result in large variations in microstructure and properties. In some systems, changing the solidification and cooling rates can also alter the microstructure, sometimes dramatically.

The fusion zone is normally very distinct from the surrounding HAZ and base metal when samples are prepared metallographically. This is due to both macroscopic and microscopic fluctuations in composition resulting from the solidification process.

In welds where the filler metal is of a different composition from the base metal, three regions theoretically exist. The largest of these is the composite zone (CZ), consisting of filler metal uniformly diluted with base metal. Adjacent to the fusion boundary, two additional regions may exist. The unmixed zone (UMZ) consists of melted and resolidified base metal where negligible mixing with filler metal has occurred. Between the UMZ and CZ, a transition zone (TZ) must exist where a composition gradient from the base metal to the CZ is present.

Three types of fusion zones have been defined: autogenous, homogenous, and heterogeneous. The classifications are based on whether or not a filler metal is used and the composition of the filler metal with respect to the base material. All three types of fusion zones are commonly encountered.

Autogenous welds are those where no filler metal is added and the fusion zone is formed by the melting and resolidification of the base metal. These are common in situations where section thicknesses are minimal and penetration can easily be achieved by the process selected. In thin sections, autogenous welding can often be applied at high speeds, and normally, a minimum amount of joint preparation is required, that is, butt joints can be used. Welding processes that are, or can be, adapted to autogenous welding include GTAW, EBW, LBW, PAW, and resistance welding. The fusion zone is essentially the same composition as the base metal, except for possible losses due to evaporation or pickup of gases from the shielding atmosphere. Not all materials can be joined autogenously because of weldability issues.

Homogenous welds involve the use of a filler metal that closely matches the base

Homogenous welds involve the use of a filler metal that closely matches the base metal composition. This type of fusion zone is used when the application requires that filler and base metal properties must be closely matched. Properties such as heat treatment response or corrosion resistance are examples of such properties. Some common examples include the use of Type 316L base metal joined with 316L filler for matching corrosion properties and the use of E10016-D2 filler metal on AISI 4130 Cr–Mo steel, which is usually given a full PWHT to provide uniform strength.

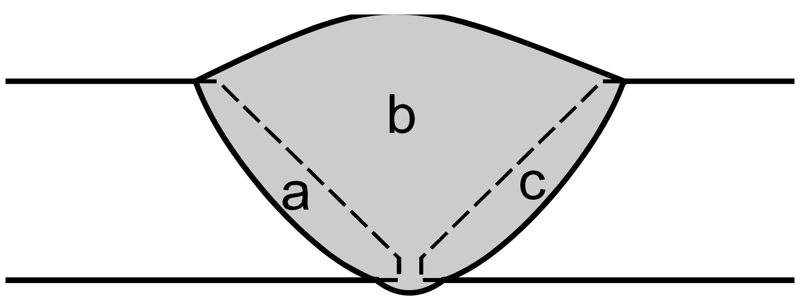
Heterogeneous welds are fusion welds made with filler metals whose composition is different from that of the base metal. In many situations, matching filler metals may not exist or the weld properties desired may not be achievable with a matching composition. It should also be recognized that many base metal compositions may have inherently poor weldability and that dissimilar filler metals are required to achieve acceptable properties or service performance. Some considerations that would require the use of a dissimilar composition filler metal include strength, weld defect formation (e.g., porosity), weldability/solidification cracking resistance, heat treatment response, corrosion resistance, filler metal cost, and operating characteristics of the consumable.

When using a filler metal that has a composition different from the base metal, dilution effects must be carefully considered or the desired outcome may not be as expected. Common examples of heterogeneous welds include the use of Type 308L filler metal on Type 304L base metal for weldability and corrosion resistance and the use of a 4043 aluminum filler metal with 6061 aluminum base metal for solidification cracking resistance.

As noted earlier, the use of heterogeneous welds often requires close attention to dilution effects. Dilution can be defined as a change in composition of a filler metal due to its mixing with the base metal during the melting process. In many cases, dilution is not desirable and must be carefully controlled. Alteration of the deposited weld metal composition by dilution can negate or lessen the desired weld metal properties that would be achieved by a filler metal in its undiluted condition. One case where dilution is particularly undesirable is in surfacing operations where filler metals are significantly different from the base material and chosen to produce very specific properties such as abrasion resistance, corrosion resistance, or impact properties. For example, if stainless steels are used as cladding on carbon steels for corrosion resistance, significant dilution (~40%) can reduce the chromium content to a level where the clad layer is no longer corrosion resistant.

Dilution

Dilution

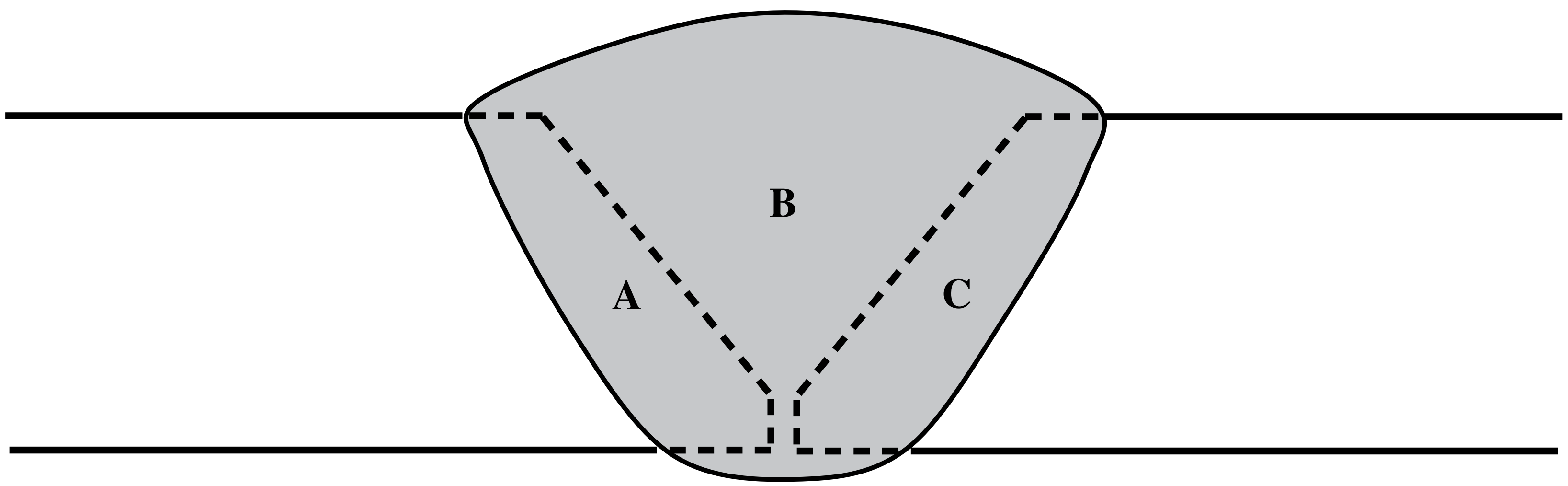


$$\text{Dilution (\%)} = \frac{a + c}{a + b + c} \times 100$$

- Amount of melted base metal mixing with filler
- Expressed as percent base metal dilution of the filler metal
  - 100% is an autogenous weld
  - 10-40% common in arc welds
- Significant effect on microstructure and properties
- Controlled by joint design, process, and parameters

Dilution

Dilution is expressed in terms of dilution of the filler metal by the base metal and is shown schematically in Figure 2.5. Mathematically, dilution is the ratio of the amount of melted base metal to the total amount of fused metal. For example, a weld with 10% dilution will contain 10% base metal and 90% filler metal. For most welding processes, dilution is normally controlled below 50%. Cross sections of welds, as shown in Figure 2.5, can be used to estimate dilution based on the original joint geometry, or the actual composition of the weld metal can be determined by analysis, and the dilution calculated if the compositions of the base and filler metals are known.



$$\text{Dilution (\%)} = \frac{A + C}{A + B + C} \times 100$$

FIGURE 2.5 Schematic illustration of the determination of dilution in a heterogeneous weld.