الجامعة التكنولوجية
قسم هندسة المواد
Department of Materials Engineering

Welding Metallurgy

3rd Level

Scientific Supervision
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Content

1.Welding Process

Means joining two pieces of metals by applying either heat or pressure or both on the original boundary surfaces of these two metals leading to formation metallic bond after their melting with each other.

The purpose of studying the principals of welding metallurgy is to understand the effect of welding parameters on the mechanical strength of produced weld joints in order to attain the desired properties for the joints.

The welding types are classified depending on the type of heat input as: Gas Welding, Arc Welding, Resistance Welding, Solid-State Welding, Thermo-Chemical Welding, Radiant Energy Welding.

Figure (1.1) presents different welding types for each major type depending on heat source.

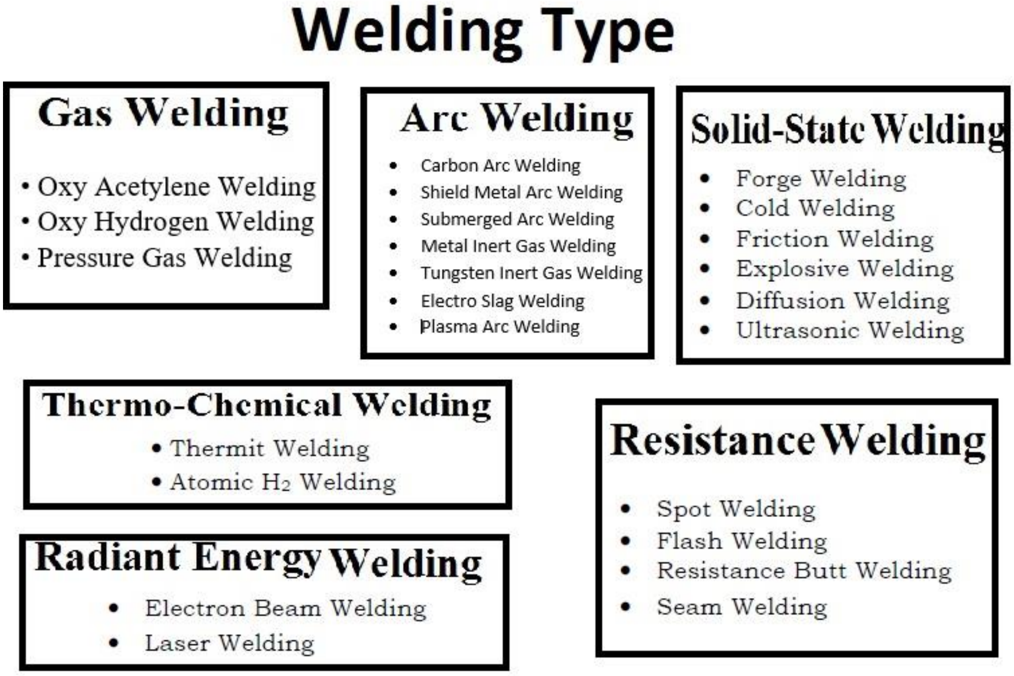


Figure1.1: Different welding types for each majors depending on heat source.

1.1 Major Welding Categories.

There are two main categories of welding process based on heat source. See welding categories in Figure (1.2).

1.1.1 Fusion Welding (Non-Pressure Welding)

The material at the joint is heated to a molten state and allowed to solidify. In this process the joining operation involves melting and solidification. So, no external forces are allowed to apply to the system during welding, as it does not play an active role in producing coalescence.

Usually fusion welding uses filler materials to ensure that the joint is filled.

All fusion welding processes have three requirements: Heat, Shielding and Filler materials. See Figure 1.2a.

1.1.2 Solid-State Welding (Plastic welding or Pressure welding)

Bonding operation takes place by applying external pressure on the pieces need to be joined after heating them and acquisition plastic state leading to produce coalescence in the two metals at temperatures below the melting point of the base materials being joined.

The pressure coalescence is produced, so, the original properties are retained with the metals being joined.

No need to add filler metal, also, the base metal does not melt due to temperature, time. See Figure 1.2b.

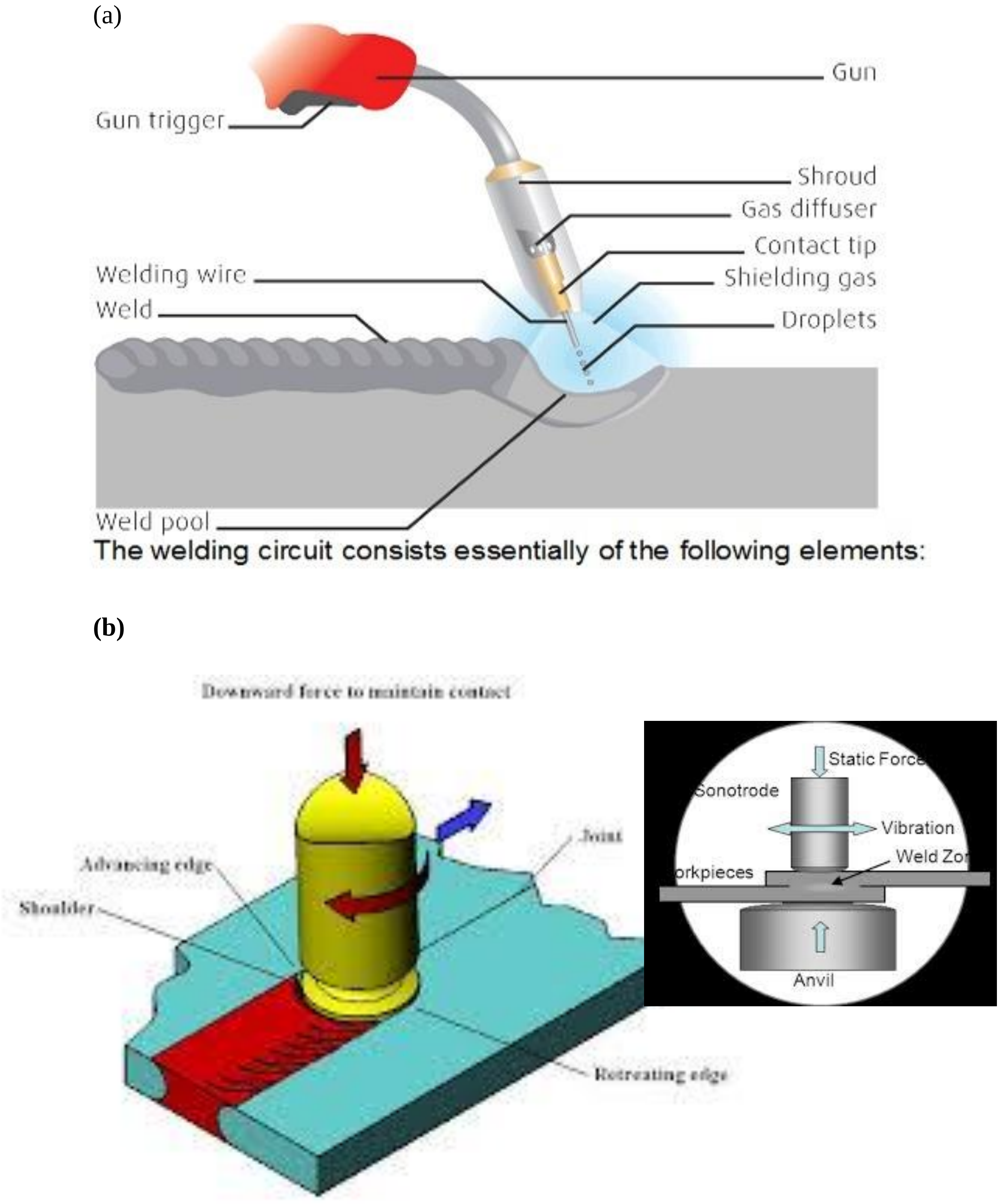


Figure 1.2: Examples of welding categories; (a) Fusion welding; (b) Solid-State Welding.

2.Welding Metallurgy

It is defined as the microstructural changes occur in metals during welding. microstructure evolution of weld structures is considered as a function of estimation the qualification of produced joints.

Microstructure evolution in welds is affected by heating amount, time, applied stress and the amount of weld metal should be deposited during any welding process. See Figure (2.1).

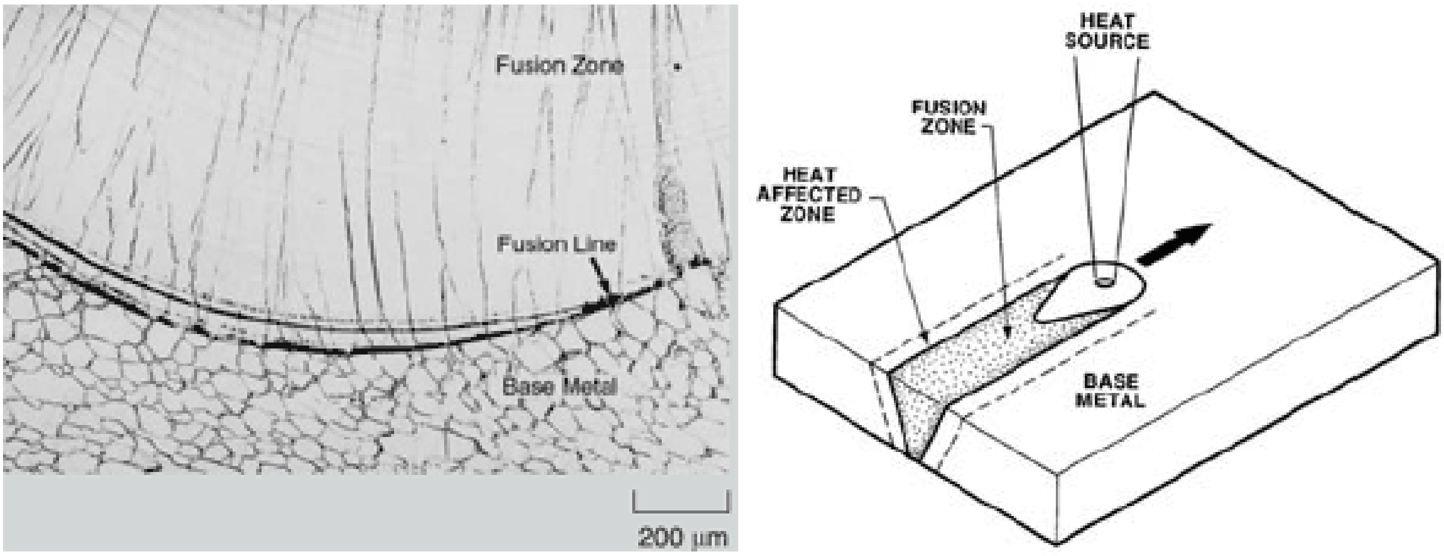


Figure 2.1: Microstructure evolution in weld joint

Welding metallurgy involves changes in chemical, mechanical, or physical properties of metals being joint with changing the microstructure of the joint after subjecting to heating and solidification cycle during welding.

<u>Chemical metallurgy</u> or (rust-صدأ): oxidation of metal, or where oxygen gets into the metal and corrodes it. There is also corrosion where the atmosphere

wastes away the metal. In welding, removal of oxygen from the molten puddle (keeping the Oxygen out of the molten weld pool) is very necessary for successful welding process because oxygen affects the weld pool adversely.

Mechanical metallurgy: involves the way that metal acts under loads and stresses. There are many different loads and stresses involving brittleness, toughness, ductility, malleability, plasticity, shear, and others. For example, tensile strength is one of the utmost mechanical parameters that should be studied for weld joints. It provides information about the ability of weld parts to resist pulling apart depending on the amount of deposited metal if subjected to tensile stress.

Physical properties: involves the interaction between the physical properties of the metal, such as thermal conductivity, melting point, and grain characteristics with the heat applied during welding. For example, the atomic structure of the metals consists of different "space lattices" which form different crystals. The crystals have grains with different sizes and shapes, grain size affects strength in metals specifically during welding. So, different structures in metals affect in changing the structure from one to another when heated during welding. See Figure (2.2).

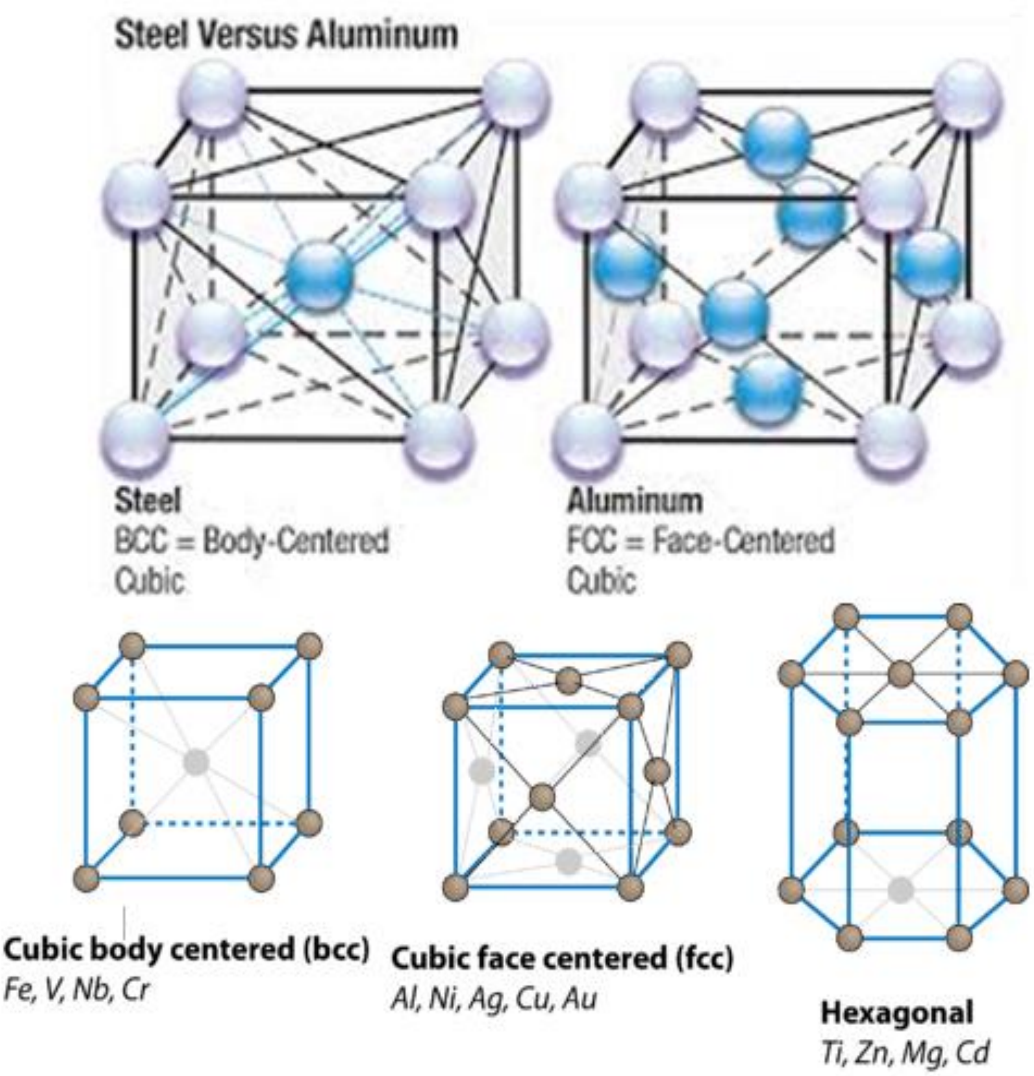


Figure 2.2: Different "space lattices" which form different crystals.

Best example shows the interaction between the three properties (chemical, physical, mechanical) of a metal need to weld and welding process is found in welding steel.

During studying its metallurgy (Figure 2.3), it is noticed that carbon content plays a big part in the strength of steel during welding. The more carbon steel, the more difficult welding. Mostly the acceptable amount of carbon in steel need to weld is about 30%.

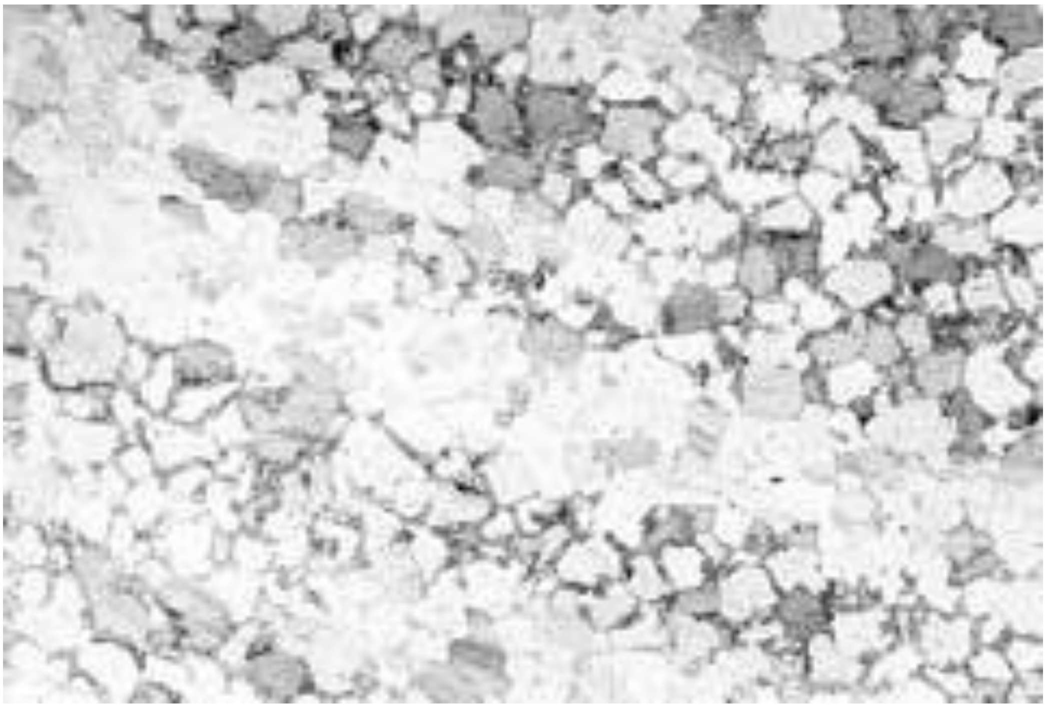


Figure 2.3: Microstructure of weld region in low carbon 12% chromium alloy steel showing banded two phase martensite and ferrite structure.

2.1Basic Principles of Welding Metallurgy.

It is also called Thermal Cycle and Residual Stresses in welds. There are two important metallurgical processes take place during welding.

(1) Melting and solidification processes, as they are the key to achieve acceptable joints in all fusion welding processes.

(2) Segregation and diffusion processes.

The metallurgical process control on the microstructure changes in the welds affecting on their properties and hence their strength because they both result in local compositional variations that influence both weld-ability and service performance. The block diagram in Figure (2.4) show the main parameters which have combined effect on the microstructure of the weldment. Weldment includes weld metal and heat-affected zone (HAZ)) relative to the base metal.

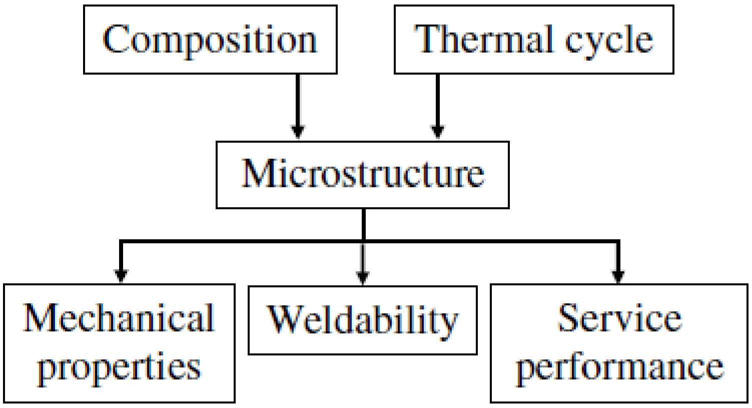


Figure 2.4: Effect of welding metallurgy on weld performance

3. Welding Zones.

Weld joints mainly have three distinct microstructural regions Figure (3.1, 3.2, 3.3):

3.a Fusion Weld (FW): is associated with melting.

3.b Heat Affected Zone (HAZ), not melted, and is affected by the heat from the joining process.

3.c Base metal (BM): is described as unaffected zone.

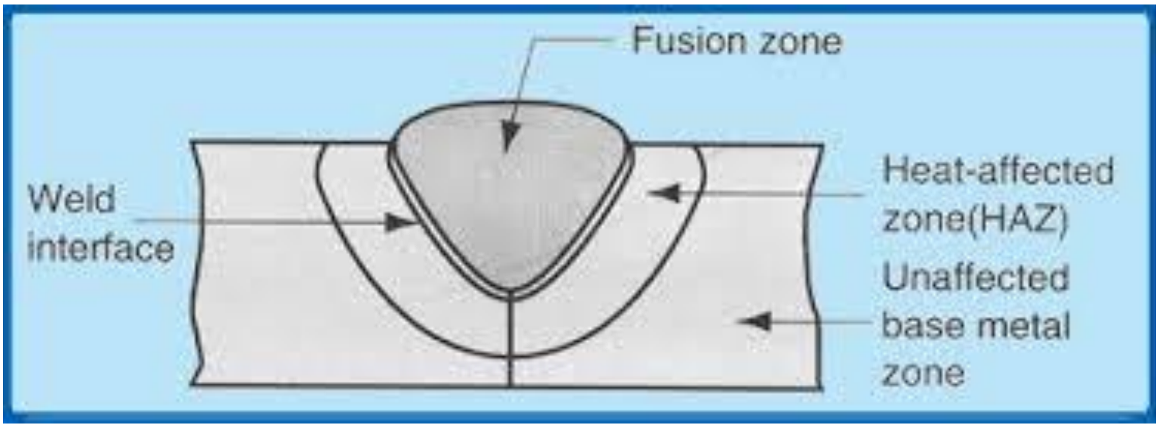


Figure 3.1: A schematic draw for welding zones.

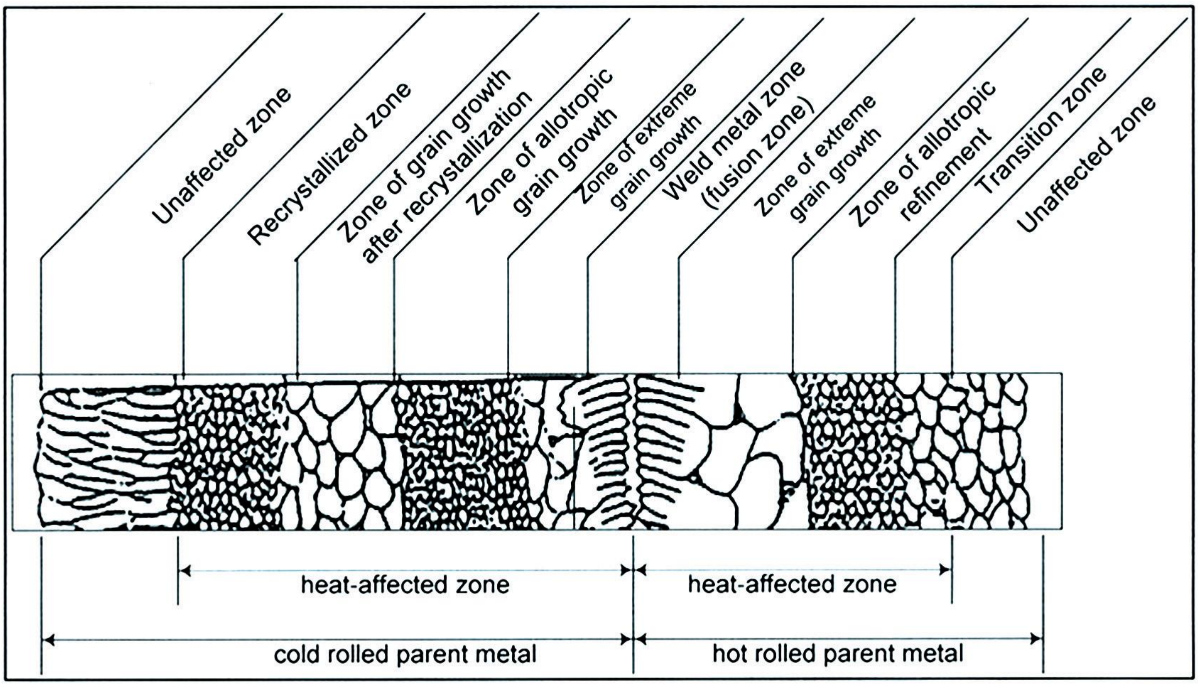


Figure 3.2: A micro-structured draw for main regions of a weld zone.

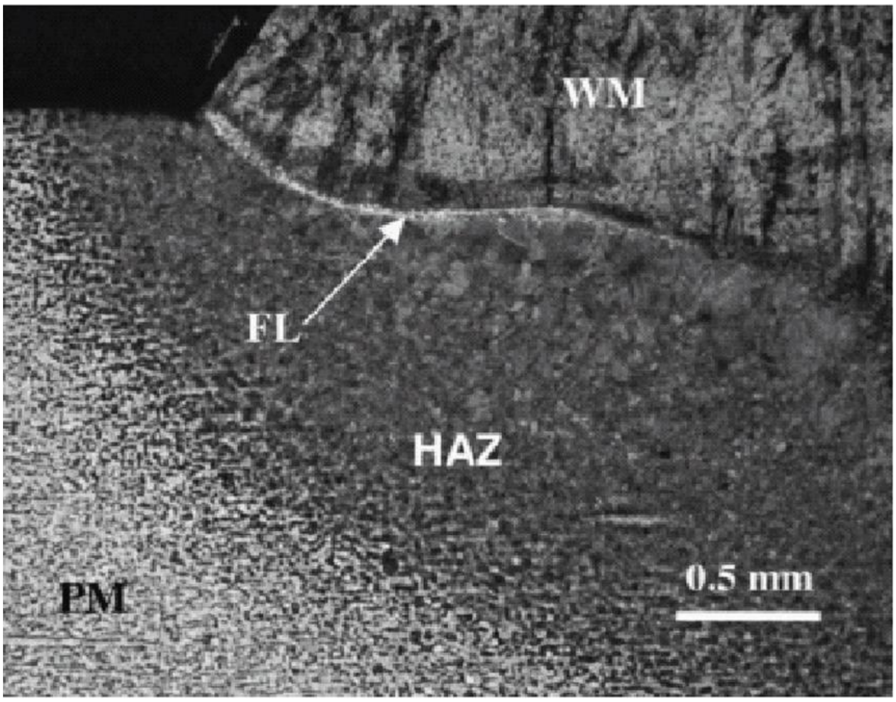


Figure 3.3: A micro-structure Image for main regions of weld zones.

Fusion Weld (FW) zone could be further subdivided to: Fusion Zone (FZ), Unmixed Zone (UMZ), Partially Melted Zone (PMZ), Heat affected zone (HAZ). Figure (3.4).

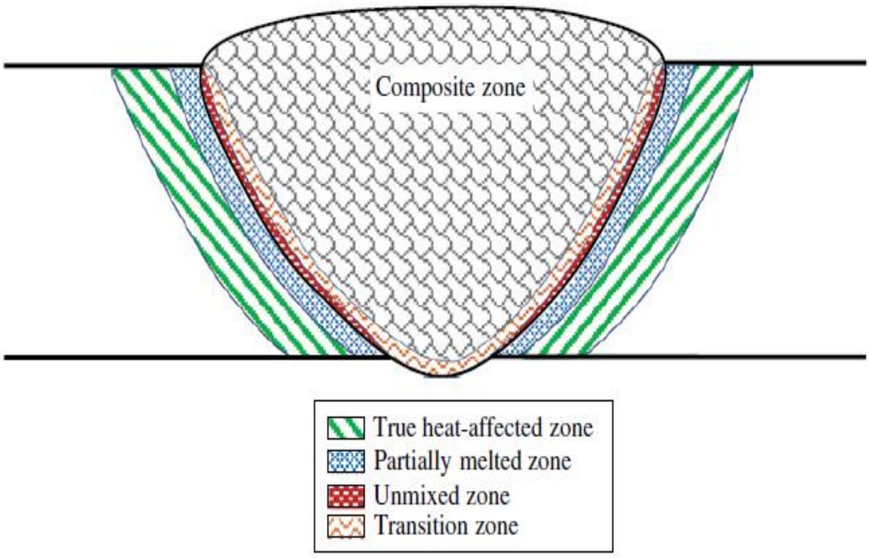


Figure3.4: Fusion weld zones.

3.a Fusion Zone

It is the region where a complete melting and re-solidification occur to form the joint, or weld. The microstructure in this zone is a function of:

- Composition: Small differences in composition result in large variations in microstructure and properties. For example, the addition of small amounts of carbon and nitrogen to some steels can change their solidification behaviour from ferritic (Bcc) to austenitic (FCC). Additions of sulphur to steels can promote severe solidification cracking in the fusion zone.
- Solidification conditions: In some systems, changing the solidification and cooling rates can also alter (change) the microstructure.

Fusion zone is classified depending on using a filler metal or not into:

- Autogenous welds: are those where no filler metal is added and the fusion zone is formed by the melting and re-solidification of the base metal. 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 weld-ability issues.
- 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. Some common examples include the use of Type 316L base metal joined with 316L filler for matching corrosion properties.
- Heterogeneous welds: Involve the use of a filler metal that it does not match the base metal composition. This type of fusion zone is used when many base metal compositions may have inherently poor weld-ability and that dissimilar filler metals are required to achieve acceptable properties or service performance such as strength, weld defect formation (e.g., porosity), weld-ability/solidification cracking resistance, heat treatment response, and corrosion resistance.

3.a.1 Dilution

Defined as a change in composition of a filler metal due to its mixing with the base metal during the melting process.

التخفيف: هو التغير في تركيب معدن الحشوه بسبب اختلاطه مع المعدن الاساس اثناء عملية الذوبان.

It occurs in the fusion zone related to the heterogeneous welds due to using a filler metal that has a composition different from that of the base metal.

يحدث في المنطقه المنصهره للملحومات الغير المتجانسه اللحام بسبب استخدام معدن حشوه الذي يحتوي على تراكيب عناصريه مختلفه عن تلك التي تعود للمعدن الاساس.

It negatively effects on the desired properties of the welds. The composition of the diluted deposited weld metal has less desired properties than that the undiluted.

وتؤثر سلبا على الخصائص المطلوب الحصول عليها في الملحومات. معدن اللحام ذا التركيب المخفف المترسب يمتلك اقل الخصائص المطلوب الحصول عليها في الملحومات مقارنة بمعدن اللحام ذا التركيب الغير المخفف.

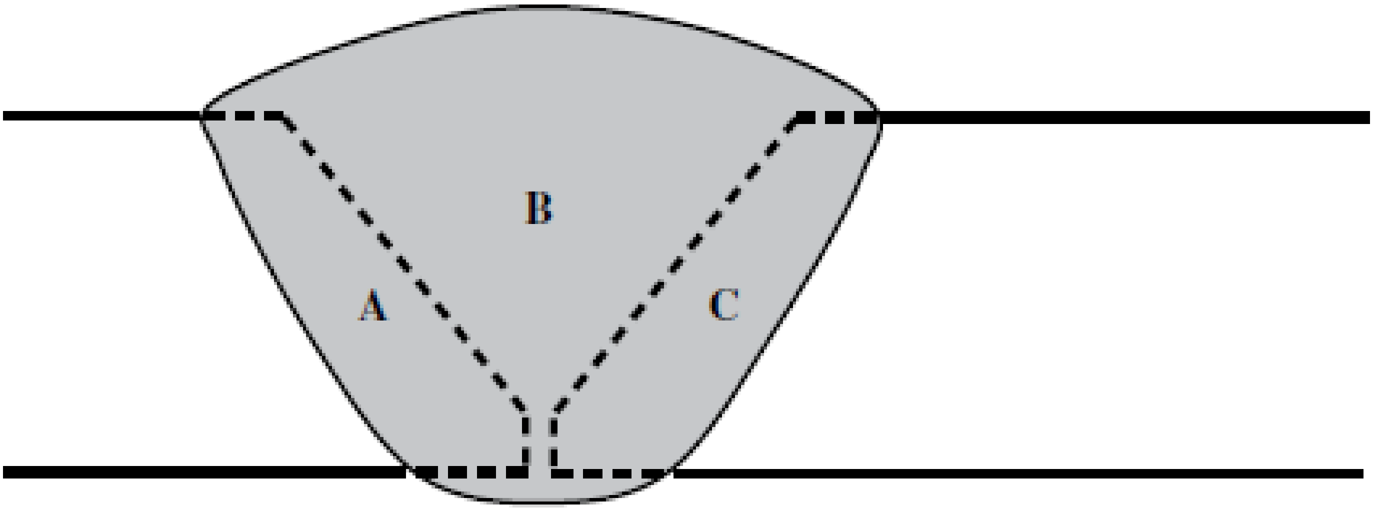
The purpose to study dilution: controlling on dilution helps avoid unexpected results for the desired properties of the welds.

الغرض من دراسة التخفيف هو للسيطره والحذر من النتائج الغير المتوقعه والتي تؤثر سلبا على الخصائص المراد الوصول اليها للملحومه.

Example for dilution effect: getting undesirable abrasion resistance, undesirable corrosion resistance, and undesirable impact properties in surfacing operations where dilution is particularly undesirable. Dilution occurred because filler metals are significantly different from the base material. 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.

$$\text{Dilution} = (\text{Amount})_{\text{melted base metal}} / (\text{Amount})_{\text{total fused metal}}.$$

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%.



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

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

3.a.2 Solidification of Metals in Fusion zone

Solidification process starts with decreasing temperature through following stages:

a- Nucleation stage where solid pieces starts to form within the liquid phase. During proceeding the transformation of the liquid-to- solid state, and starting formation the initial solid, the heat fusion generated by the transformation is dissipated or removed with decreasing temperature. This mechanism normally occurs through conduction the solid away from the solidification front.

b- Re-distribution process of the solutes take place between liquid and solid. This occurs because the composition of the liquid and solid in contact at the solidification front changes continuously with decrease the temperature within the solidification range. During re-distribution process, if the solid does not have time to reach its equilibrium composition.

The redistribution will result in local variation (انحرافات داخليه) in composition in the solidified structure. This phenomenon is common in most casting and welding processes. Solidification shrinkage contributes to the residual stress that is associated with fusion welds. It occurs as a result of a negative volume change when the fusion welds solidify as it imparts or (carries) stresses upon the as-solidified structure that may lead to solidification cracking.

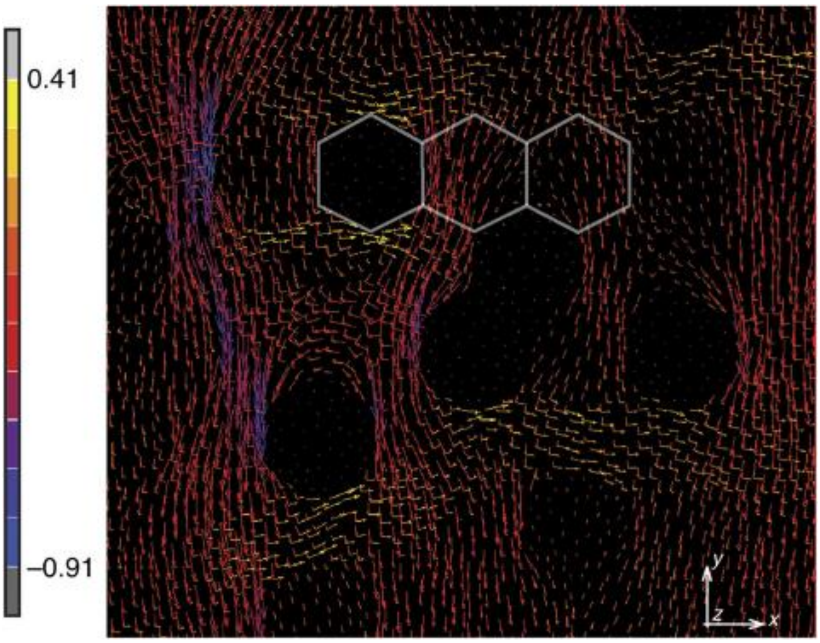


Figure 3.5: Local variations in weld system.

3.a.3 Weld Solidification Parameters.

Four parameters are useful in describing micro- structure development when nucleation and solute re-distribution stages proceed during solidification.

1-Partition Coefficient/ (the solute redistribution coefficient)/ (*k*): It is the ratio of the solid and liquid composition in contact with each other at a given temperature within the solidification range [$k = C_S/C_L$]. Considering solute segregation during solidification, values of *k* are assumed to be in three cases:

Either $k < 1$ (solute will partition to the liquid) = nucleation stage.
Or $k \sim 1$ (solute redistribution during solidification is reduced) = redistribution.
Or $k > 1$ (solute will be depleted in the liquid).

2-Liquid Temperature Gradient (G_L): It dictates the nature of the temperature field in advance of the solid–liquid (S–L) interface. In situations where some undercooling of the liquid has occurred prior to solidification, this gradient will be negative. This would be the typical situation for the solidification of a casting. During weld solidification, however, this gradient is normally positive since the weld pool is superheated by the welding heat source.

$$G_L = dT_L / dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where:

dT_L: temperature field of liquid

dx: (S-L) interface line.

3-Solidification Growth Rate (R): Is dictated by how fast the S–L interface is moving during the solidification process

$$R = dx/dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Where:

dx: (S-L) interface line

dt: time (s, Min, h)

4- Cooling Rate: Is dictated by coupling solidification Liquid Temperature Gradient (G_L) with solidification growth rate (R) at the S–L interface. So, the local cooling rate at the S–L interface can be determined by the following equation:

$$G_L.R = \frac{dTL}{dx} . \frac{dx}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

$$G_L.R = \frac{dTL}{dt} \quad \ldots\ldots\ldots\ldots (3.4)$$

Where:

$G_L.R$: cooling rate (T/(*s*, *Min*, *h*))

($G_L \cdot R$) has an influence on the dimensions of the solidification sub-structure (بنية), such as dendrite arm spacing.

3.a.4 Weld Solidification Nucleation

The solidification process begins with nucleation solid within the liquid phase. This can occur either homogeneously or heterogeneously when a nucleating particle (such as solid of critical, or threshold) or solid substrate (ركيزه صلبه) is present, Figure (3.6).

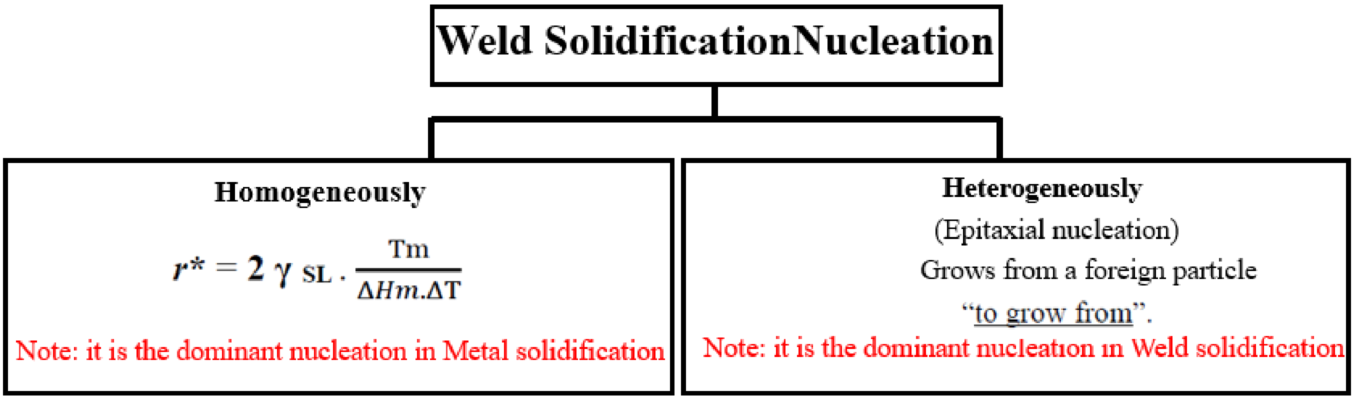


Figure 3.6: Weld solidification nucleation.

Homogeneous nucleation requires that solid of a critical (نقطه حرجه لصلب ما), or threshold (نقطة بدايه, عتبه, مستهل) size form within the liquid.

The size of this spherical nucleant can be defined by a critical radius size (r^*).

$$r^* = 2\,\gamma_{SL} \cdot \frac{T_m}{\Delta H_m . \Delta T} \quad ....3.5$$

γ_{SL}: S–L interfacial energy (الطاقه البينيه)

Tm: melting temperature

ΔH_M: latent heat of melting (الحراره الكامنه للذوبان)

ΔT: amount of liquid undercooling

Note that as the amount of undercooling increases, the critical radius size decreases. Solid spheres less than r^* will simply re-melt, while those exceeding r^* will grow.

Heterogeneous nucleation (Epitaxial nucleation), during metal solidification, homogeneous nucleation is the dominant, and heterogeneous nucleation may accompany homogeneous nucleation or not. While in case of weld solidification, heterogeneous nucleation is the dominant form of nucleation.

Heterogeneous nucleation is also called ‘Epitaxial nucleation’, which means “To grow from”. Epitaxial nucleation grows from a foreign particle (such as an oxide, nitride, sulphide, etc.) or an existing solid substrate. The foreign particles form as heterogeneous sites which are stable at or above the melting temperature of the alloy, so a little or no undercooling is required for nucleation process to occur. Heterogeneous sites which possible to could act as a nucleation site in the liquid during weld solidification are different, they possible to be grown from:

a-Formation tips of dendrites at the solidification front, or tips of grains around solid metal in the liquid during convective fluid flow. So, they are subjected to be detached by sweeping into the liquid leading to form a heterogeneous site depending on the liquid undercooling and size of the detached solid species.

b-Higher melting point particles added to or formed within the liquid can also serve as nucleation sites. Sometimes called inoculants (لقاحات), these particles can substitute for the homogeneous nuclei. This type of nucleation can occur on the surface of the liquid, particularly if an oxide surface layer forms. In some cases, it may be possible to add nucleons (نويات) directly to the molten pool, but this is usually not practical.

c-The use of "seed crystals" in the liquid of metals which demands crystal growth applications is a form of epitaxial nucleation. For example, single-crystal Ni-base turbine blades are manufactured using a "seed" crystal of a given orientation as a heterogeneous nucleation site. Epitaxial nucleation requires no undercooling or other driving forces. As a result, solidification begins immediately upon cooling below the liquids temperature.

3.a.5 Mechanism of Heterogeneous Weld Solidification.

Figure (3.7) presents main profile for how the mechanism of weld solidification works heterogeneously.

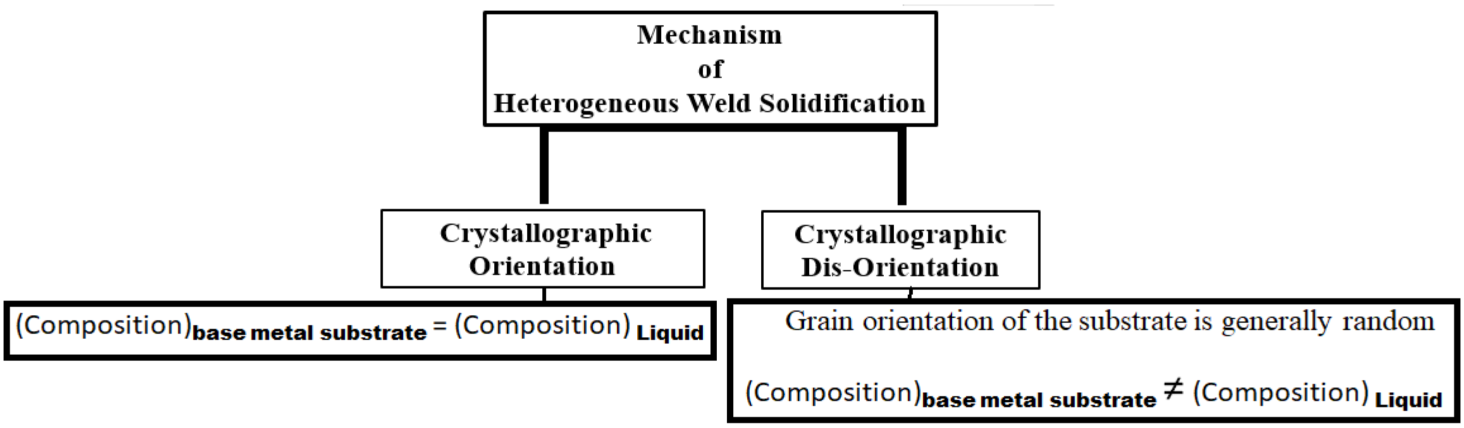


Figure 3.7: Main profile for heterogeneous weld solidification.

When the compositions of the base metal substrate (ركيزه – او نقطة نشوء التجمد) and liquid are similar, the solidification front that grows from a given grain on that substrate will retain the same crystallographic orientation. Since grain orientation of the substrate is generally random, this results in a continuation of the crystallographic disorientation of the base metal grains across the fusion boundary into the solidifying solid, as illustrated in Figure 3.8. That is to say, grain boundaries are continuous across the original fusion boundary where epitaxial nucleation occurred.

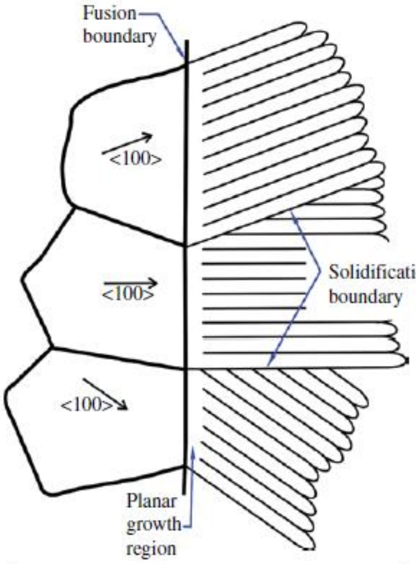


Figure 3.8: Schematic illustration of epitaxial nucleation.

3.a.6 Solidification Modes of Welds.

The solidification modes describe the different morphological (علم الشكليات) forms that can exist at the S–L interface. Stability of the solidification modes are dictated by the combined effect of liquid temperature gradient (GL), solidification growth rate (R) and composition. Multiple solidification modes can occur in metals and welds, Figure (3.9), such as:

-Planar Growth (plane front solidification**) (التجمد مستوي السطح)**: it occurs under conditions of low solidification rates, steep temperature gradients, or both. In actual practice, a planar solidification mode is normally not stable, it can be maintained at very slow growth rates in pure materials only.

- **Cellular Growth:** observed in fusion welds

D**endritic Growth**: observed in fusion welds, it is shaped with more complex morphologies than cellular. Its modes have different profiles like:

- Cellular dendritic mode (نموذج شجيري خلوي)
- Columnar dendritic mode (نموذج شجيري متالف من اعمده).
- Equi-axed dendritic mode (نموذج شجيري متساوي المحاور): not normally observed in fusion welds due to the large constitutional super-cooling required (الحاجه الى عدد كبير من الركائز الصلبه لبداية التجمد المتساوي المحاور).

Most welds solidify in either cellular, cellular dendritic, columnar dendritic, or a combination of these. However, other types of modes are still apparent when cooled to room temperature in many cases such as:

Primary Dendrite Arm Spacing (PDAS),

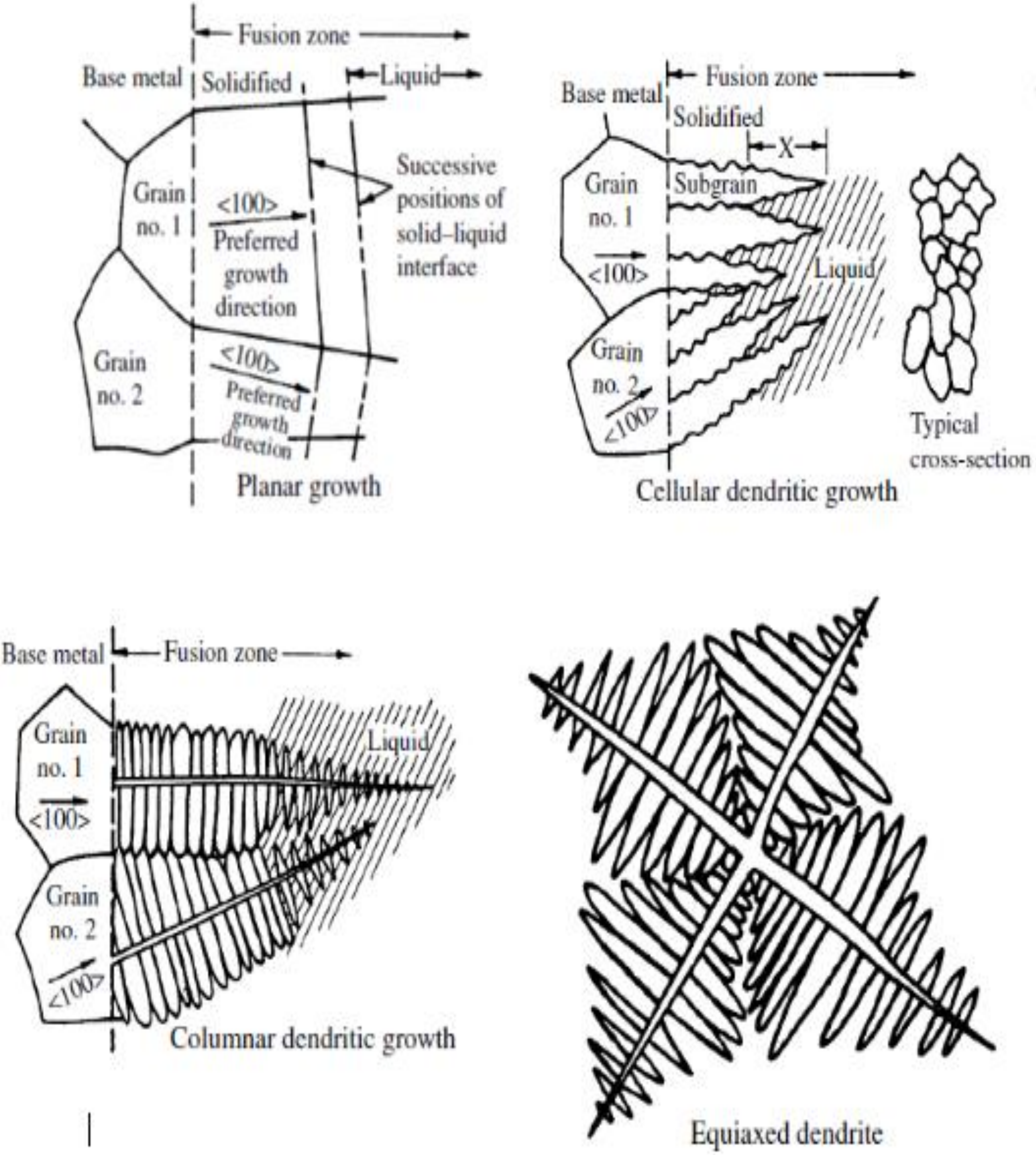
Secondary Dendrite Arm Spacing (SDAS),

The importance of knowing how these terms (PDAS) and (SDAS) are measured promotes identification the final shape of the solidified structure, whether it is very fine structure, low growth rate (LGR), Or high growth rate (HGR).

Quantification the structural aspects of solidification welds same as in castings. It is normally determined by measuring the distance between the axial centres of the cells or dendrites, sometimes called the cell or dendrite core.

This distance may range from several millimetres in very large castings to a few microns in laser or electron beam welds.

So, the terms (PDAS) and (SDAS) are often used to define the size or scale of solidification substructure size that form with high cooling rates (high values of $G\mathrm{L}\cdot\mathrm{R}$) promoting very fine structures.


Planar growth

Cellular dendritic growth

Columnar dendritic growth

Equiaxed dendrite

Figure 3.9: Different modes of weld solidification.

3.a.6.1Factors Influencing Formation of Solidification Modes.

a- Effect of Cooling Rate Parameters,

(temperature gradient, *G*L, and solidification growth rate, *R*).

The combination effect of temperature gradient, *G*L, and solidification growth rate, *R*, on solidification mode in weld region is described in the relationship shown in the Figure (3.10).

When the temperature gradient is high with increase solidification rate, the solidification mode shifts to **cellular and then dendritic**. The combination effect of increasing temperature gradient, *G*L, and solidification growth rate, *R*, on solidification mode results in an increase in cooling rate (G_L.R), so the structures that form become finer. This results in cellular or dendritic structures. This is mostly common in welds. For example, formation (PDAS) or (SDAS). When the temperature gradient is high and the solidification rate is very low, a **planar growth mode** is formed. This exists in pure metals or casting only. When the temperature gradient decreases to minimum value (extremely low), with increase solidification rate, **Equi-axed dendritic growth** is possible to form. This does not exist in fusion welds.

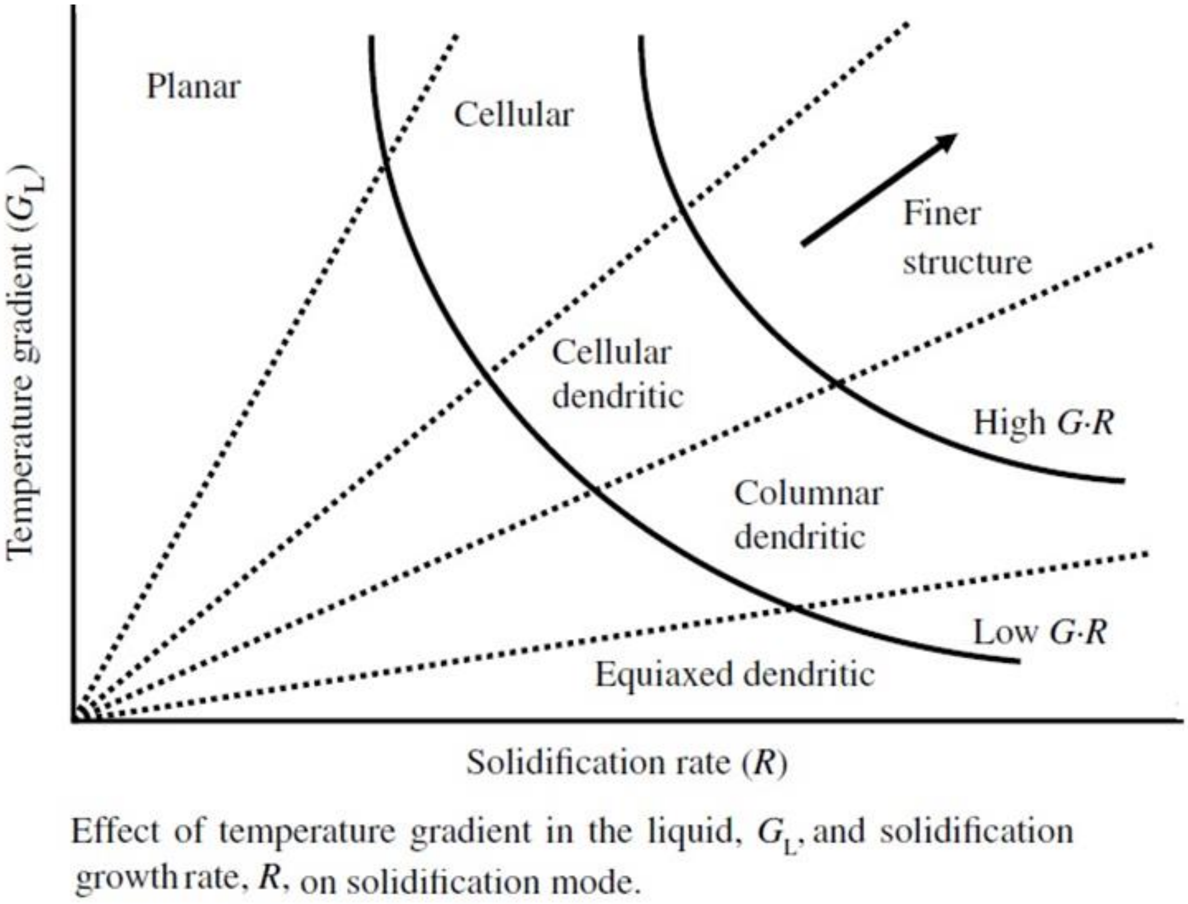
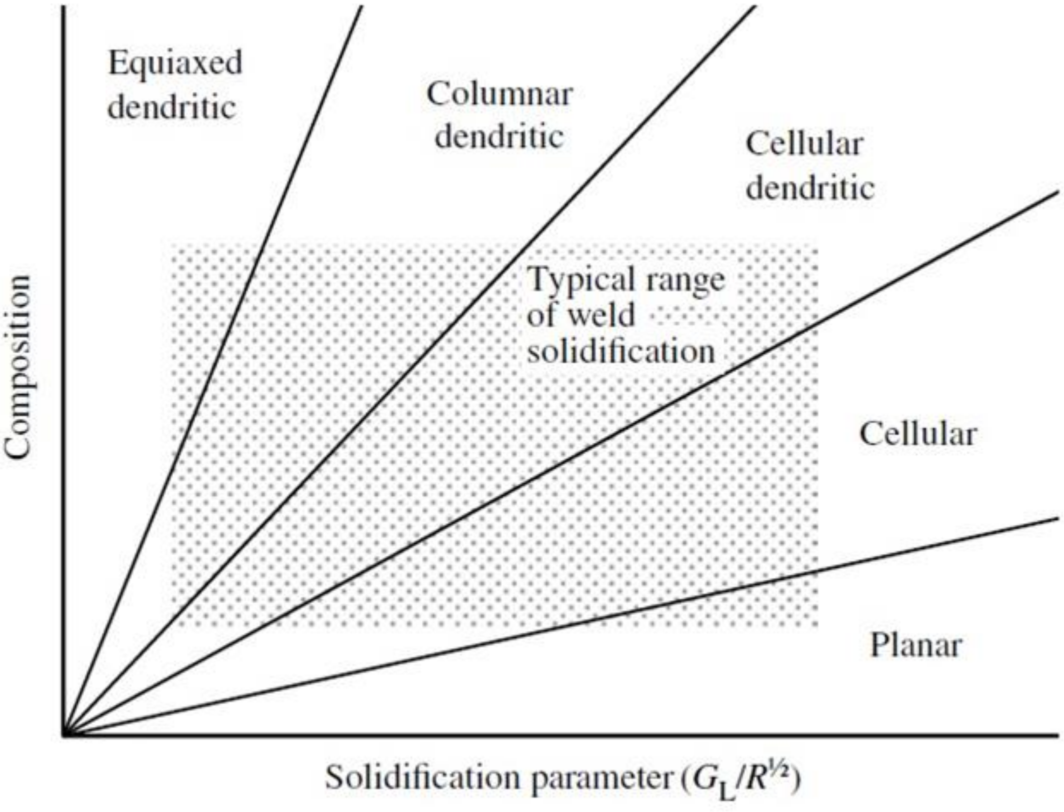


Figure3.10: The combination effect of temperature gradient, *G*L, and solidification growth rate, *R*, on solidification mode in weld region.

b-Effect of Composition

Figure (3.11) shows the relationship between weld's compositions and weld solidification parameters. Solidification parameters of welds represent the local cooling rate at the S–L interface during transformation stages from liquid to solid.

With increasing composition and cooling rate parameters, most welds subject to dendritic or cellular modes during solidification, as illustrated by the shaded region in the diagram. With decrease composition (welds made from joining pure metal) and increasing cooling rates parameters, the welds subject to planar solidification. So, adding some solutes or impurity elements is favoured in this situation to be as an initiation point for starting nucleation stage to solidify. This situation exists only in castings, not in welds. With increase composition and decrease cooling rates, equi-axed dendritic growth during solidification will be formed, this is because the temperature gradient of the liquid is very shallow (واضح وبارز). A condition that usually does not exist in fusion welds.



Effect of composition and solidification parameter on solidification mode

Figure 3.11: Effect of composition and solidification parameter on solidification mode.

3.a.7 Interface Stability

Most practical situations of solidification welds are either a cellular or dendritic modes. Some theories attribute this phenomenon to occurrence solute re-distribution at the S–L interface during alloy solidification which lead to transformation the planar growth solidification (ideal situation) to either cellular or dendritic solidification.

The constitutional super-cooling theory proposed by Chalmers involves an effective undercooling of the liquid at the S–L interface that promotes planar interface instability. The constitutional super- cooling theory of Chalmers is based upon the premise أفتراض that solute partitioning occurs in advance of the S–L interface. Assuming a plane front, a solute gradient exists perpendicular to the front to a certain distance into the liquid. Figure (3.12) describes easily the concept of constitutional super-cooling that leads to the breakdown of a planar solidification front to either dendritic or cellular.

Assuming the solute profile in advance of the S–L interface (for $k<1$), an effective temperature profile can be constructed that *increases* as a function of distance from the interface. This is **an *effective* temperature profile** since an actual temperature gradient exists in the liquid that has previously been defined as GL.

- If the actual gradient (*G*actual) is less than the slope of the line tangent to the effective temperature profile at the S–L interface (*G*critical), a region of *constitutional supercooling* will exist and the planar interface will be unstable.

- If the temperature gradient exceeds the slope of the tangent, the planar front is stable. Based on this theory, plane front solidification of alloys is only possible.

- When the temperature gradient (*G*L) is very steep. In fusion welds, this condition is only satisfied at the fusion boundary.

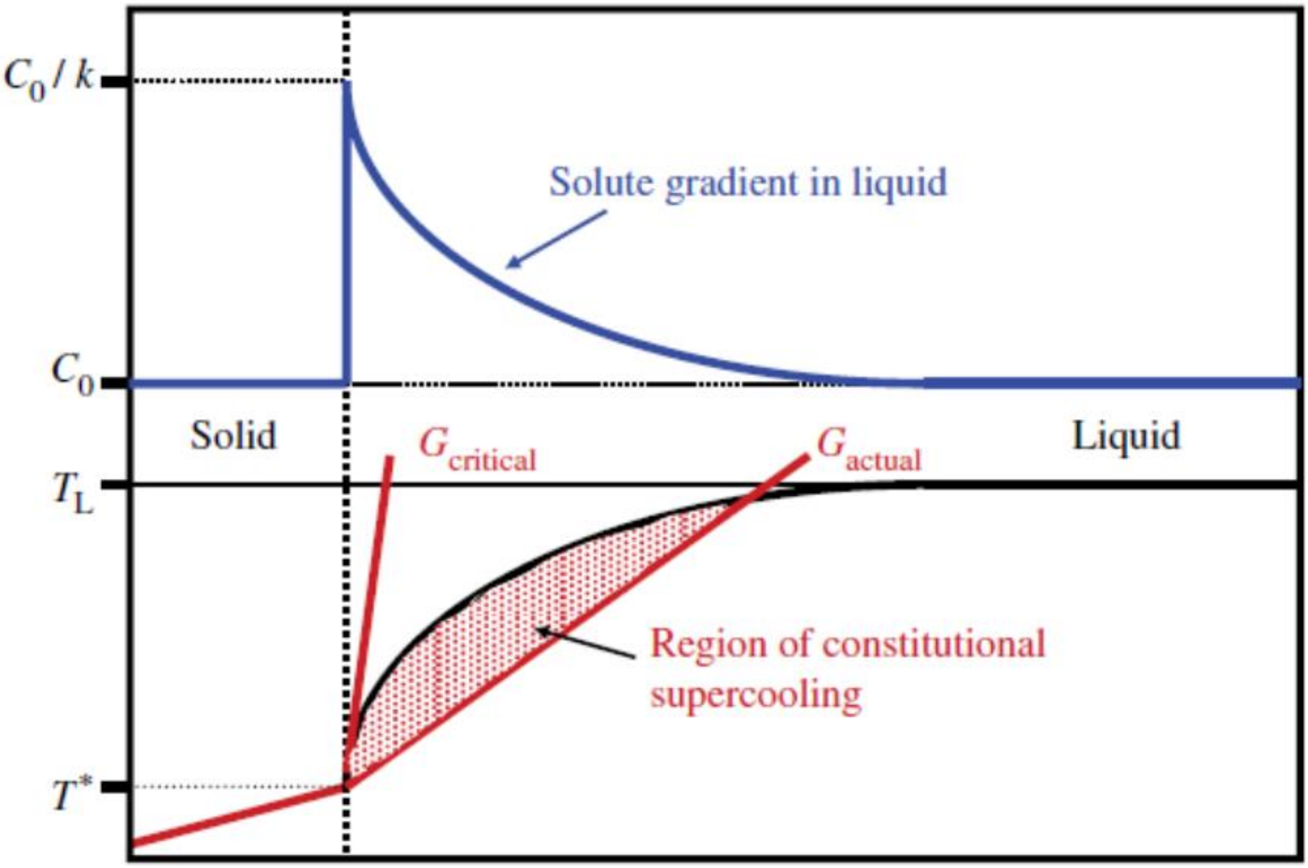


Figure 3.12: Simple schematic of the constitutional super cooling theory for the case of k<1.

3.a.8 Aspects of Weld Solidification

Explain the occurrence of solidification welds under non-equilibrium conditions, the weldment solidification’s aspects in the weld pool region must be studied macroscopically and microscopically. See Figure 3.13.

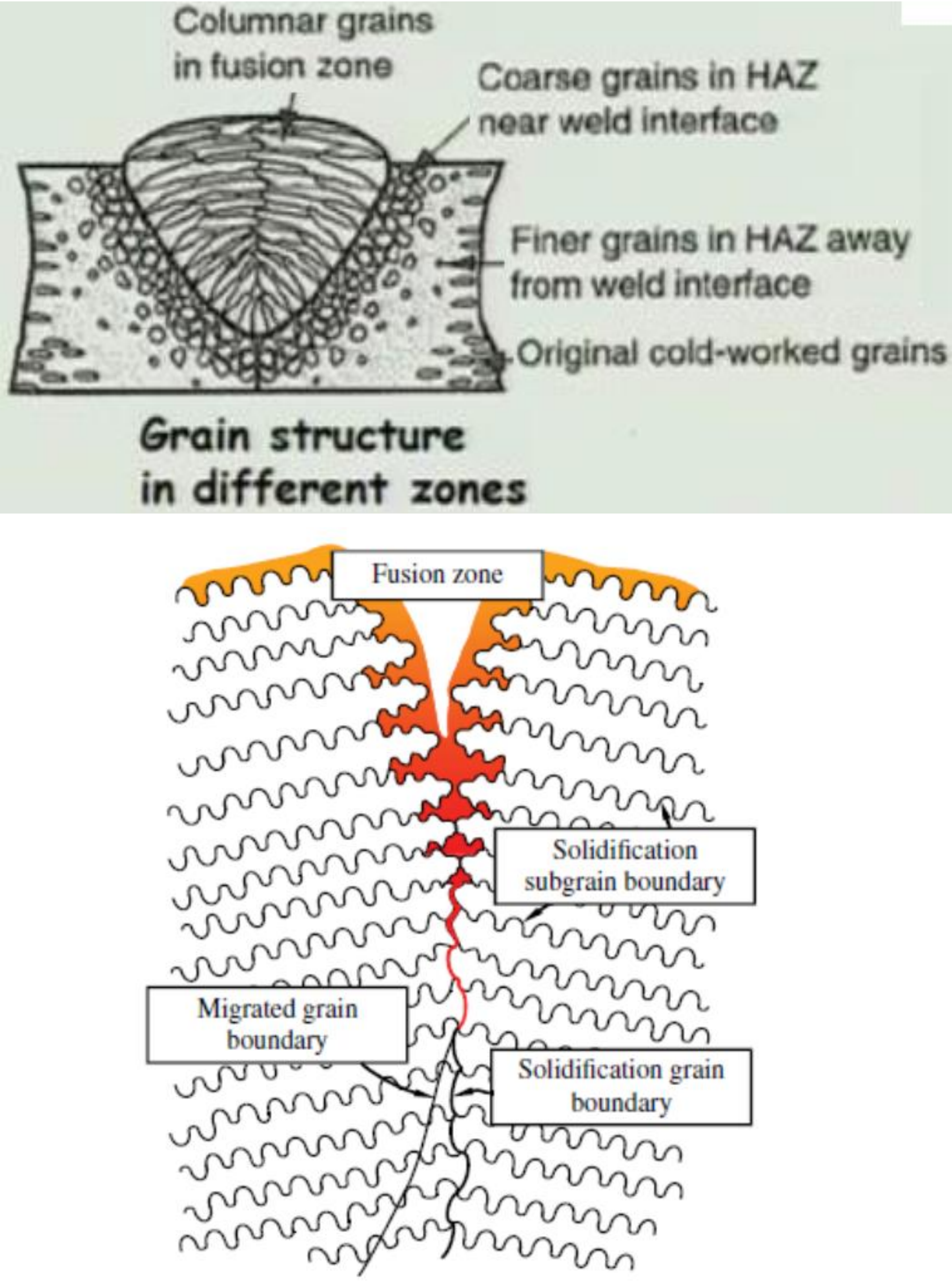


Figure 3.13: Weld pool and grain Boundaries (GB) in weld pool.

3.a.8.1 Macroscopic Aspects of Weld Solidification.

It is defined as the changes in the solidified shape of the weld pool as a function of welding condition and physical properties of the weld material. Leading to formation either cellular or dendritic weld micro-structure observed macroscopically as solidified grain boundaries (SGB), (SSGB), (MGB). See Figure (3.13).

To estimate the solidification procedure in welds macroscopically, it is necessary to:

First- Consider the **solidification front as a plane front** which is usually cellular or dendritic. See Figure 3.14.

أعتبار واجهة التجمد كواجهه مستويه التي عادة ماتكون اما خلويه/مساميه او شجيريه في الملحومات

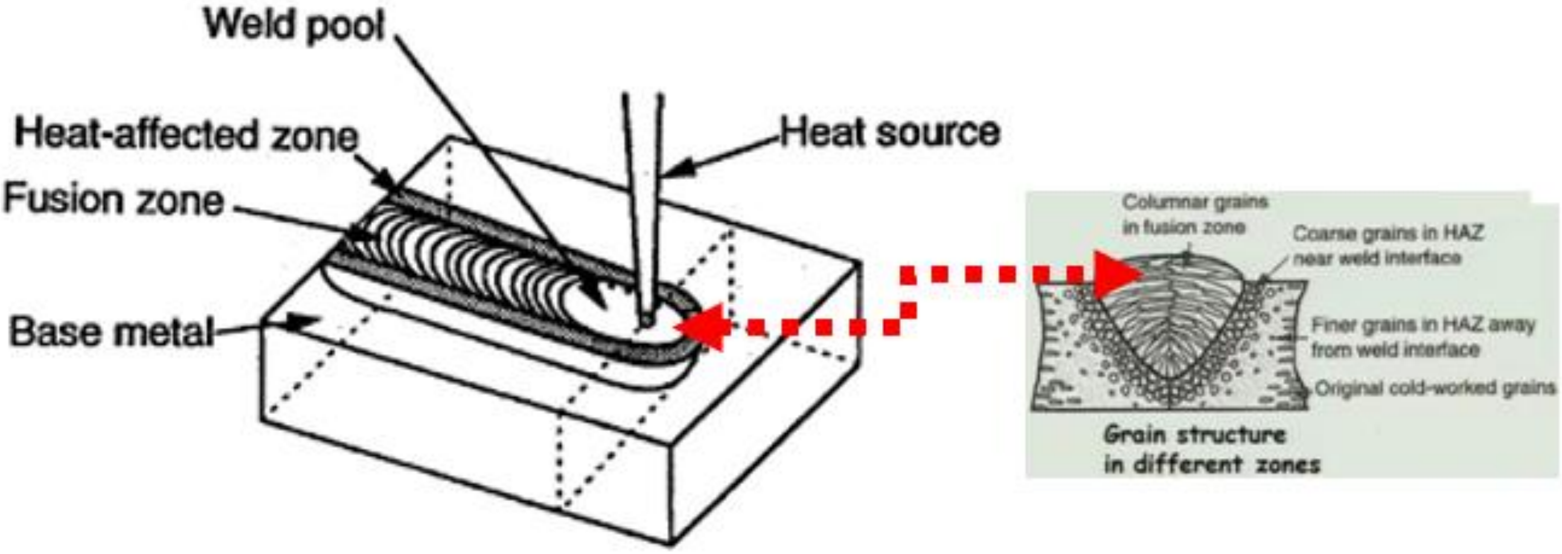


Figure 3.14: Solidification front in welds.

Second- Focus on **the trailing edge** of the weld pool and **along solidification grain boundaries (SGBs).** See Figure 3.15.

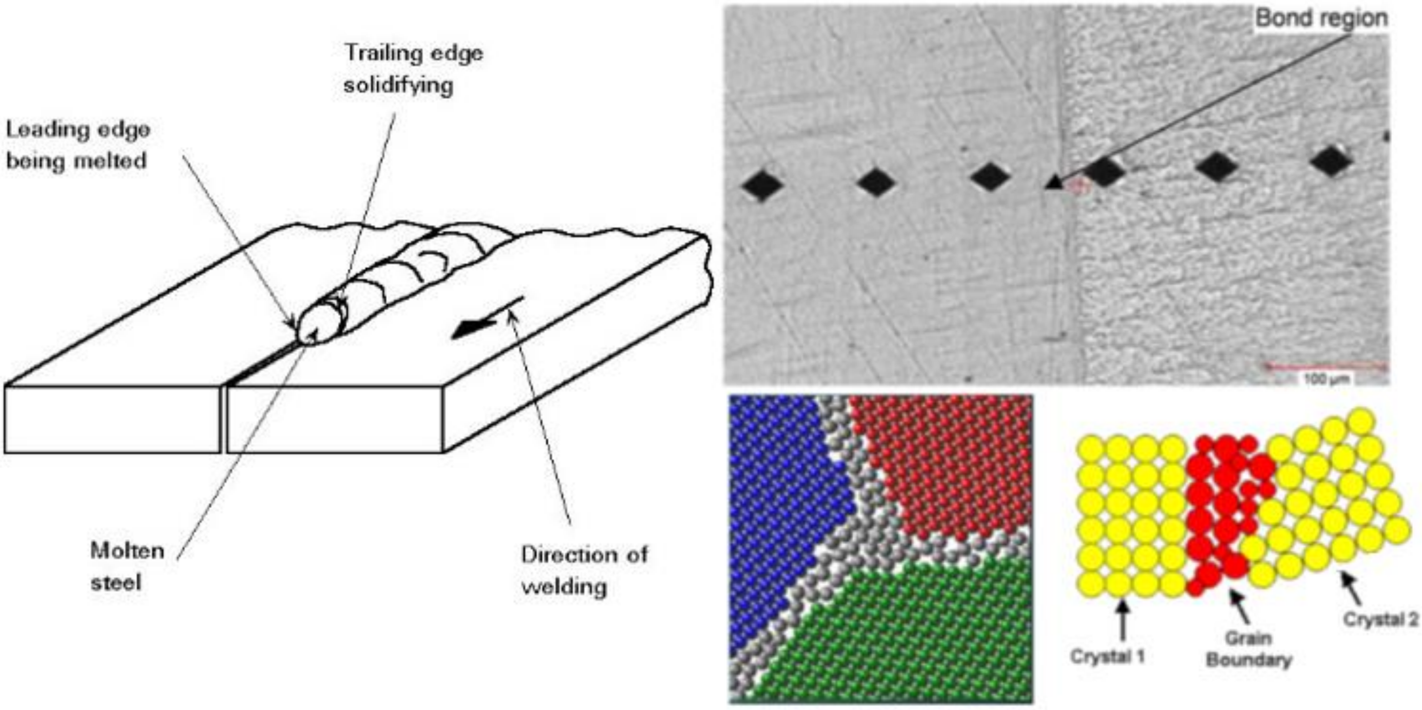


Figure 3.15: Trailing edge and grain boundaries.

Third- Consider the effect of flowing fluid on weld pool, as shown in Figure (3.16).

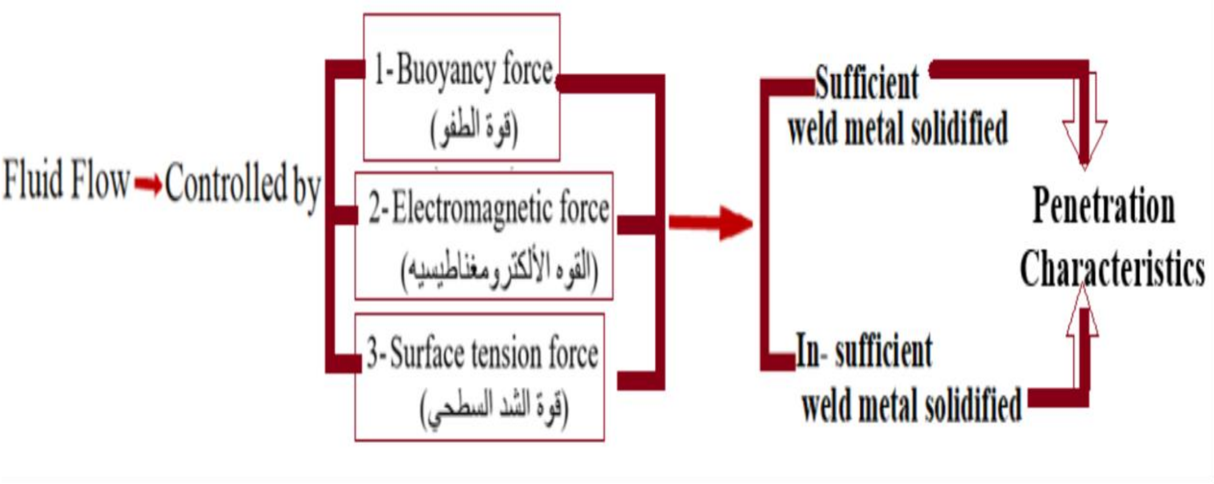


Figure 3.16: the relationship between weld pool and flowing fluid in the weld.

Weld pool is strongly affected by flowing fluid in the weld. This is because fluid flow is controlled by a number of forces which affects positively or negatively on the penetration characteristics of welds leading to either sufficient or in-sufficient amount of weld metal solidified. These forces are buoyancy force (قوة الطفو), electromagnetic force (القوه الألكترومغناطيسيه), and surface tension force (قوة الشد السطحي).

Surface tension Force is the more dominated force in some cases, resulting in significant heat-to-heat variations in weld pool shape and penetration characteristics as shown in Figure (3.17). This is because in systems where surface tension decreases as temperature increases, the hot fluid under the arc flows along the surface to the periphery of the weld and causes melting at the weld edge, or toe providing bad penetration.

في الأنظمه التي يحدث فيها نقصان لظاهرة الشد السطحي بزيادة درجة الحراره, فأن المائع الساخن تحت تأثير القوس الحراري ينساب على طول السطح الى محيط الملحومه مسببا ذوبان حافات الملحومه او نتوءاتها منتجا تغلغل غير كفوء لمادة اللحام التي يراد تبريدها فيما بعد. أي أن التغلغل لكمية المعدن السائل تكون قليلة العمق مما ينتج لحام ضعيف الخواص. لاحظ الشكل ادناه.

While, in systems where surface tension increases as temperature increases, the hot fluid under the arc has a strongly downward flow at the root of the weld providing best weld penetration.

في الأنظمه التي يحدث فيها زياده لظاهرة الشد السطحي بزيادة درجة الحراره, فأن المائع الساخن تحت تأثير القوس الحراري ينزل بقوه بأتجاه جذر الملحومه بعيدا عن حافات الملحومه او نتوءاتها منتجا شد قوي للحافات و تغلغل كفوء

لمادة اللحام في منطقة الجذر. أي أن التغلغل لكمية المعدن السائل تكون كافية العمق بالشكل الذي يخدم الملحوما منتجا خواص لحام جيده او مقبوله .

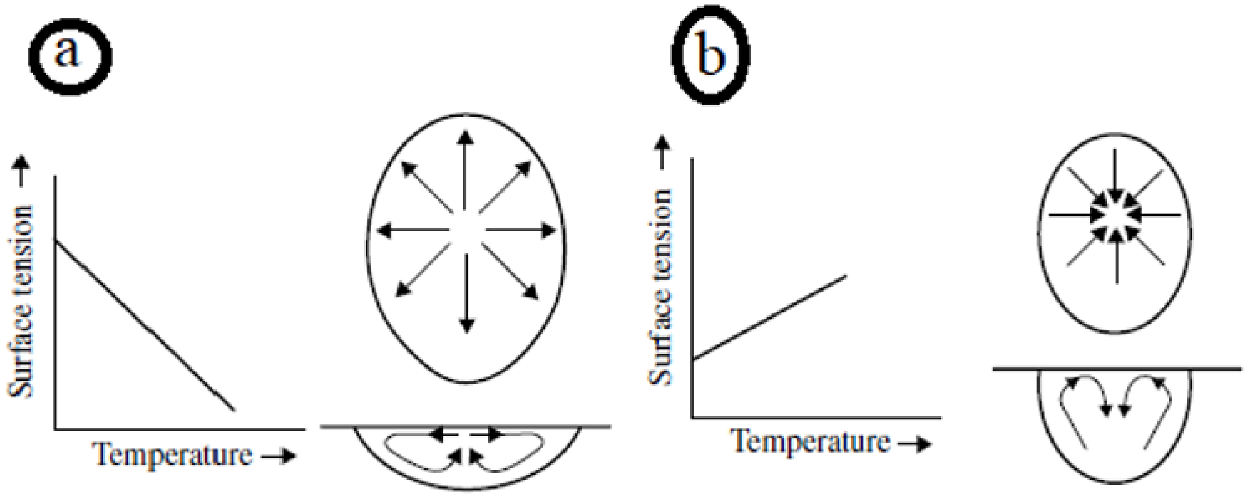


Figure 3.17: Surface tension force and penetration characteristics relationship in welds.

However, small changes in composition can promote large changes in penetration due to the so-called "Marangoni", as shown in Figure (3.18).

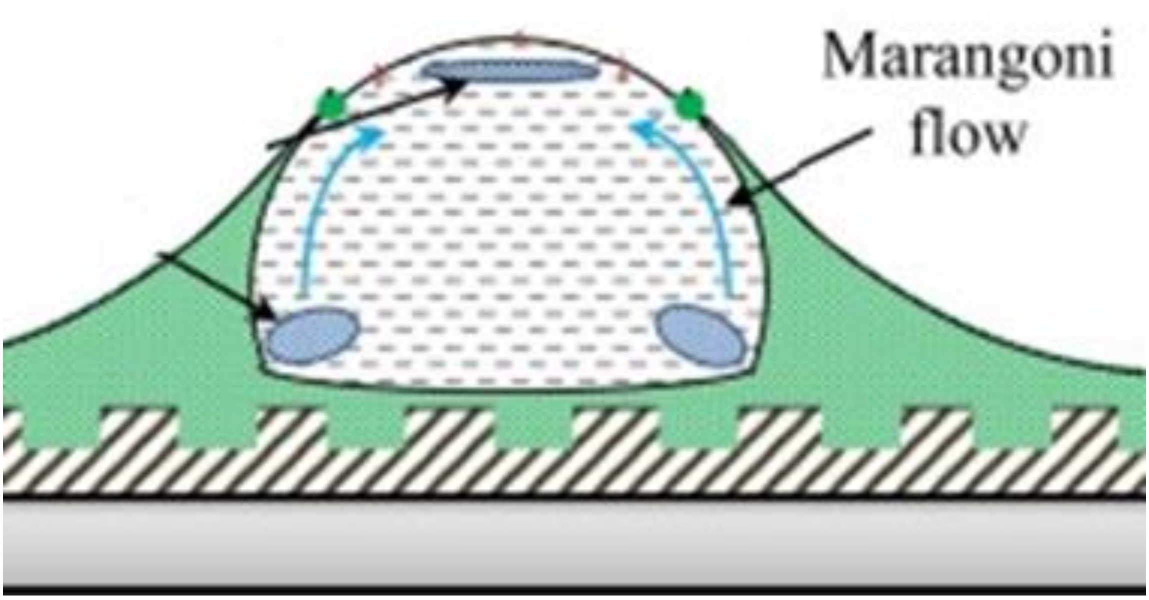


Figure 3.18: Marangoni mechanism.

Fourth- Consider the effect of welding conditions on weld pool shape, as in the example shown in Figure (3.19). This is because weld pool shapes are necessary to determine weldment properties.

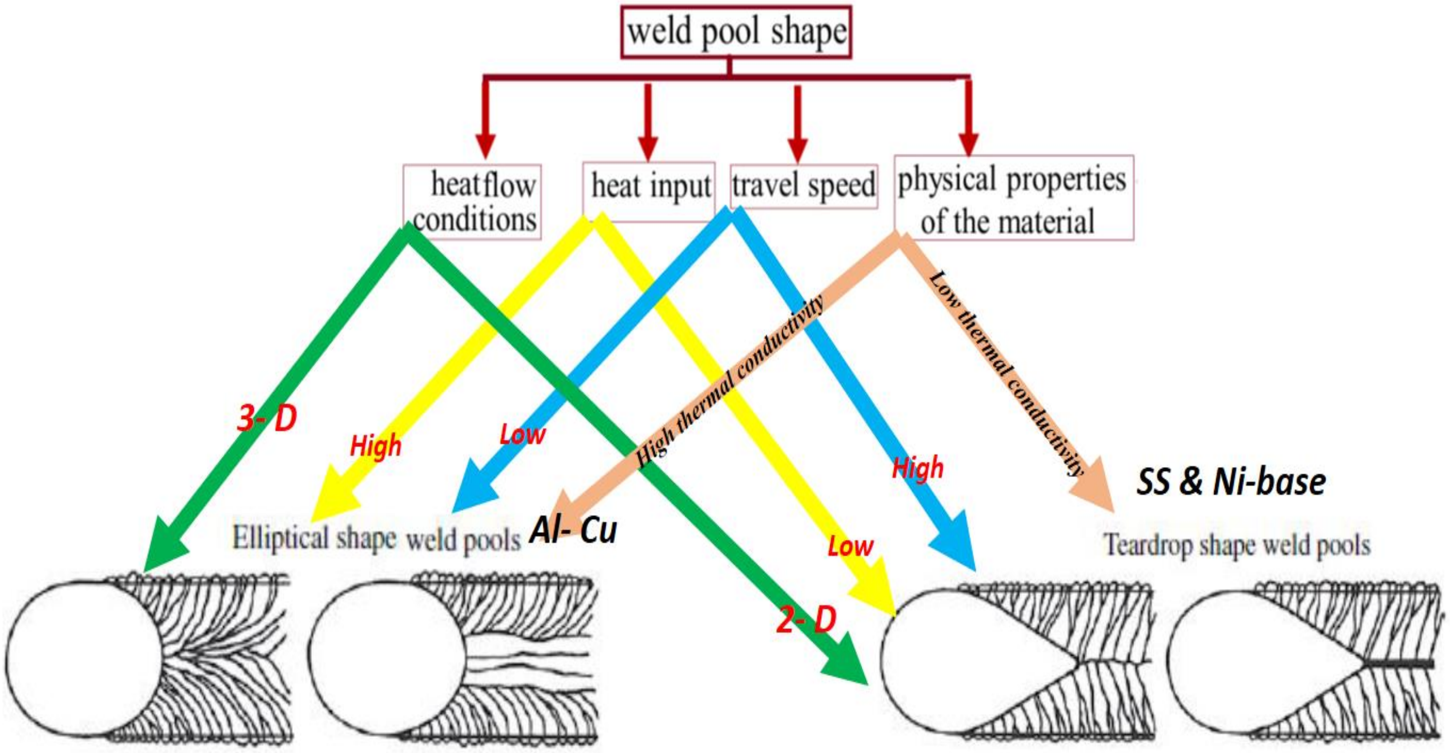


Figure 3.19: Effect of welding conditions on weld pool.

Weld pool shape is strongly affected by welding conditions, such as heat flow conditions, heat input, travel speed, physical properties of the material. Elliptical pool shapes (بركة بيضاوية الأشكال) are usually associated with high heat input, low travel speeds, and 3-D heat flow conditions. Materials with high thermal conductivity, such as aluminum and copper, form elliptical weld pools over a wide range of conditions.

Teardrop pool shapes (بركة دمعيةالأشكال) are most favored when travel speeds are rapid or high, thermal conductivity is low, and heat flow is 2-D. For example, austenitic stainless steels and nickel-base alloys often exhibit teardrop shape pools when welded in thin-sheet form at high travel speeds. Figure 3.20 presents magnified sketches for weld pool shapes.

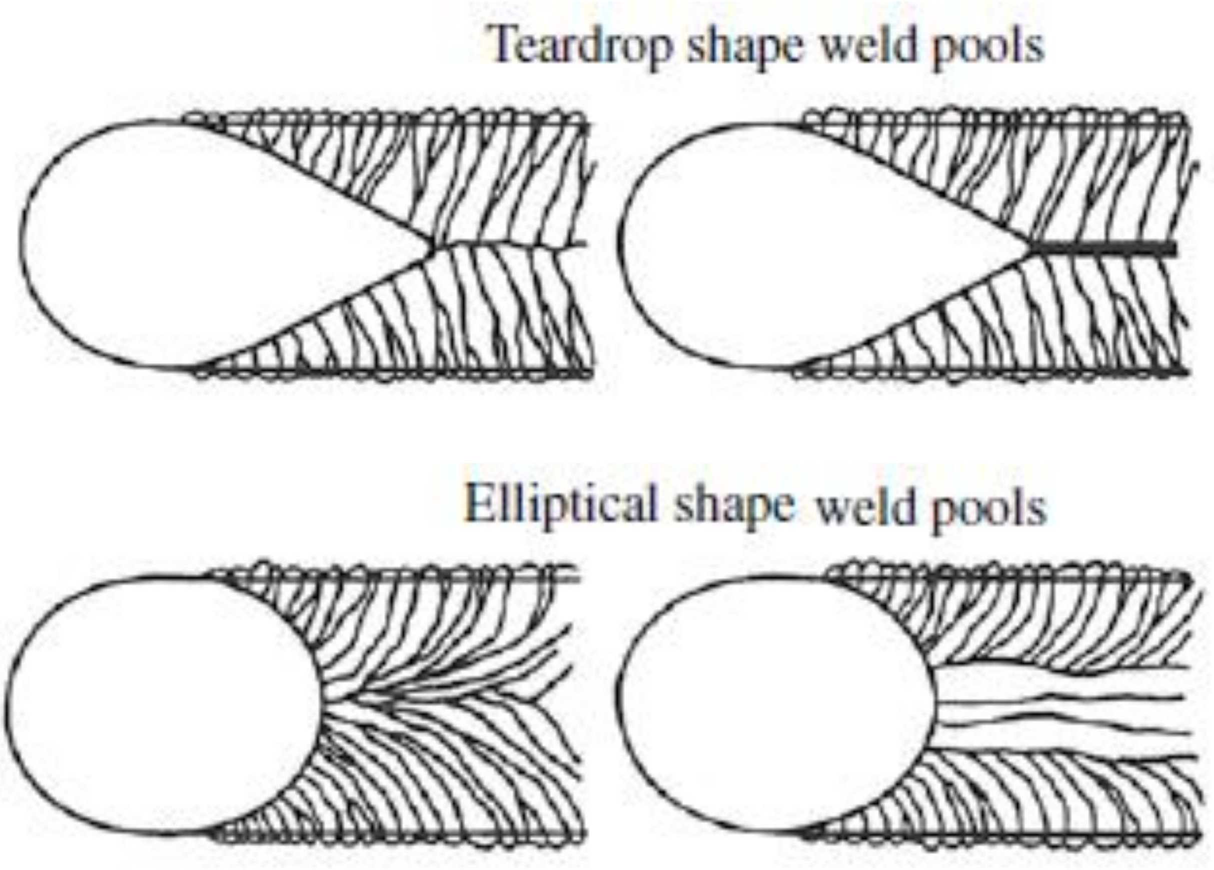


Figure 3.20: Magnified sketches for weld pool shapes.

3.a.8.1.1 Effect of Travel Speed and Temperature Gradient on Weld Pool Shape.

Weld pool shape is usually controlled by adjusting travel speed for welds. This is because travel speed possible causes transformation weld pool shape from elliptical to teardrop and vice versa depending on the thermal conductivity properties of the material need to weld. For example, the weld pool with materials of low thermal conductivity difficulty losses heat while solidifying making the weld pool tends to elongate, Figure 3.21.

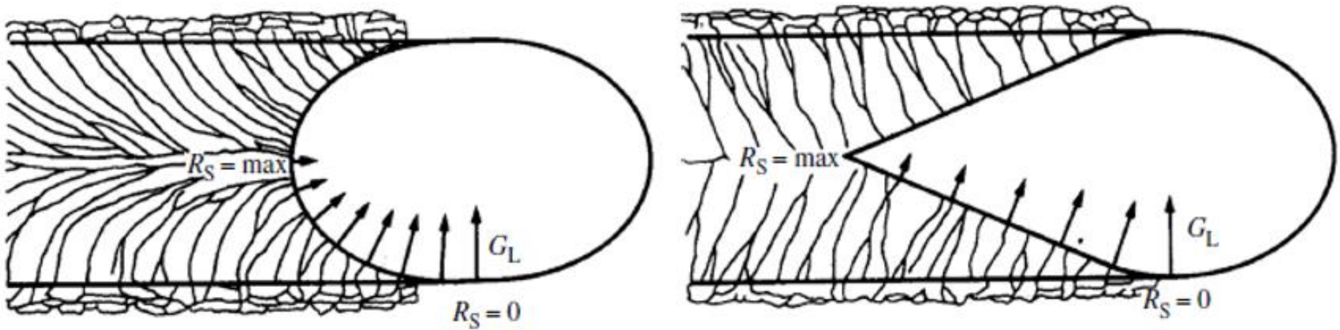


Figure 3.21: Transformation direction for weld pool shape from elliptical to teardrops.

The mechanism of elongation at this point is attributed to the angular relationship between the direction of weld travel speed and heat flow at the S–L interface relative to the fusion boundary. See Figure (3.22).

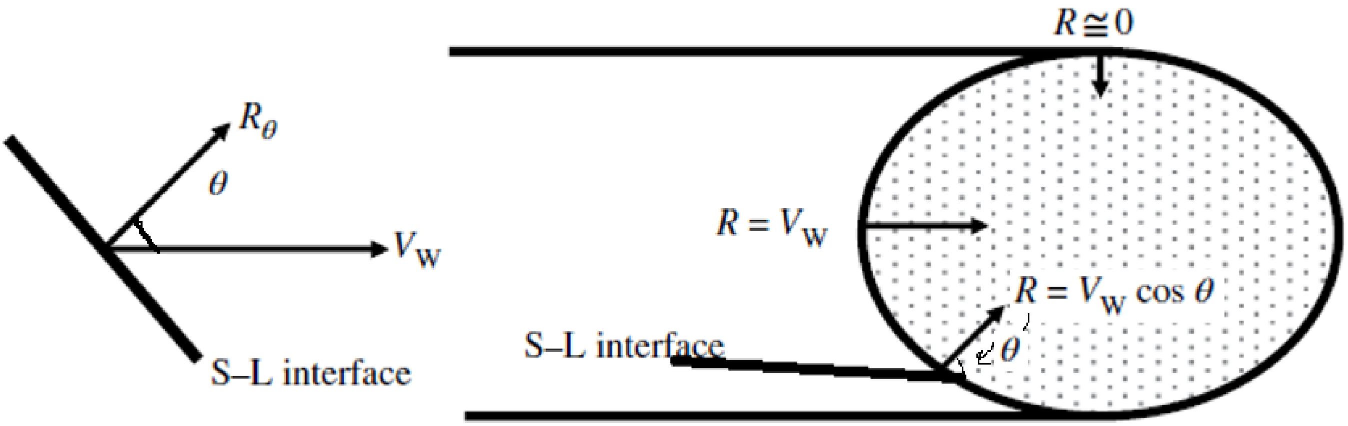


Figure 3.22: Travel speed and Elongation mechanism.

This relationship gradually changes from perpendicular in-case of elliptical weld pool shape to parallel upon moving toward the centerline. This results in considerable competitive growth along the solidification front. The formed shapes of weld solidified structure are always either a cellular or dendritic shapes, as shown in Figure 3.23.

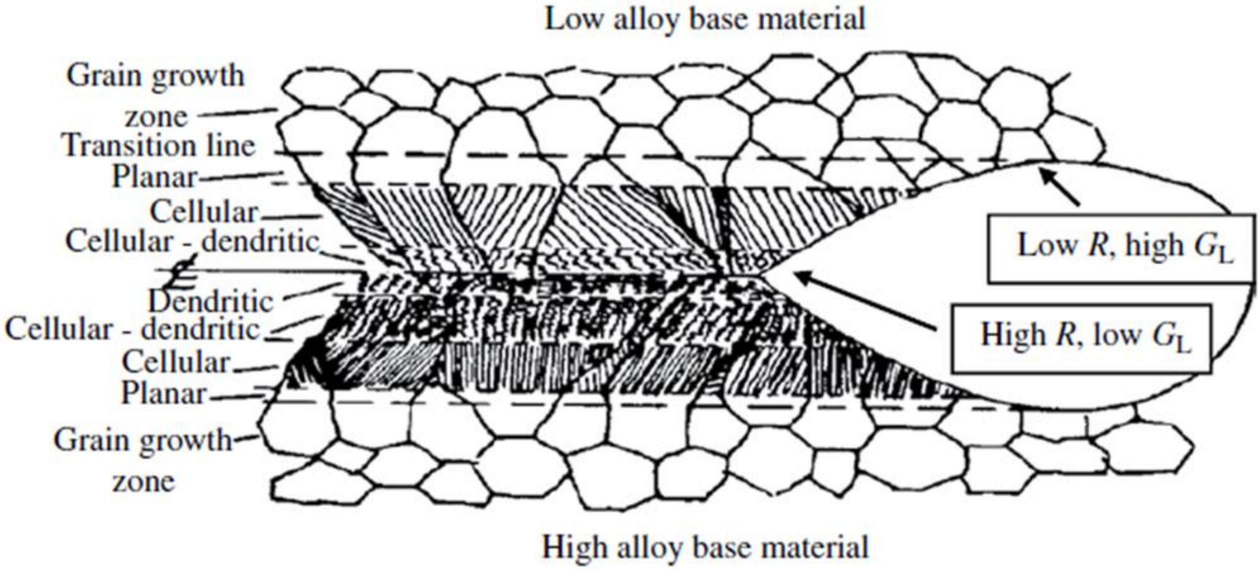


Figure 3.23: The formed shapes of weld solidified structure are always either a cellular or dendritic shapes.

This is because at the fusion boundary, (*G*L) is the steepest or higher of anywhere along the S–L interface since heat flow into the surrounding base metal is most efficient at this point, while (R) is very low since the angular relationship is ~90°, that means perpendicular to each other leading to formation a planar solidification front (Compare Figure 3.23 with 3.10).

However, after crossing short distance from the fusion boundary, the planar front converts to cellular and dendritic modes because of combination effect of a decrease in *G*L and an increase in *R* (Compare Figure 3.23 with 3.10). So, it is concluded that travel speed during welding and (*R*) rate are always equivalent at the weld centerline, which progressively decreases upon moving along the S–L interface toward the fusion boundary due to high GL.

3.a.8.1.2 Macroscopic Mechanism of weld solidification (producing solidified grain boundaries).

From a solute re-distribution standpoint, nucleation in fusion welds is dominated by epitaxial growth from the surrounding base metal. The thermodynamic driving force required for epitaxial nucleation is very low, and essentially, no undercooling is required for nucleation to occur, Figure 3.24.

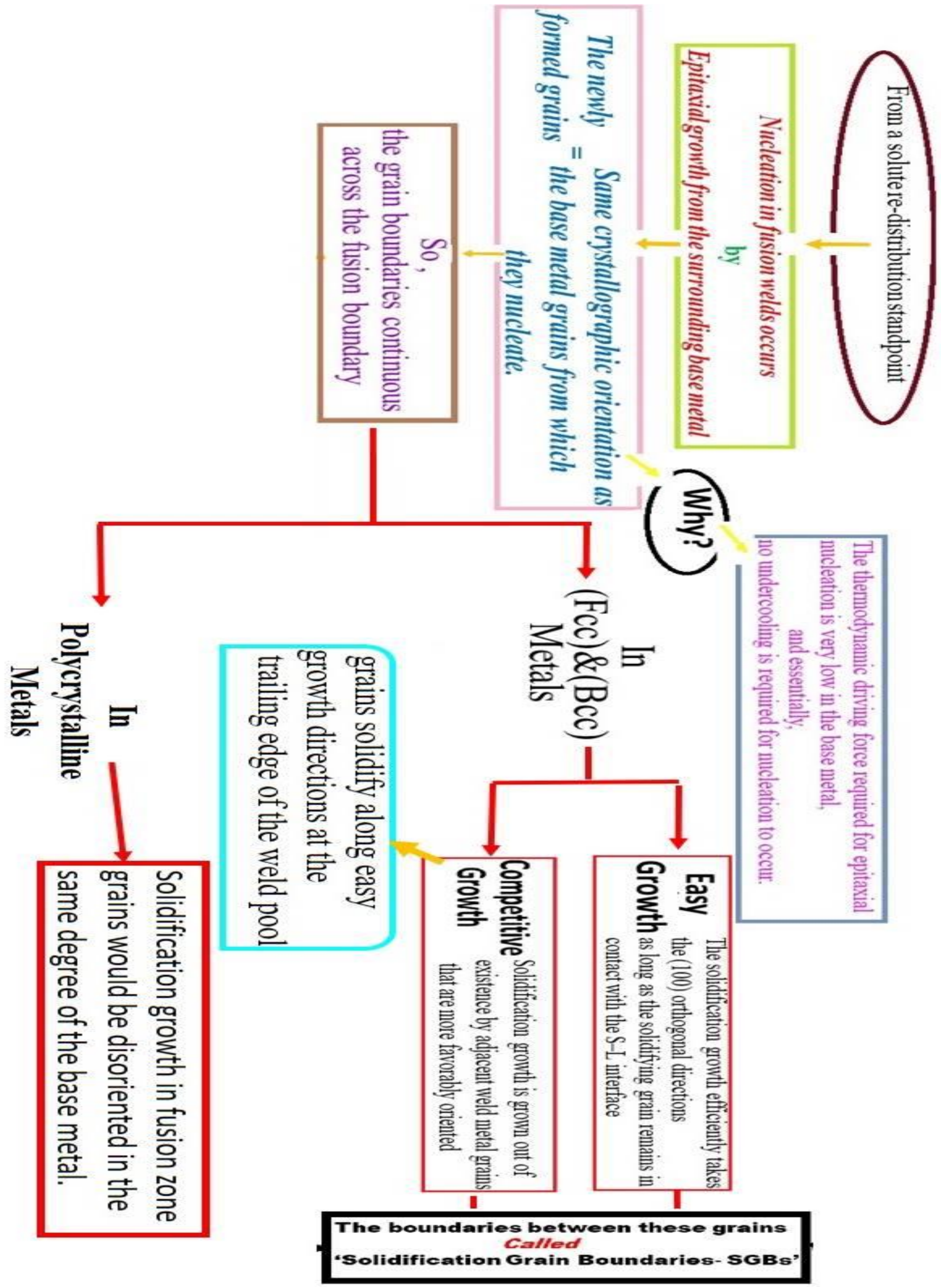


Figure3.24: A sketch shows the mechanism of continuing growing grain boundaries (GB) in fusion welds across the fusion boundary.

The newly formed grains maintain the same crystallographic orientation as the base metal grains from which they nucleate. As a result, grain boundaries are continuous across the fusion boundary.

التخليق في الملحومات المنصهره ينشأ في الغالب من المعدن الأساس المحيط بالملحومه المنصهره. القوه الدافعه الحراريه الحركيه المطلوبه للتخليق الغير متجانس جدا واطئه وجوهريا الأفراط في التبريد غير مطلوب لكي يحدث التخليق. الحبيبات المتشكله الجديده تأخذ نفس أتجاه أو ترتيب ألأتجاه البلوري لحبيبات المعدن الأساس التي حدث التخليق منه. نتيجة لهذا, حدود الحبيبات مستمره عبرحدود الأنصهار.

In fcc and bcc metals, which constitute the bulk of the engineering alloys that are commonly welded, solidification occurs preferentially along the cube edge, or <100> directions. These are sometimes called “easy growth” directions because solidification is most efficient in these orthogonal directions. This growth direction is maintained as long as the solidifying grain remains in contact with the S–L interface or until it is grown out of existence by adjacent weld metal grains that are more favorably oriented. This latter phenomenon is called “competitive” growth.

في المعادن ذات المكعب متمركز الوجه والجسم, والتي تشكل القوام للسبائك الهندسيه والتي هي قابله للحام, التجمد يحدث في افضل حالاته على طول حافة المكعب أوبأتجاهات ≥100≤. وهو مايسمى بالنمو سهل الاتجاهات. لأن النمو متعامد على بعضه البعض مما يزيد من كفائة التجمد. أتجاه النمو يستحصل عليه كلما حافظت الحبه المتجمده على أتصالها مع الخط البيني الفاصل بين الصلب والسائل, أو حتى أن تنمو هذه الحبه المتجمده خارج الموجود عن طريق حبيبات المعدن الملحوم المجاوره او القريبه والتي هي قريبه من اتجاه التجمد.

The boundaries between these grains are defined as ‘Solidification grain boundaries- SGBs’. The concepts of epitaxial nucleation and competitive growth are illustrated in Figure 3.25.

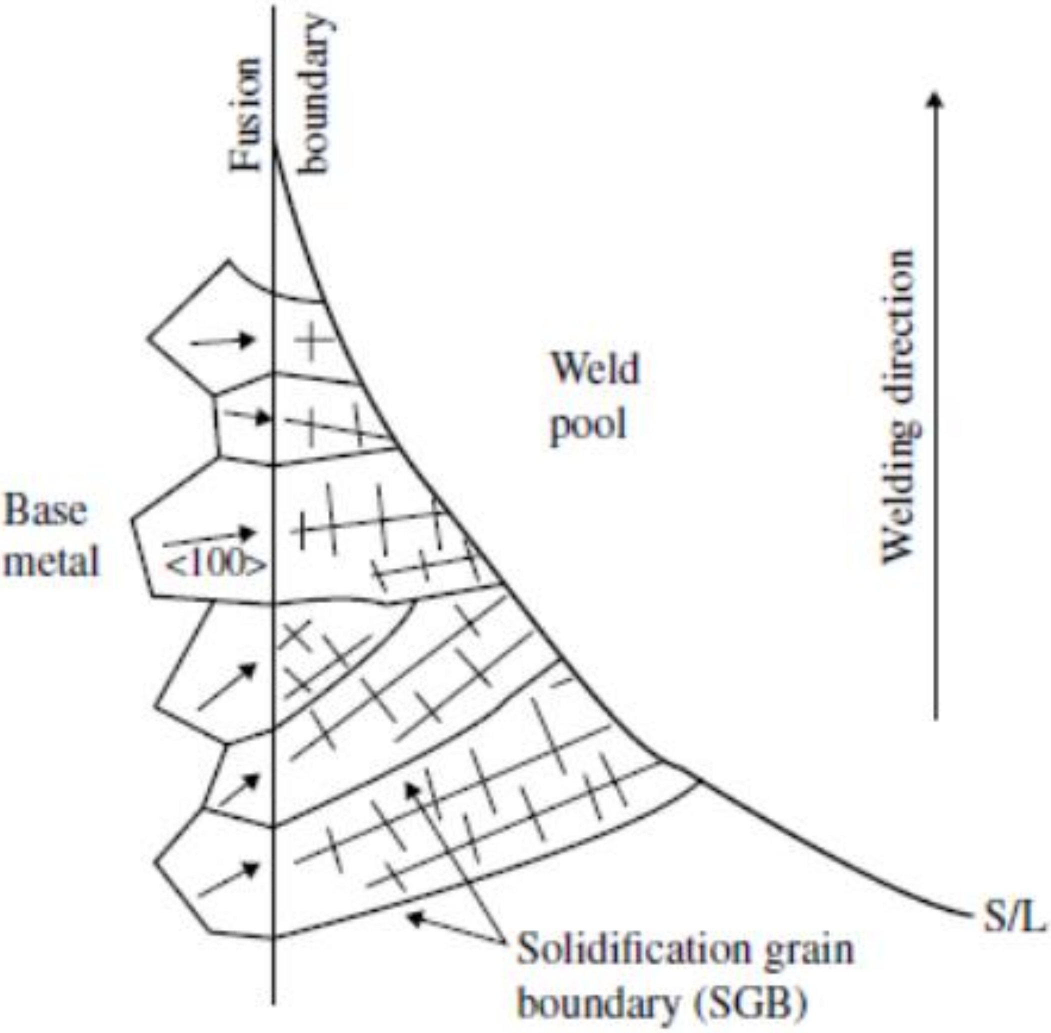


Figure 3.25: The macroscopic concepts of epitaxial nucleation and competitive growth for welds.

Because of epitaxial nucleation and growth grains solidify along easy growth directions at the trailing edge of the weld pool.

خلال تجمد الملحومات, وبسبب ظاهرة التخليق والنمو المتواليه, الحبيبات تتجمد على طول اتجاهات النمو السهل عند الحافه الخلفيه لبركة اللحام.

Base metal grains in polycrystalline metals are normally randomly oriented, and the resulting fusion zone grains will adopt the same degree of mis-orientation. Growth is most favorable along the heat flow direction or, conversely, perpendicular to the temperature isotherms at the S–L interface. These isotherms run roughly parallel to the S–L interface. Grains are most favored whose growth direction is most nearly perpendicular to the S–L interface.

حبيبات المعدن الاساس في المعادن المتعددة البلورات هي عشوائية الاتجاه, وحبيبات المنطقه المنصهره الناتجه تتبع نفس درجة العشوائيه في النمو والتجمد. النمو غالبا مايكون مفضل على طول اتجاه جريان حرارة اللحام او بالعكس يكون عمودي على درجة الحراره المتوازنه عند السطح البيني مابين الصلب والسائل. هذه التغيرات المتوازنه تحدث بصوره عشوائيه موازية للسطح البيني الفاصل بين الصلب والسائل. الحبيبات المفضله هي التي اتجاه النمو فيها تقريبا متعامد على الخط الفاصل مابين الصلب والسائل.

3.a.8.2 Microscopic Aspects of Weld Solidification.

The microscopic estimation of weld solidification is defined as understanding the nature of boundaries (interfaces) in the fusion zone, since many of the defects associated with this region during fabrication and service, are associated with these boundaries.

التقييم المجهري لتجمد الملحومات يعرف بأنه قائم على فهم طبيعة الحدود في منطقة الأنصهار, وذلك لأن الكثير من العيوب المتعلقه بهذه المنطقه خلال التصنيع والخدمه هي متعلقه أساسا بهذه الحدود.

Microscopically, there are three type of boundaries observed as in Figure 3.26. They are (***SSGB), (SGB),(MGB)***. These boundaries have different microstructures represented by the formation and solute re-distribution of solidification sub-grains, such as cells and dendrites. As described deeply below.

هذه الحدود تحتوي تراكيب مجهريه مختلفه تمثلت بتشكيل وأعادة توزيع المذاب لتجمد أشباه الحبيبات, مثل الخلايا والشجيرات

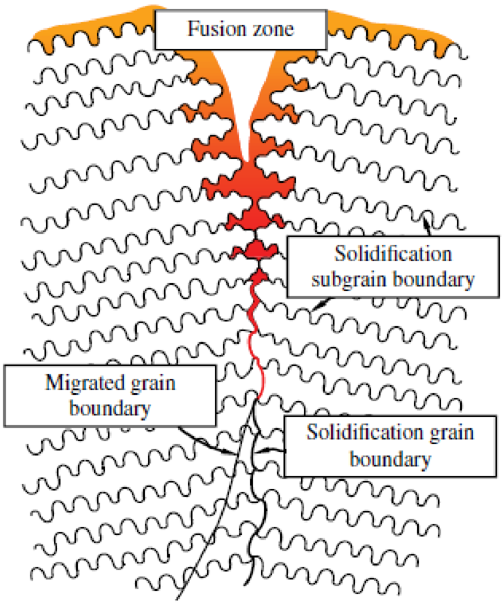
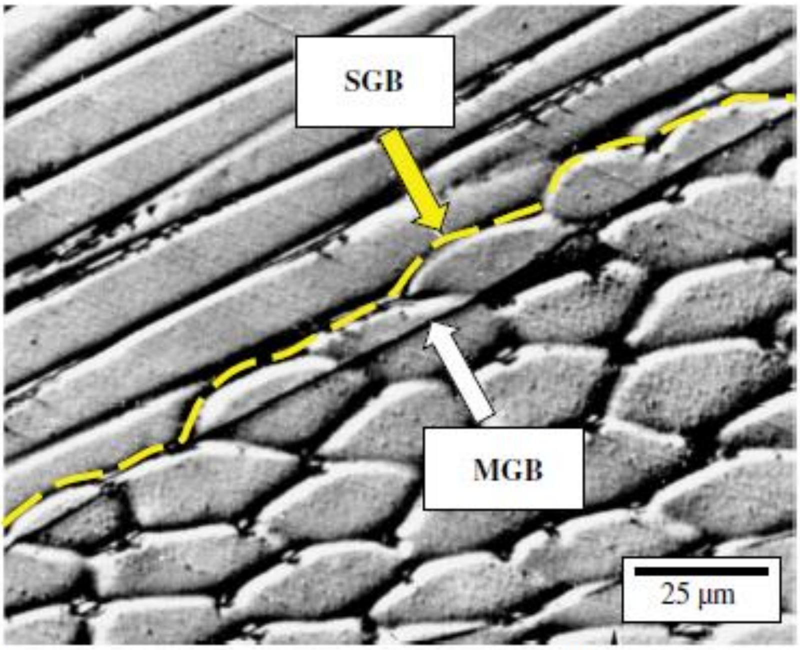


Figure 3.26: Nature of grain boundaries (GB) observed microscopically in the fusion zone.

3.a.8.2.1 Solidification Sub-Grain Boundaries (SSGB).

They represent the finest structure under the optical microscope examination. They result from formation of cells and dendrites during the solidification process and the boundary separating adjacent sub-grains is known as an SSGB. These boundaries are evident in the microstructure because their composition is different from that of the bulk microstructure. There is no crystallographic mis-orientation across the SSGB, because that sub-grains growth occurs along preferred crystallographic directions (or easy growth directions). Because of this, the dislocation density along SSGB is generally low since there is not a large mis-orientation to accommodate. Examples of solidification sub-grains having cellular and cellular dendritic character are shown in Fig 3.27.



Examples of boundaries in the fusion zone of a fully austenitic (fcc) stainless

Figure 3.27: Magnified Image for Solidification sub-grain boundaries (SSGB).

3.a.8.2.2 Solidification Grain Boundaries (SGBs).

They are formed from the intersection of packets رزم of sub-grains or groups, of sub-grains, resulting in a crystallographic mis-orientation across the boundary. So, the original SGB is tortuous ملتوي since it forms from the intersection of opposing cells and dendrites.

تتشكل من تقاطع رزم شبه الحبيبات منتجة أتجاه بلوري مبعثر أو غير منتظم الاتجاه عبر الحدود. ولهذا, الحدود الحبيبيه ملتويه لانها تتشكل من تقاطعات الخلايا المعاكسه والشجيريه.

SGBs are the direct result of competitive growth that occurs along the trailing edge of the weld pool. See Figure 3.23.

تجمد الحدود البلوريه هو النتيجه المباشره للنموالتنافسي الذي يحدث على طول الحافه الخلفيه لبركة اللحام.

Because each of these packets of sub-grains has a different growth direction and orientation, their intersection results in a boundary with high angular mis-orientation. These are often called “high angle” grain boundaries. This mis-orientation results in the development of a dislocation network along the SGB. The SGB also exhibits a compositional component resulting from solute redistribution during solidification.

بسبب أن كل من هذه الرزم من شبه الحبيبات تمتلك اتجاه نمو مختلف, فأن تقاطعاتهم تنتج حدود بزاويه عالية التشتت أو عدم الانتظام, وهذه غالبا ماتسمى الحدود الحبيبيه ذات الزاويه العاليه. وهذا يؤدي الى زياده في نمو كثافة الانخلاعات على طول الحدود الحبيبيه المتجمده, الحدود الحبيبيه المتجمده أيضا تكشف عن وجود مكون تركيبي ناتج من أعادة توزيع المذاب خلال التجمد

3.a.8.2.3 Migrated Grain Boundaries (MGB)

They represent true crystallographic grain boundaries in the fusion zone. These boundaries maintain the mis-orientation of the parent SGBs that they migrated from following solidification.

تمثل الحدود الحبيبيه البلوريه الحقيقيه في منطقة الانصهار.هذه الحدود تمثل الخط الغير المنتظم للحدود البلوريه الاساسيه التي هاجرت من التجمد اللاحق أو الاتي.

In some situations, it is possible for the crystallographic component of the SGB to migrate away. This new boundary that carries with it the high-angle mis-orientation of the “parent” SGB is called an MGB.

في بعض الحالات, من الممكن للمكون البلوري للحبيبات البلوريه ان يهاجر بعيدا.

الحد الجديد الذي يحمل معه عدم الانتظام بأعلى زاويه للحد البلوري المتجمد الاساسي يسمى الحد البلوري المهاجر.

The driving force for migration is the same as for simple grain growth in base metals, a lowering of boundary energy.

القوه الدافعه للهجره هي نفسها المطلوبه لنمو الحبيبات البسيطه في المعادن الاساسيه, والتي هي عباره عن خفض للطاقه الحديه اي التي على حدود الحبيبات.

The crystallographic boundary can lower its energy by straightening and pulling away from the original SGB. Further migration of the boundary is possible during reheating, such as during multi-pass welding.

الحد البلوري يمكن أن يخفض طاقته بالأستقامه والسحب بعيدا من الحدود البلوريه المتجمده الاصليه. هجره أبعد للحد ممكنه خلال التسخين. مثلا خلال اللحام متعدد الأشواط .

3.a.9 Solute Redistribution (Mass Transportation).

It is described as the restriction process for the transported mass (redistributed solute) in the solid, liquid, or both during proceeding welds solidification, which occurs under a non-equilibrium state. The restriction mechanism for transportation mass (solute redistribution أعادة توزيع المذيب) could occur either through the liquid via mixing and in the solid by diffusion. See Figure 3.28.

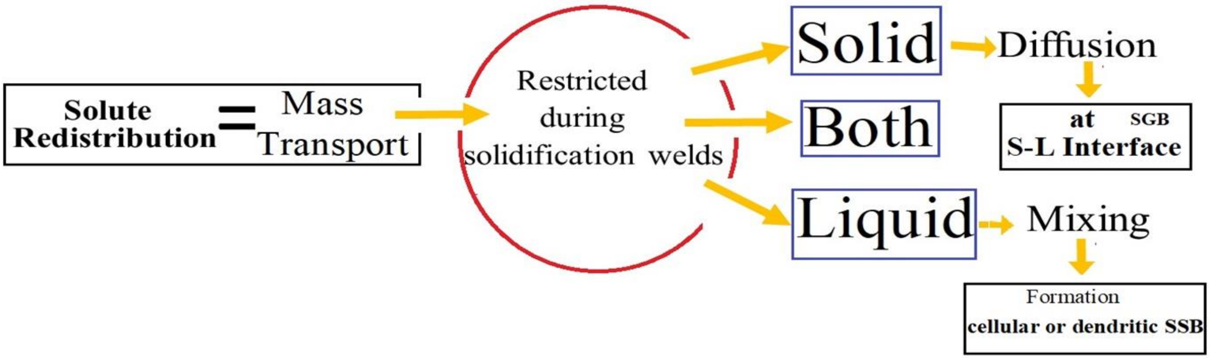


Figure 3.28: Mechanism's type for mass transportation (solute redistribution) in the liquid, solid, or both.

Liquid mixing mechanism means occurrence diffusion within the liquid, since distances are so small and the movement of the mass in the liquid is rapid (Microscopic diffusion). This represented in the case of formation of cellular or dendritic sub grains in the welds during solidification, transportation mass is completed via liquid mixing mechanism**.** No solid diffusion is considered and liquid diffusion is allowed.

Diffusion mechanism occurs via liquid at the liquid boundary with the solid boundary in the case of allowance short range diffusion at the S-L interface. This is because transportation mass is restricted and completed via both the solid and liquid. However, no long range diffusion by liquid or solid could be occurred after this step. The macroscopic and microscopic modes of weld solidification were shown schematically in Figure 3.23.

3.a.9.1 Macroscopic Solidification for Solute Re-distribution.

During macroscopic weld solidification explained in Section (3.a.7.1) shown in Figure 3.14, which considered the solidification front as a plane front with cellular or dendritic modes of weld solidification, a small volume of liquid in plane front solidification represents solute re-distribution, Figure 3.29. Macroscopic solidification can be defined by three distinct regions:

(i) An initial transient.

(ii) A steady-state region.

(iii) A final transient.

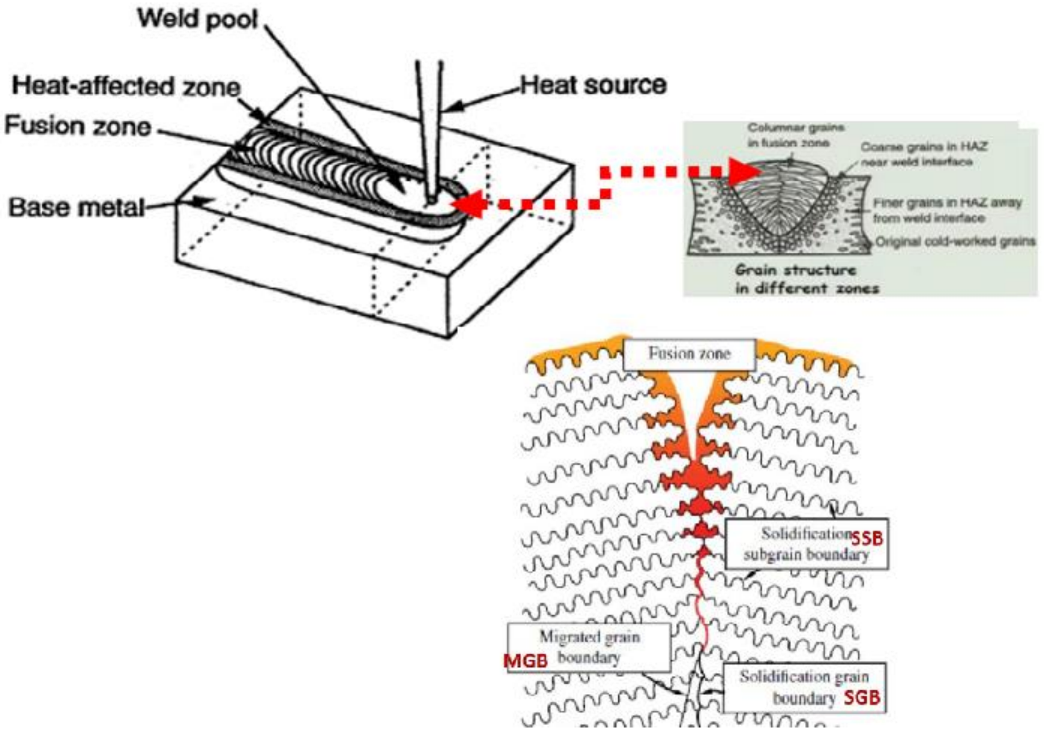
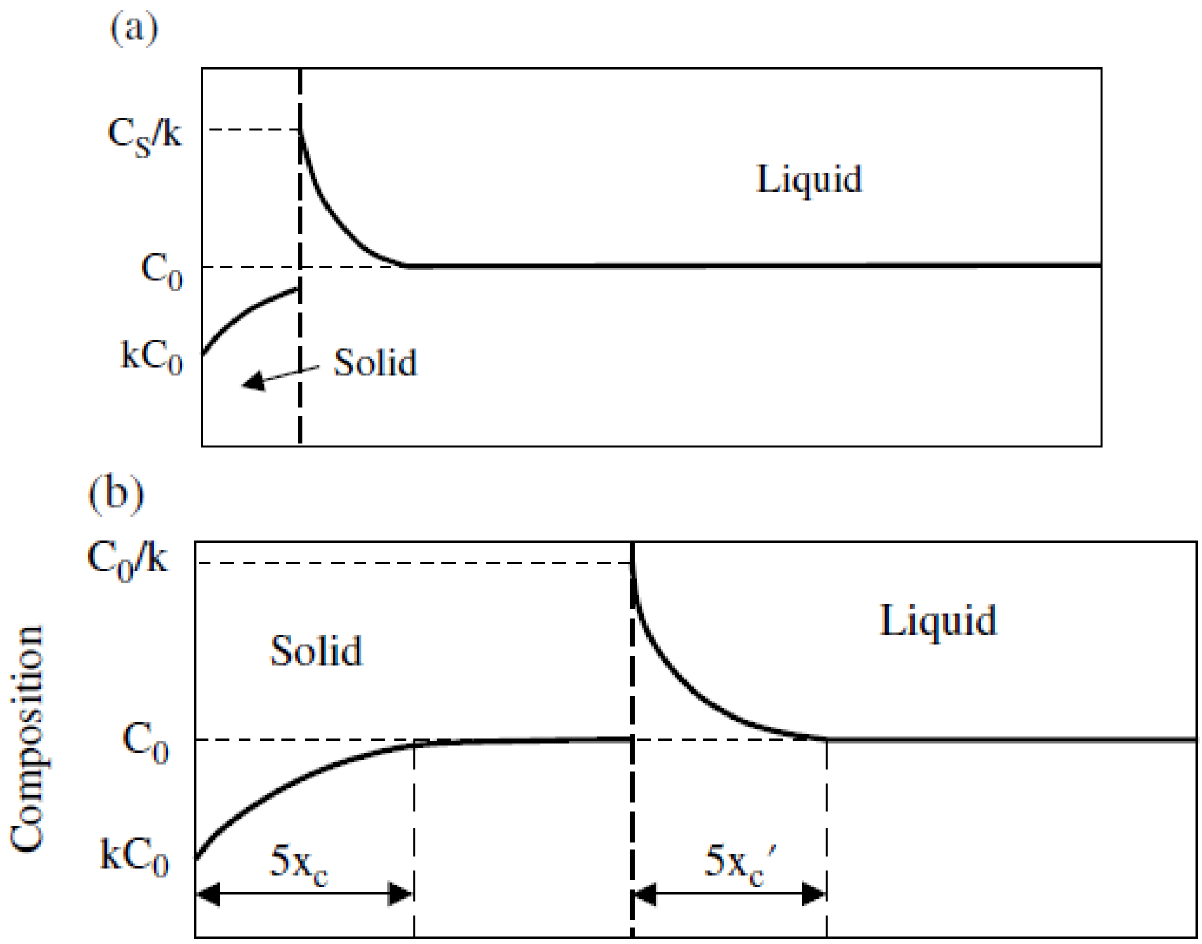


Figure 3.29: A small volume of liquid in plane front solidification represents the solute re-distribution.

The solute profiles shown in Figure3.30 represent an alloy with *k*<1.



(c)

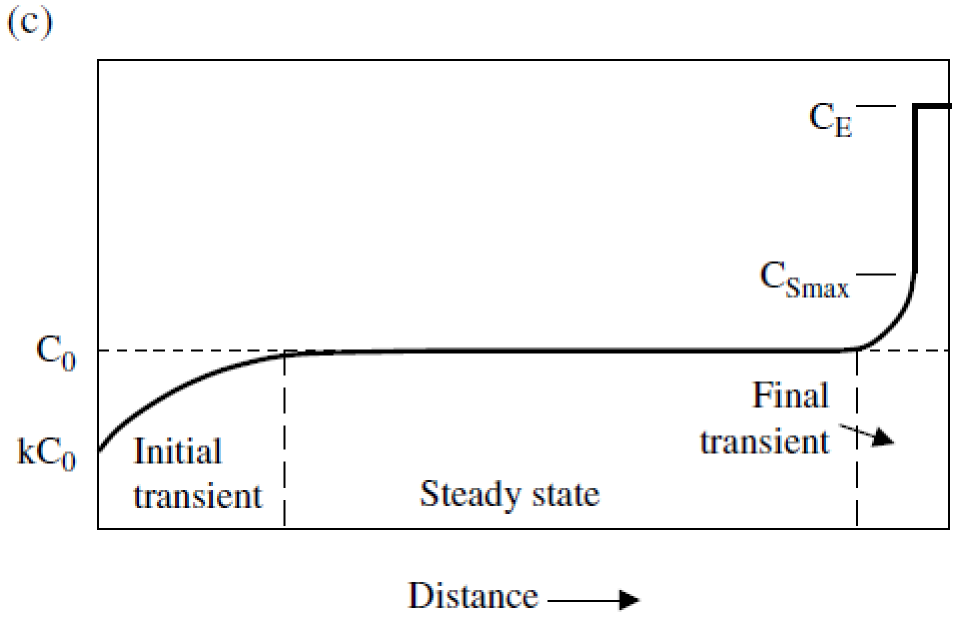


Figure 3.30: Macroscopic Solidification for Solute Re-distribution: (a)An initial transient: (b) A steady-state region: (c) A final transient.

(i) The initial transient:

It represents starting solidification process at the fusion boundary where (*kC*0) solid composition is in contact with (*C*0) liquid composition at the S-L interface.

Where:

***kC*0**: Composition of the initial solid phase

***C*0**: Nominal composition of liquid.

As solidification proceeds, the composition of the solid phase (*kC*0) increases (for *k*<1). The liquid composition (*C*0) at the interface also increases since microscopic equilibrium (as dictated by the phase diagram) must be maintained. This stage ends when the solid composition reaches *C*0.

عندما تبدأ عملية التجمد في المنطقه المنصهره للملحومه, التركيب العناصري للطور الصلب () يزداد ل(). أيضا التركيب العناصري للطور السائل () عند السطح البيني يزداد وذلك لان التوازن المجهري الدقيق يجب أن يكون محافظ على توازنه وفقا لمخطط التوازن الطوري للسبائك والمعادن المختلفه.

Solute profiles for the solid in the initial transient is represented by Eq. (3.6), note that as *k* or *R* decreases, the width of the transient increases according to Equation (a).

$$C_S = C_0\left[1-(1-k)\exp\left(\frac{-kRx_C}{D_L}\right)\right]\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.6)$$

Where:

$5x_c = 5D_L/kR$: Width of the initial transient..….. (a)

k: Partition coefficient =(Cs/CL)

R: Solidification growth rate

Xc: distance or a '***characteristic distance***'

D_L: temperature field of liquid.

(ii) Steady-State Solidification:

This stage occupies most of the solidification process under macroscopic solidification conditions. This stage starts with ending (the initial transient) stage. So the solid composition (*C*0) based on macroscopic solidification, which formed from liquid of *C*0/*k*, based on microscopic equilibrium at the S–L interface is considered to be the beginning point of this stage.

هذه المرحله تبدأ من نهاية المرحله التي قبلها والتي هي مرحلة (الانتقال الأولي). ولهذا التركيب العنصري للصلب المتجمدعيانيا والذي تكون من السائل () اعتمادا على التوازن المجهري عند السطح البيني للصلب- سائل تم اعتباره البدايه لهذه المرحله.

The liquid in the steady-state region have been given by:

$$C_L = C_0\left[1+\left(\frac{1-k}{k}\right)\exp\left(\frac{-Rx_C'}{D_L}\right)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots(3.7)$$

In advance of the macroscopic interface, a solute gradient is established in the liquid of finite width, as described in Eq. (3.7).

بتقدم أو تطور السطح البيني العياني, تدرج المذاب ينشأ في السائل محدود العرض, كما موصوف في المعادله (3.7).

بمعنى أوضح أن تطور نمو حجم الصلب او المذيب في السائل ذا العرض المحدد تم وصفه بالمعادله أعلاه:

Where:

C_L: Liquid composition
C_0: Solid composition
k: Partition Coefficient (Cs/CL)
R: Solidification growth rate
Xc: distance or a '***characteristic distance***'
D_L: temperature field of liquid

The width of this gradient is a function of DL and R and is approximately equal to $5xc = 5D_L/R$ ………...(b)

العرض المحدد لهذا التدرج يتاثر بمسار درجة الحراره داخل السائل عند تجمد السائل وتحوله الى صلب,

وايضا يتاثر بنمو الحبيبات وهو تقريبا يساوي المعادله اعلاه.

Note that as the solidification rate (R) increases, the width of the solute gradient decreases according to Eq.(b).

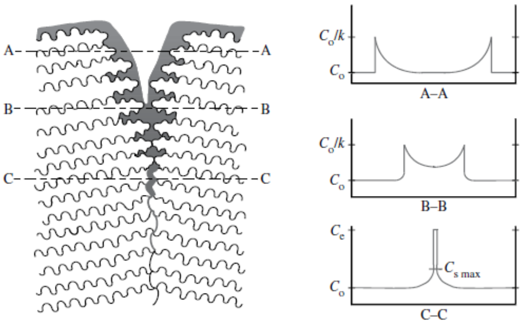
(iii) Final Transient

As the final liquid is consumed at the end of the solidification process, the solid composition again rises (for $k<1$). This "dumping" of solute occurs over a very narrow region, typically on the order of a few microns or less. The solute enrichment (تخصيب) in the final transient must equal the depletion (أستهلاك أو نفاذيه أو أذابه) in the initial transient. Because of this enrichment, the solidification temperature decreases relative to the bulk alloy, and in systems that exhibit a eutectic reaction, some eutectic constituents are formed. This solute/impurity “dumping” effect gives rise to the compositional component of an SGB. Upon reheating, this would be the first region in the microstructure to melt.

التخصيب في مرحله الانتقال النهائي أو التحول النهائي يجب أن يكون مساو للنفاذيه أو مدى أنتشار الصلب في السائل في مرحلة الأنتقال الأولي. بسبب ألتخصيب, فأن درجة حرارة التجمد تقل أعتمادا على حجم السبيكه , وفي الأنظمه التي تتواجد بها تفاعلات ايوتكتيكيه اي سهلة الانصهار, بعض المكونات الايوتكتيكيه السهلة الانصهار تتكون. هذه تعتبر بمثابة شوائب يمكن أن يكون لها تاثيرالغرق مسببة ارتفاع في مركبات التكوينيه للحدود البلوريه المتجمده. مع أعادة التسخين, سوف تكون هذه المكونات في البنيه التركيبيه في المقدمه على استعداد للذوبان.

An example of solute redistribution mechanism along the grain boundary as solidification proceeds (again for the case of $k<1$ is shown in the Figure 3.31.

The schematic shows models of Macroscopic weld solidification for solute redistribution at the trailing edge of the weld pool and along SGBs. This results in the formation of low-melting liquid films along these boundaries that can potentially promote weld solidification cracking.



Solute profiles during formation of a solidification grain boundary, assuming $k<1$

Figure 3.31: Models of Macroscopic weld solidification for solute redistribution at the trailing edge of the weld pool and along SGBs.

3.a.9.2 Microscopic Solidification for Solute Re-distribution.

Solute redistribution under microscopic conditions is quite different than those during macroscopic solidification, since complete mixing in the liquid is considered. This requires that the liquid composition remains constant throughout the process, while no diffusion is allowed in the solid. The composition of solid and liquid in contact at the interface is dictated by microscopic equilibrium and is determined by the phase diagram.

عملية أعادة توزيع المذيب او المذاب عند تجمد الملحومات تحت الفحص المجهري يختلف كثيرا عما هو عليه في حالة الفحص العياني وذلك بسبب أعتبارخلط كامل في السائل. هذا الامر يتطلب ان يكون تركيب السائل يبقى ثابت خلال حدوث التجمد, في نفس الوقت لايسمح ان يكون هناك عملية انتشار في الصلب.

تركيبة الصلب والسائل على اتصال مع بعضهما البعض عند السطح البيني مملوءه بواسطة التوازن المجهري وتحسب بواسطة المخطط الطوري.

Complete mixing is considered because distances are short and rapid diffusion in the liquid eliminates any another solute gradient, in another words, prevent growing up any another solute may be available in the liquid. This form of solute redistribution is represented by sub-grains of cells and dendrites solidification and predicts solute profiles across SSGBs.

أعتبار الخلط تام يعود الى وجود مسافات قصيرة بين الذرات المذابه وايضا الانتشار السريع في السائل يزيل اي عملية نمو اخرى من قبل مذاب اخر في الخليط. الشكل الناتج المعاد اذابته يتمثل بتكوين شبه حبيبات من خلايا وشجيرات متجمده ويتوقع وجود هيئه لهذا المذاب عبر الحدود المتجمده لشبه الحبيبات.

A schematic for solute redistribution during microscopic solidification is shown in Figure 3.32.

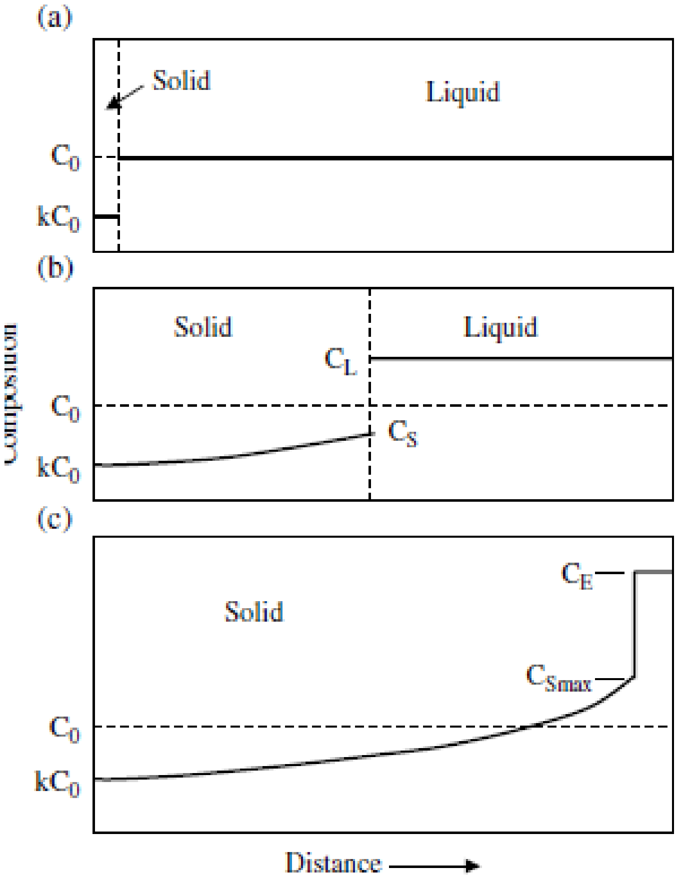


Figure 3.32: Microscopic solidification considering no solid diffusion and complete mixing in the liquid.

The equation for describing the composition of the solid as a function of the solute distribution coefficient, *k*, and the fraction solidified, *f*S, under non-equilibrium lever law condition for welds is as follows (3.8):

$$C_S = kC_0\left(1 - f_S\right)^{k-1} \text{............}(3.8)$$

Solidification begins at the tip of the cell or dendrite and proceeds until solidification is complete at the cell/dendrite boundary.

The initial solid to form is of composition kC_0. The solid composition gradually increases outward from the cell core and then rises rapidly at the conclusion of solidification.

In systems that exhibit a eutectic reaction, this may result in the formation of eutectic constituents along the sub-grain boundary. This relationship can be useful in determining the fraction eutectic in eutectic systems where the solute level is less than C_{Smax}. Since the amount of eutectic constituent can influence solidification cracking resistance, this relationship can be used to predict the weld-ability of some alloy systems.

Although solid diffusion is not considered in Equation 3.8, it can be considered under microscopic solidification conditions by the addition of an α-factor to the equation. α- factor is difficult to determine especially at elevated temperature.

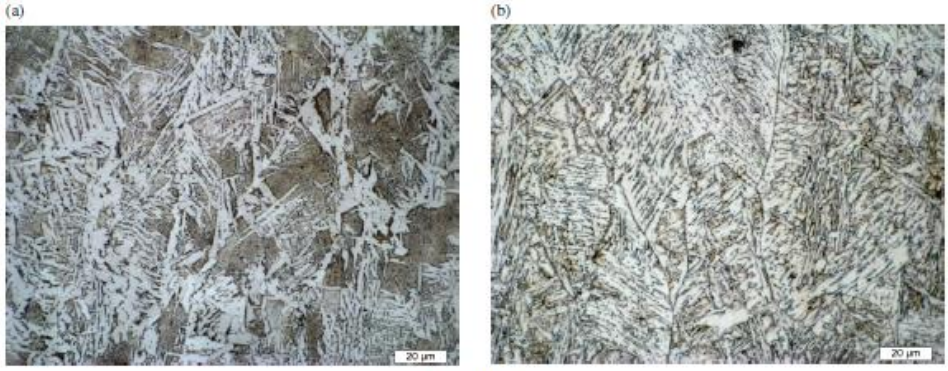
However, in systems that contain fast diffusing elements such as carbon and nitrogen, diffusion in the solid must be considered in order to accurately approximate the solute gradients and microstructure evolution during solidification.

3.a.10 Examples of Fusion Zone Microstructures.

The fusion zone microstructure can vary depending on composition and welding process. This section demonstrates the microstructure of fusion zone

(FZ) which is observed microscopically for a number of common material systems.

Steels are including plain-carbon and low-alloy steels mostly, solidify as bcc ferrite (delta ferrite) and transform to austenite almost immediately upon cooling below the solidification temperature range. The combination of solidification as ferrite and transformation to austenite on cooling tends to eliminate any evidence of the solidification substructure. In addition, these weld metals transform to lower-temperature products (ferrite, bainite, and martensite) upon cooling below the upper critical temperature (*A*3). The resultant fusion zone microstructures show evidence of a columnar solidification pattern, but SGBs and SSGBs are not observed. Examples of the fusion zone microstructure in two such steels are shown in Figure 3.33.

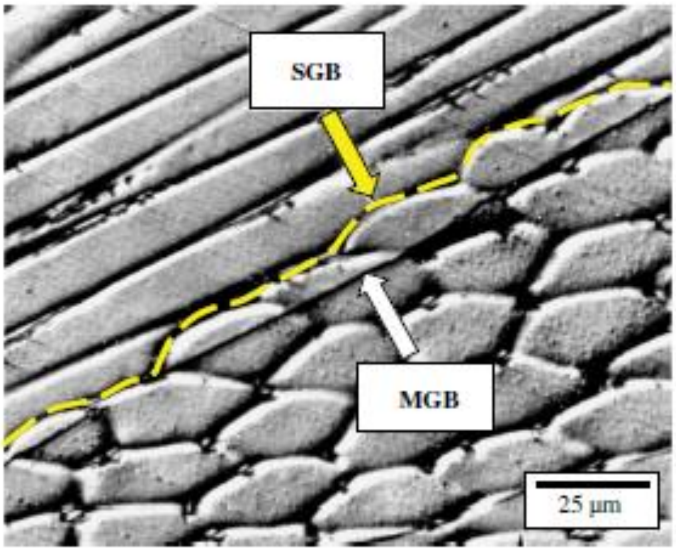


FUSION ZONE

Fusion zone microstructure of (a) plain-carbon steel, (b) low-alloy steel.

Figure 3.33: Fusion zone microstructure of (left) plain carbon steel, (right) low – alloy steel.

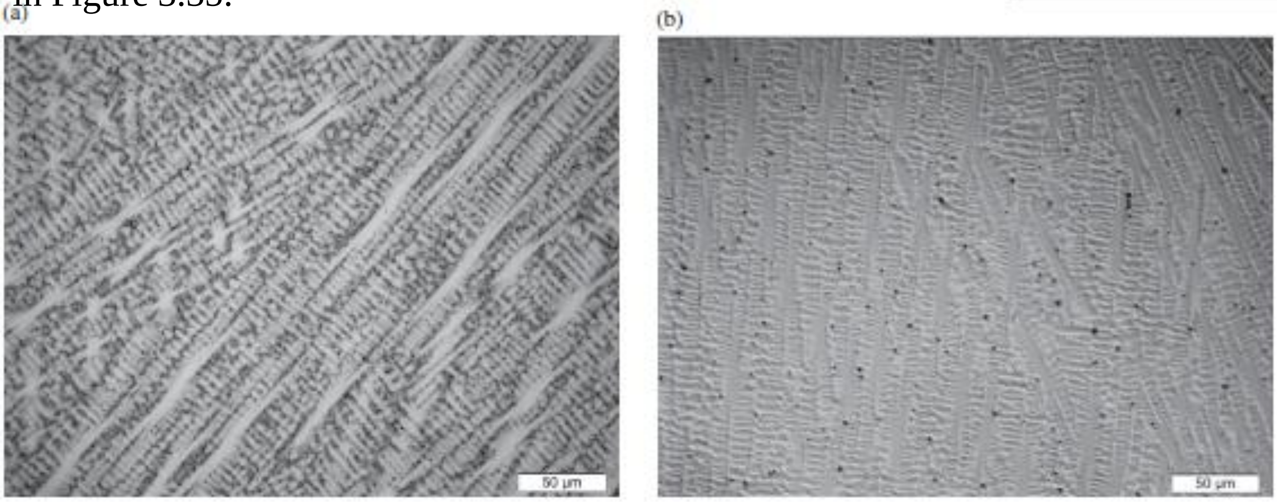
Stainless Steels: when steels solidify as fcc austenite, the solidification substructure becomes more apparent, as already shown in the austenitic stainless steel fusion zone in Figure 3.34.



Examples of boundaries in the fusion zone of a fully austenitic (fcc) stainless steel.

Figure3.34: Fusion zone microstructure the austenitic stainless steel.

Other alloy systems, such as Ni-base, Cu-base, and Al-base alloys, also solidify as an fcc phase and exhibit distinct solidification substructure, as shown in Figure 3.35.



Representative fusion zone microstructure of different alloy systems: (a) Ni base, (b) Cu base,

Figure 3.35: Fusion zone microstructure; (left) NI base; (right) Cu base.

This occurs since diffusion is relatively slow in the fcc phase relative to bcc, and the original solute segregation patterns established during solidification are preserved.

هذه الظاهره تحدث لان الانتشار جدا بطئ في الاطوار متمركزة الوجه ذات الصله بالاطوار متمركزة الجسم, وايضا انماط انعزال المذيب الاصلي التي اختلقت خلال التجمد تم خزنها.

In some aluminium alloys a twinning phenomenon can occur following solidification, giving rise to what are described as “feather crystals” in the fusion zone microstructure, Figure 3.36.

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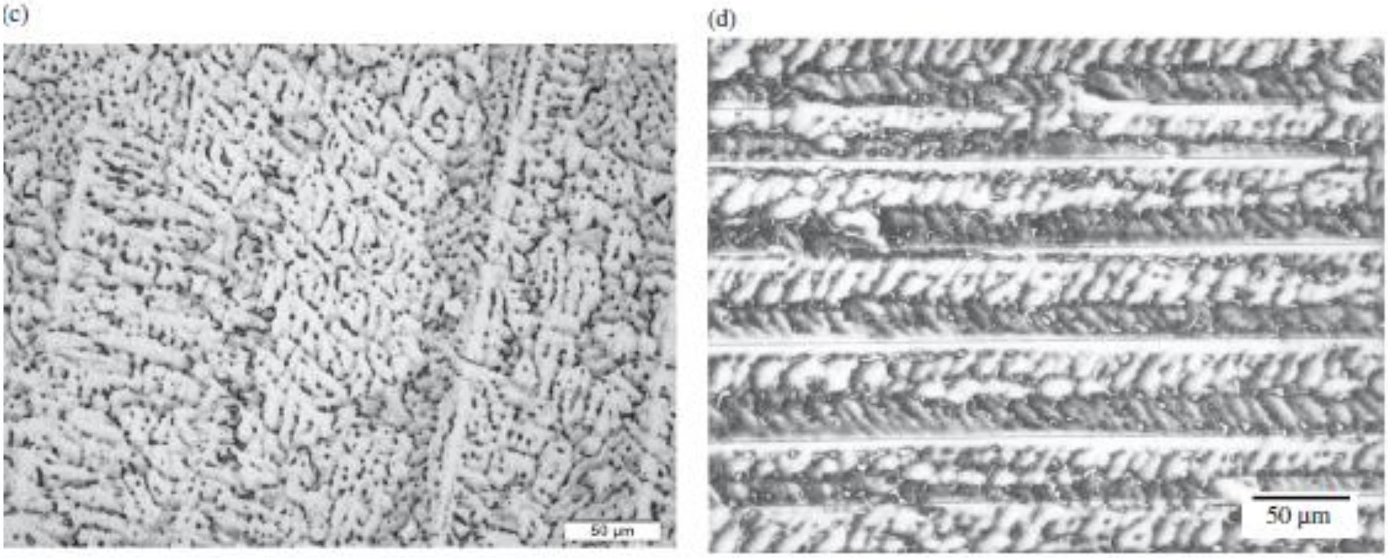


(Continued) (c) Al base, and (d) Al base with twinned crystals.

Figure 3.36: Fusion zone microstructure in AL alloys: (left) Al base; (right) Al base with twinned crystals.

3.b Transition Zone (TZ)

It is located between the fully mixed weld metal (fusion zone) and the base metal (unaffected zone and heat affected zone) in heterogeneous welds only.

There are two cases for this region, the first (TZ) is not apparent clearly, because a small difference in composition between the base and filler metal. So, the microstructure and properties relative to the base and filler metals exhibit no differences or close microstructure.

While in the second case (TZ) is apparent clearly, because a big difference in composition between the base and filler metal. So, the microstructure and properties relative to the base and filler metals exhibit differences.

Figure 3.37 presents a schematic for (TZ).

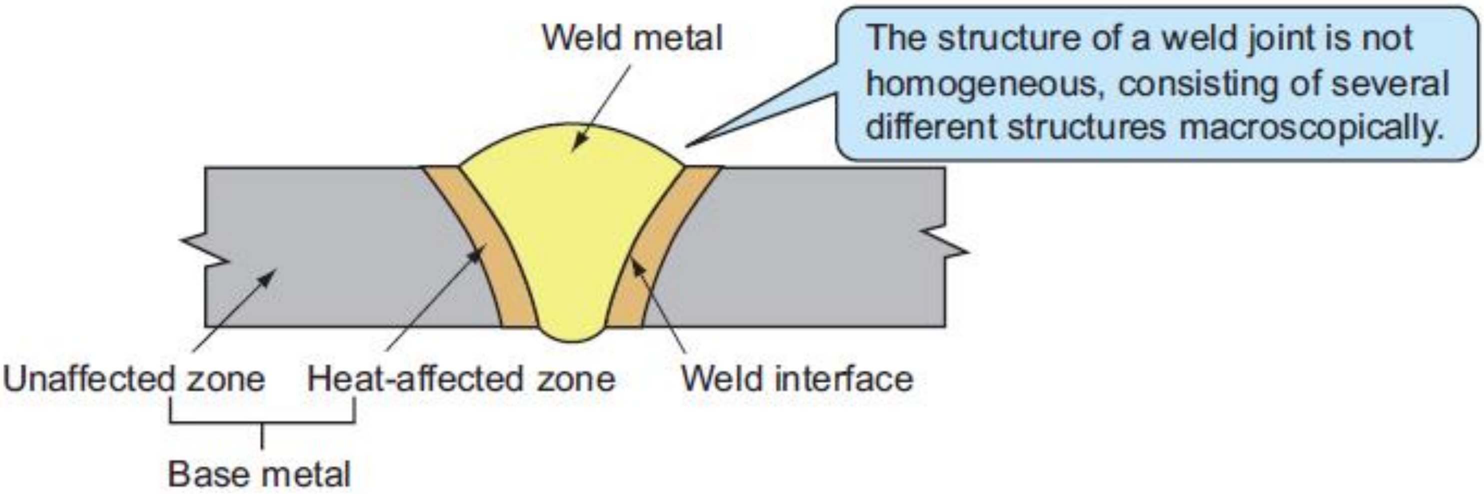


Figure3.37: Transition zone (TZ).

3.b.1 Examples of Transition Zone Microstructures.

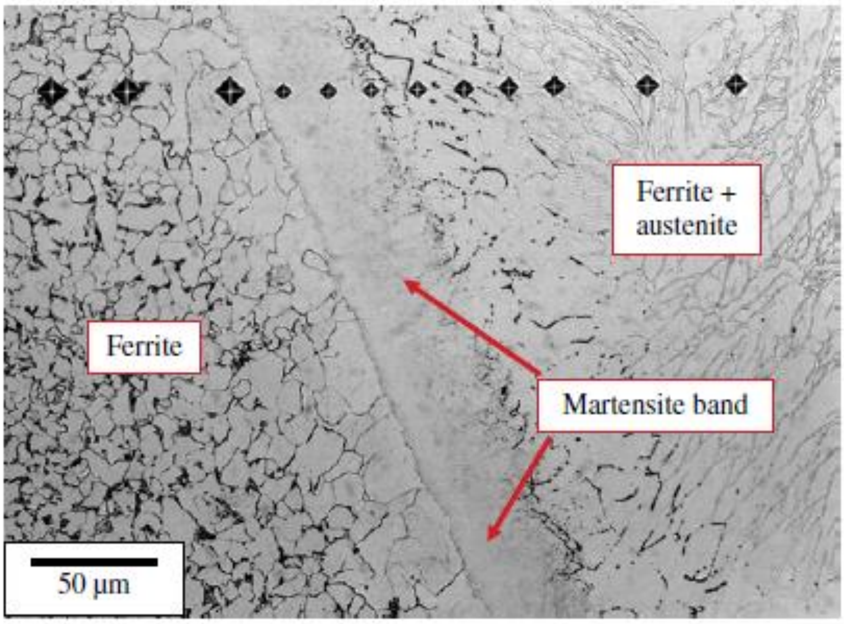
(i)Alloy Type 308 Austenitic Stainless Steel

Carbon steels cladded with Austenitic stainless steels. The purpose is for corrosion protection during solidification welds.

cooling to room temperature causes transformation the formed Austenite in (TZ) to Martensitic structure leading to formation a narrow band of martensite close to the fusion boundary.

This bands cause increase the hardness for as-welded regions much more than the base metal or composite fusion zone.

So, for further services this situation would be demanded to subject for some type of heat treatment to make the whole properties of the weld regions homogenous. See Figure 3.38.



Transition zone in carbon steel clad with Type 308L austenitic stainless steel.

Figure 3.38: Transition zone microstructure in carbon steel clad with austenitic stainless steel type 308L.

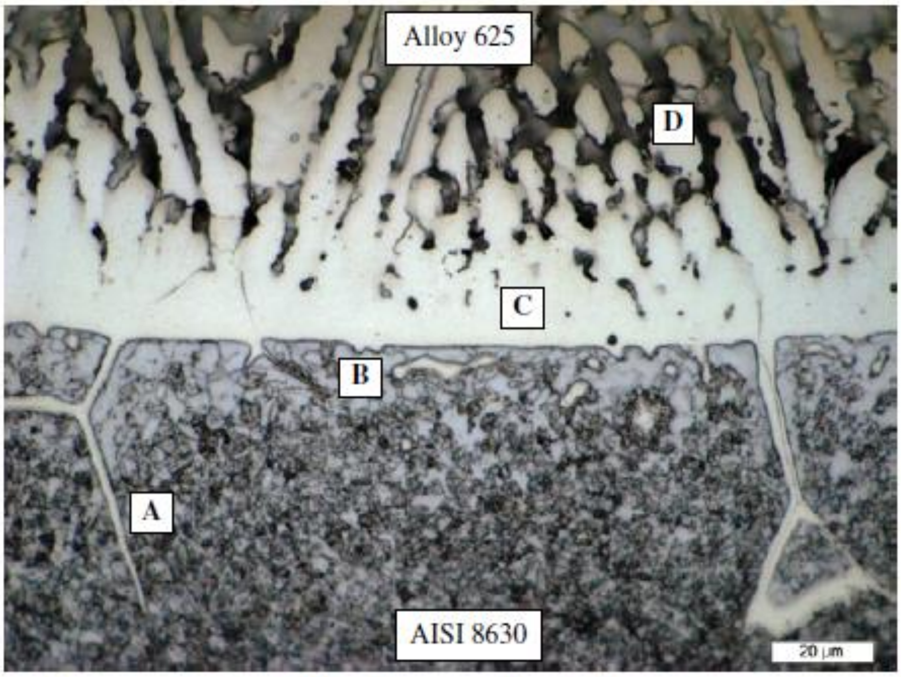
(ii) Steel type AISI8630

Post weld heat treatment (PWHT) applied, for using Ni-base alloys (625) to join or clad steels AISI8630 During welding or cladding process.

A planar growth region appears at the fusion boundary within the TZ, This planar growth region transforms quickly to cellular and cellular dendritic solidification due to the high amount of (Ni), so the (TZ) here have Austenitic structure (fcc), same its structure when it was formed at elevated temperature due to its stability. So, no possibility for martensite (ferrite) formation at this region.

However, due to subjecting the (HAZ) in (Steel type AISI8630) to some type of heat treatment called (pre-weld heat treatment/ PWHT) in order to increase its hardenability, carbon migration occurs from the steel to the fusion boundary region at the interface near the clad region or planar growth region.

This cause decrease carbon amount in steel and increase it in the clad region at the interface, leading to form Martensite structure (ferrite) in the clad region at the interface, and a band of hard Austenitic structure in the planar growth region of the cladding or Ni alloy. See Figure3.39.



Transition zone between AISI 8630 steel clad with Ni-base Alloy 625 after PWHT: (a) penetration of weld metal down the grain boundary, (b) carbon-depleted zone, (c) planar growth region, and (d) cellular growth region. (From Ref. [23]. © Springer)

Figure 3.39: Transition zone microstructure in the weld joint of AISI 8630 and Alloy 625 stainless steel.

3.c Unmixed Zone (UMZ).

It is the narrowest region in the whole fusion zone, located adjacent to the fusion boundary, considered a negligible zone because it is difficult to be seen and always associated with heterogeneous welds, where the relative compositions and physical properties of the base and filler metals are quite different. See Figure (3.40).

تعتبر المنطقه الأضيق ضمن منطقة الانصهارباكملها وواقعه بجوار حدود الانصهار. وتعتبر من المناطق المهمله لان من الصعب رؤيتها او تمييزها. وهي غالبا ماتتكون في الملحومات الغير متجانسه, التي تتميز بالاختلاف الواضح في تركيبها السبائكي وخواصها الفيزياويه للمعدن الاساس ومعدن الحشوه.

(UMZ) possible to be existed in the autogenous and homogenous welds due to evaporation or contamination effects which may cause slight differences in the composition of the adjacent weld metal compared with the filler metal.

المنطقه الغير مختلطه ممكن ان تتواجد في الملحومات المتجانسه والذاتيه التجانس نتيجة تاثيرالتبخيراو التلوث الذي من الممكن ان يسبب اختلاف واضح في التركيب للمعدن الملحوم المجاور مقارنة بمعدن الحشوه

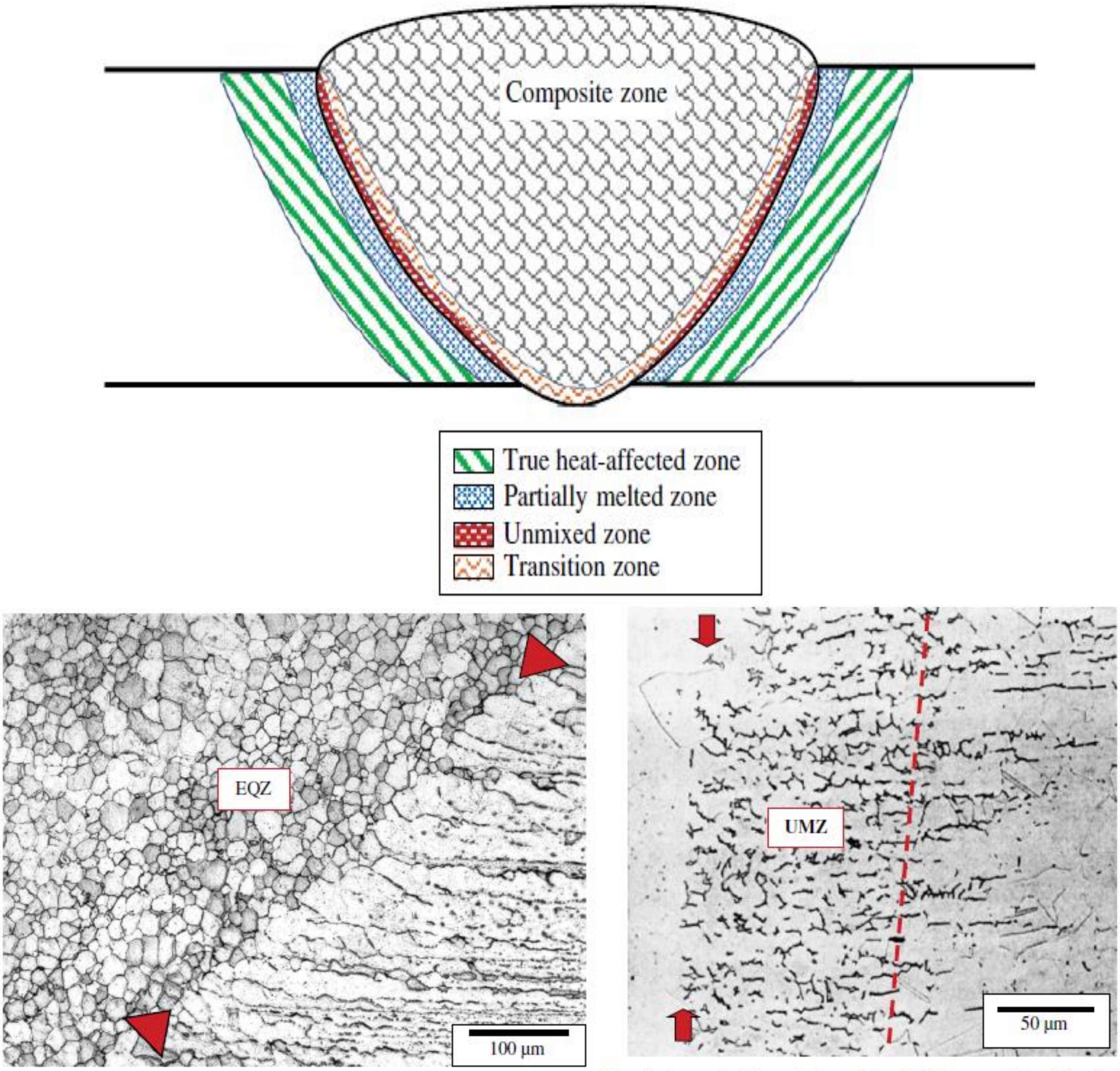
For some dissimilar combinations, the mechanical properties or corrosion properties of the UMZ can be significantly different from those of the base and filler metals causing cracking or localized corrosion.

عند لحام مادتين مختلفتين (سبيكتين مختلفتين),فأن الخواص الميكانيكيه وخواص التاكل لهذه المنطقه المسماة (المنطقه الغير مختلطه) ضمن مناطق اللحام المعروفه يمكن أن تكون مختلفه في خواصها بنسبه كبيره مقارنه بمعدن الاساس لكلا السبيكتين المختلفتين ومعدن الحشوه مسببة تشقق او تاكل موضعي.

Theoretically, UMZ forms in every fusion weld near the fusion boundary at (S-L interface) represented by some finite thickness of a stagnant liquid layer.

While it is practically unseen as its microstructure is similar to that of the bulk fusion zone.

نظريا, المنطقه الغير مختلطه تتكون في كل ملحومه منصهره بالقرب من حدود الانصهار عند السطح البيني الفاصل بين الصلب- والسائل بينما عمليا غير ظاهره لان تركيبها المجهري يشبه تركيب المجهري للمنطقه المنصهره.



Unmixed zone in an Al–Li alloy (Arrows indicate the fusion boundary)

Unmixed zone that forms between Type 304L base metal and Type 310 filler metal (Arrows indicate the fusion boundary.)

Figure 3.40: The microstructure of (Unmixed zone) in different alloys.

3.c.1 Factors Affect Formation unmixed zone (UMZ).

The size and nature of the UMZ can vary depending on a number of material and process variables as below:

- Large differences in the composition of base and filler metals may result in important differences in melting temperature and fluid properties.

- Base metals with a higher melting temperature than the weld metal is probably more susceptible to formation UMZ.

الاختلاف الكبير في التركيب بين معدن الاساس ومعدن الحشوه ربما ينتج اختلافات مهمه في درجة حرارة الانصهار وخصائص المائع. حيث ان درجة حرارة الانصهار العاليه للمعدن الاساس مقارنة بدرجة حرارة انصهار معدن الملحومه من المحتمل ان يكون عرضه لتكوين هذه المنطقه الغير المختلطه.

-Differences in fluid viscosity may also be important. For example, if the molten base metal is more viscous than the weld metal, the UMZ is less likely to be disturbed.

الاختلاف في لزوجة المائع, فاذا كان معدن الاساس الذائب اكثر لزوجة من معدن الملحومه فان هذايؤدي الى تكوين منطقه غير مختلطه اقل عرض للاختلال.

-The ability of the two fluids to mix, may also influence UMZ formation.

-The type of welding process, such as high energy/density processes almost never cause formation UMZ, due to low heat inputs.

Both fluid flow in the weld pool and the temperature gradient along the fusion boundary have an important influence on UMZ formation.

كلا أنسيابية المائع في بركة اللحام والتدرج الحراري على طول حد الأنصهار له تاثير مهم في تكوين المنطقه الغير المختلطه.

If fluid flow is vigorous,قوي the UMZ would be stirred سهله الحركه باتجاه into the weld metal.

If fluid flow is sluggish بطئ, this would form a distinct UMZs.

The temperature gradient at the fusion boundary can influence the width of the UMZ, since it affects the distance over which the base metal is molten.

التدرج الحراري عند الحد البلوري يمكن أن يؤثر على عرض المنطقه الغير مختلطه لانها تؤثرعلى المسافه التي عن طريقها يتم أذابة المعدن الاساس.

3.d Partially Melted Zone (PMZ)

It is a transition region between 100% melting in the fusion zone (UMZ at the fusion boundary) and the 100% solid region of the weld (HAZ).

In a pure metal: (PMZ) is existed because there is no liquid–solid temperature range.

In an isotropic(متماثل) alloy: (PMZ) is existed represented by the temperature range between the solidus and liquids points.

This is due to non- occurrence of segregation (عملية فصل) or local variations (أنحرافات داخليه) in the composition of such those types of alloys.

For **most alloys:** (25–100) ° C range of temperature is narrow in most iron- and nickel-base alloys, so (PMZ) would predict to be a narrow zone.

3.d.1 Factors Affect (PMZ) Extension.

In most engineering alloys, segregation of alloying and impurity elements increases the solidus (effective) melting temperature range of the base material. The temperature ranges between the liquids and solidus temperatures is generally used to describe the extent of the PMZ.

في بعض أنواع السبائك الهندسيه, فصل عناصرالسبيكه والشوائب ترفع من مدى درجة حرارة بداية الذوبان للمعدن الاساس. المدى الحراري بين درجتي حرارة بداية ونهاية الذوبان بصوره عامه تستخدم لوصف مدى أتساع منطقة الذوبان جزئيا.

There are a number of factors that increase the magnitude of this extension by promoting liquation reactions under non-equilibrium thermal conditions.

هناك العديد من العوامل التي تزيد من حجم هذا التوسع او التمدد في هذه المنطقه بواسطة تنشيط تاثيرات زيادة السيوله تحت ظروف حراريه غير متوازنه.

(PMZ) in isotropic alloys would simply represent the temperature range between the solidus and liquids on the phase diagram.

المنطقه الذائبه جزئيا في السبائك المتماثله تمثل ببساطه المدى الحراري بين درجتي بداية ونهاية الذوبان أو الانصهارفي المخطط الطوري.

Solute and impurity elements are distributed non-uniformly in the base metal, and further segregation may occur during the weld thermal cycle (heating and solidification). The net effect is that local variations in composition in the HAZ adjacent to the fusion boundary will promote melting at temperatures below that of the bulk microstructure.

عناصر الذوبان والشوائب موزعه بصوره غير منتظمه في معدن الاساس, وعملية فصل أضافيه ربما تحدث خلال الدوره الحراريه للحام. النتيجه هو أن الأنحرافات الداخليه في التركيب في المنطقه المتاثره حراريا المجاوره لحد الأنصهار سوف تشجع الذوبان عند درجات حراره ادنى من درجة الحراره العائده للتركيب المجهري بأكمله أو ذا الحجم الأكبر.

Concentration of alloy and impurity elements are typically gathered along the grain boundaries more than its interiors resulting in lowering in melting temperature of the grain boundaries compared to that of the bulk material, so these boundaries will generally melt at lower temperatures than the bulk microstructure during heating the base metal surrounding the weld.

تركيز عناصر التسبيك والشوائب نموذجيا يتجمع على طول الحدود الحبيبيه اكثر من داخلها مؤديا الى تخفيض في درجة حرارة الحدود الحبيبيه مقارنة بالماده بأكملها, ولهذا الحدود سوف تذوب بدرجات حراره اقل من درجه حرارة التركيب المجهري للجزء بأكمله خلال تسخين المعدن الاساس المحيط بالملحومه.

Figure (3.41) shows the grain boundary melting phenomenon. The amount of melting depends on the nature and degree of segregation represented by orange colour, while the extent (distance from the fusion boundary to the depth of the hole) depends on the temperature gradient, which pointed out by either to be shallow or steep.

شكل (3.41) يبين ظاهرة ذوبان الحدود الحبيبيه. كمية الذوبان تعتمد على طبيعة ودرجة العزل أو الفصل متمثلة باللون البرتقالي, بينما المدى (المسافه من الحد البلوري الى عمق الحز) يعتمد على التدرج الحراري المشار اليه اما أن يكون ظاهر وواضح جدا أو شديد الأنحدار.

Specific particles or precipitates may undergo a phenomenon called “constitutional liquation” whereby the constituent particle reacts with the surrounding matrix resulting in interfacial melting.

جسيمات محددة أورواسب من الممكن أن تتعرض الى ظاهرة ماتسمى "بالسيوله التكوينيه", بواسطتها يتفاعل الجسم المكون مع المزيج أو الخليط المحيط منتجا ذوبان بيني.

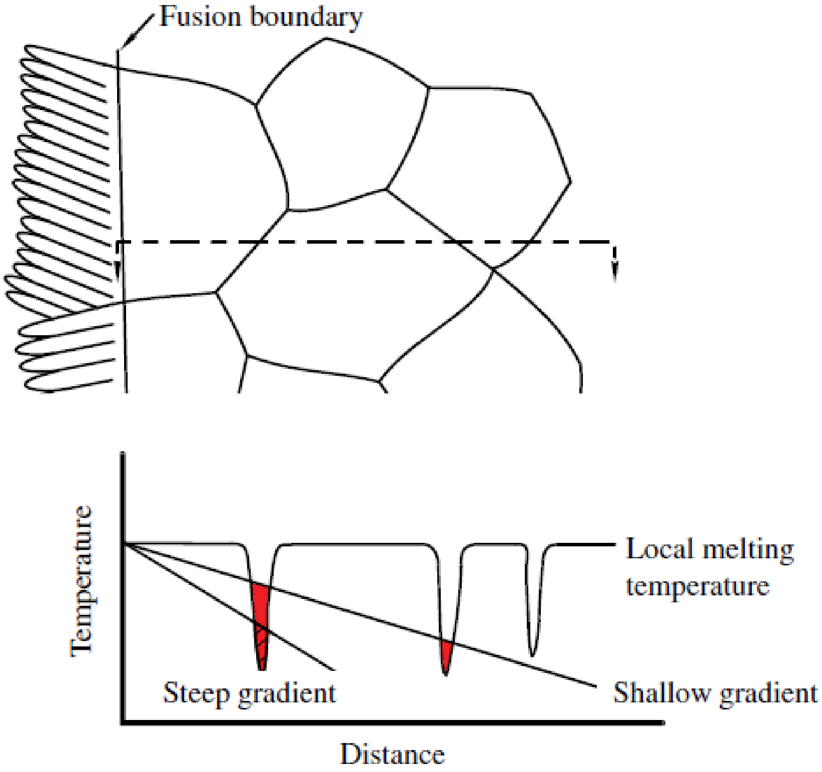


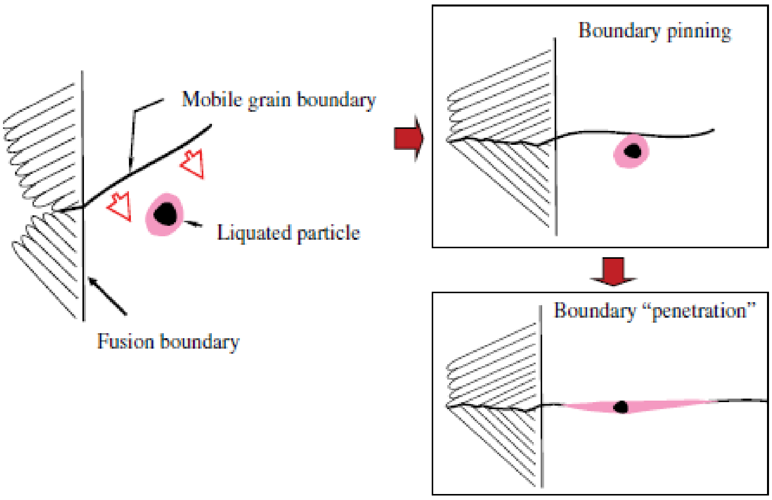
Illustration of local melting along grain boundaries in the PMZ associated with the temperature gradient in the solid.

Figure 3.41: Grain boundary (GB) melting phenomenon.

3.d.1.1 Basic Liquation Mechanisms.

Penetration Mechanism (خاصية التغلغل), requires both a liquation phenomenon and grain boundary motion. It occurs through discrete or localized liquation phenomenon. Discrete Liquation, includes an interaction between the liquated region in the zone and the mobile grain boundary, this would help penetration the liquid and spread it along the grain boundary. Figure3.42 shows a constitutional liquation case and a simultaneous boundary motion. When the boundary encounters the liquated region surrounding the particle, it would be pinned and inhibits further motion. Depending on the wetting characteristics of the liquid/ boundary combination, the liquid may then penetrate along the boundary resulting in formation grain boundary liquid films, which is located in the PMZ for some alloys.

شكل 3.42 يبين حالة سيوله تكوينيه وحركه متزامنه للحدود. عندما تواجه الحدود المنطقه السائله المحيطه بالجسم, فأنها سوف تلتصق بها وتعيق استمرار حركتها. أعتمادا على خصائص الترطيب للسائل والحد الحبيبي, فان السائل سوف يتغلغل على طول الحد الحبيبي مكونا طبقه سائله من الحد الحبيبي, ممكن ان تكون واقعه ضمن المنطقه الذائبه جزئيا في بعض السبائك.



Penetration mechanism for PMZ formation.

Figure3.42: Constitutional liquation case and a simultaneous boundary motion

Localized Liquation: it includes an interaction between the liquated region in the zone and the grain interiors. It has less deleterious than liquid spreading along the grain boundary.

السيوله الموقعيه: يتضمن التفاعل مابين المنطقه السائله في منطقة اللحام و مافي داخل الحبيبه. وهي تعتبر أقل ضررا من تبعثر السائل على طول الحدود الحبيبيه.

3.d.2 Mechanisms to Form (PMZ)

Localized melting in the PMZ may occur via undergoing to incipient melting (أنصهار أولي) phenomenon, which occurs at the grain boundaries for welds. This phenomenon has high thermal energy sites which combine with the energy of the grain boundaries to contribute to allow melting at a temperature below bulk melting. So this incipient melting (أنصهار أولي) phenomenon represents PMZ

خلال التعرض لظاهرة لأنصهار الأولي التي تحدث على الحدود الحبيبيه للملحومات. هذه الظاهره لها طاقه حراريه عاليه التي تتحد مع طاقة الحدود الحبيبيه لتساهم في اذابة بدرجات حراره اقل من درجة حرارة المنطقه الملحومه بالكامل

Localized melting in the PMZ may occur via formation inter-dendritic modes of welds solidification in the cast materials when subject to welding. The inter-dendritic modes melt at a lower temperature than the matrix because they are dictated by the melting temperature of the inter-dendritic region. So, PMZ would be formed.

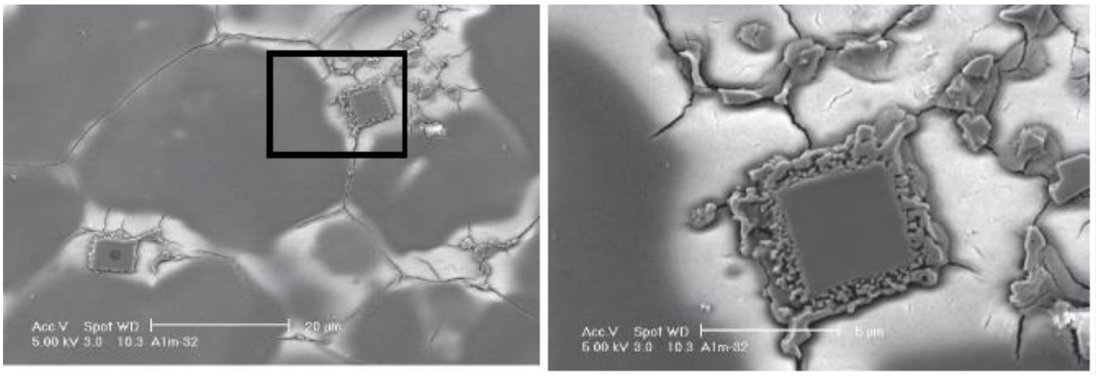
المنطقه الذائبه جزئيا تحدث من خلال تكون النماذج الشجيريه البينيه في الملحومات المتكونه من لحام المعادن المصبوبه عند تعرضها للحام. الشجيرات البينيه تذوب عند درجة حراره اقل من المزيج بأكمله لانها ملزمه بدرجة حرارة الذوبان للمنطقه الشجيريه البينيه والتي تمثل المنطقه الذائبه جزئيا.

Localized melting in the PMZ may occur via formation local compositional banding in some cast materials, after subjecting them to thermomechanical process such as directional rolling operations. Because the compositional banding causes fluctuations in the compositions, hence fluctuations in their melting temperature during welding thermal cycle (**Section 2.1**). This fluctuation cause fluctuation in formation PMZ. So, the lower melting point of these fluctuated composition, the PMZ is represented.

عن طريق تكون المكون الشريطي الموقعي في بعض المصبوبات بعد تعرضها الى معالجات حراريه كعمليات الدرفله الاتجاهيه. لأن المكون الشريطي هذا يسبب تذبذبات في العناصر المكونه للسبيكه أو مايسمى بتركيبها الكيميائي وبالتالي تذبذبات في درجة حرارة ذوبانها خلال الدوره الحراريه للحام. هذه التذبذبات تسبب تذبذب في تكون المنطقه الذائبه جزئيا. ولهذا فأن المنطقه التي لها أقل درجة حرارة ذوبان هي التي تمثل المنطقه الذائبه جزئيا.

Localized melting in the PMZ may occur via formation “constitutional liquation phenomenon” shown in Figure 3.43, which occurs in some materials. This phenomenon occurs in welding’s situations as it needs rapid heating rates to enable the conditions of thermal transition at the interface between the particle/matrix in the weld region. The SEM photomicrograph in Figure shows constitutional liquation.

يحدث عند تكوين ظاهرة السيوله التركيبيه التي تحدث في بعض المواد. هذه الظاهره تحدث في حالات اللحام لانها تحتاج الى معدلات حراره سريعه لتسهيل الانتقال الحراري عند السطح البيني مابين الجسيم والمزيج في منطقة اللحام.



Constitutional liquation associated with Ti-rich MC carbides in a Waspaloy hot ductility sample heated to a peak temperature of 1300°C (2370°F)

Figure3.43: Constitutional liquation phenomenon.

3.d.2. 1 Segregation Mechanism (خاصية العزل أو الفصل).

Localized melting in the PMZ may occur along grain boundaries via **‘’Segregation mechanism’’**.

الاذابه الموقعيه في المنطقه الذائبه جزئيا ربما تحدث على طول الحدود الحبيبيه عن طريق خاصية العزل.

It means segregation solute or impurity elements at the grain boundaries leading to liquation in an appropriate temperature field. Gathering impurity along grain boundaries increase impurity concentration leading to reduce in the melting temperature relative to the bulk composition. This represents the PMZ,

خاصية العزل تعني عزل أو فصل المذيب أو الشوائب على الحدود الحبيبيه مؤدية الى سيوله في مجال حراري مناسب. تجمع الشوائب على طول الحدود الحبيبيه تزيد من تركيزها على الحدود مؤدية الى انخفاض في درجة حرارة الذوبان التي تعود الى التركيب باكمله.

There are at least three segregation mechanisms:

1- **Gibbsian segregation,** grain boundary consists of numerous sites of arrays of dislocations. This sites of dislocations could capture atoms that naturally diffuse or segregate into it causing reduce in the free energy of the system. This represents the primary driving force for the type of segregation known as “Gibbsian” segregation. This represents appearance PMZ here at this point.

الحدود الحبيبيه تتضمن مواقع كبيره من صفوف الانخلاعات. هذه المواقع من الانخلاعات يمكن ان تلتقط الذرات التي بطبيعتها تميل الى الانتشار او العزل الى الحدود الحبيبيه مسببة نقصان في الطاقه الحره للنظام. هذا يتمثل في القوه الدافعه الاوليه لنوع العزل المسمى عزل "غبسيان" . وهذه بدورها تمثل المنطقه الذائبه جزئيا.

2- **Grain Boundary Sweeping**, possible for the atoms which have a high affinity for boundaries or surfaces in the weld zone to be swept up by grain boundary movement. This causes an increase in the concentration of solute or impurity atoms. So, it becomes more difficult for the boundary to “drag” these atoms along, leading to either the boundary slows down, or it may break away, leaving a solute-/impurity-rich region behind. This latter effect may result in the formation of a “ghost” grain boundary. When the solute/impurity concentration reaches some critical level in a given temperature field, the boundary will melt. The extent of this melting will define the bounds of the PMZ.

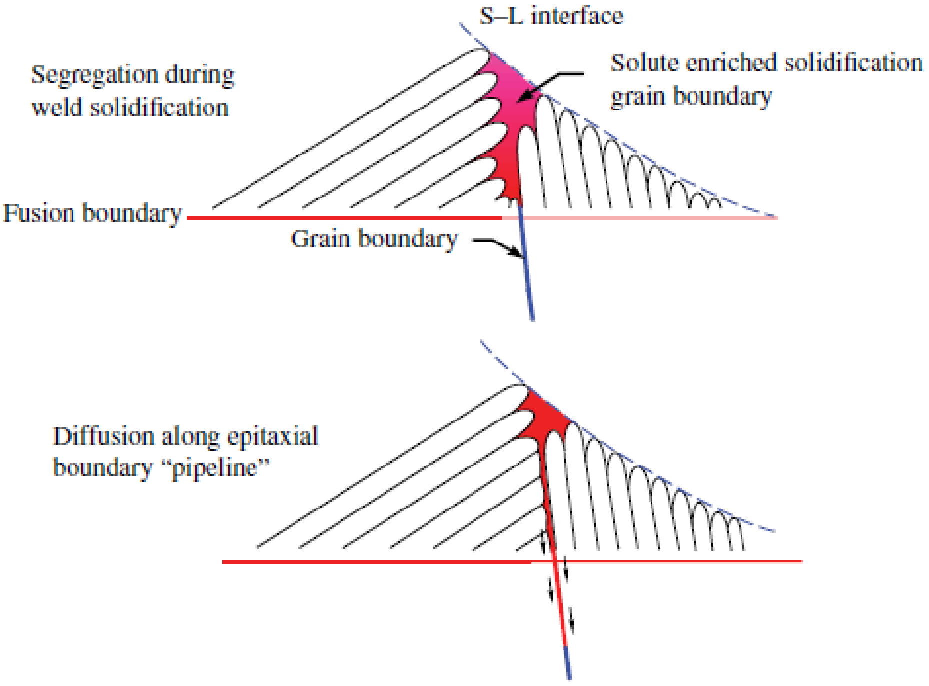
بالامكان للذرات التي تمتلك جاذبيه عاليه للحدود الحبيبيه او للسطوح في المنطقه الملحومه ان تنجرف مع اتجاه حركة الحدود الحبيبيه. هذا يسبب زياده بتركيز ذرات المذيب على الحدود الحبيبيه. وبهذا تصبح من الصعب للحدود ان يسحب الذرات على طول حدود الحبيبه. هذا يؤدي الى أما أن تبطئ الحدود الحبيبيه حركتها أو تترك منطقه غنيه بذرات المذيب خلفها. وهذا ينتج تشكيل مايسمى بالشبح او شيء باهت بطئ الحركه. عندما تركيز الشوائب يصل الى مستوى حرج في مجال حراري قيمته معطاة, فان الحد الحبيبي سوف يذوب. مدى الذوبان سوف يحدد حجم المنطقه الذائبه جزئيا.

3- **Pipeline diffusion** (Figure 3.44), the grain boundary represents a fast diffusion path. Because grain boundaries are continuous across the fusion boundary due to epitaxial nucleation and growth, a natural grain boundary pipeline from the fusion zone into the HAZ is created.

الحدود الحبيبيه تمثل مسار الانتشار السريع. لان الحدود الحبيبيه مستمره عبر الحدود المنصهره بسبب النمو الغير متجانس, الحد الحبيبي الطبيعي من المنطقه المنصهره الى المنطقه المتاثره بالحراره يتكون.

In the fusion zone, solute redistribution along the SGBs results in a high concentration of alloying and impurity elements (for k<1) in close to the HAZ. Diffusion of these elements along the grain boundary pipeline into the HAZ can result in significant enrichment of the HAZ boundaries and promote grain boundary melting. Grain boundary diffusion can be quite rapid. As a result, solute gradients created by solidification in the fusion zone can promote segregation along the grain boundary pipeline into the HAZ.

في المنطقه المنصهره, اعادة توزيع المذيب على طول الحدود الحبيبيه المتجمده للملحومه تنتج تركيز عالي لعناصر التسبيك والشوائب القريبه من المنطقة المتاثره بالحراره. أنتشار هذه العناصر او الشوائب على طول الحد الحبيبي الى المنطقه المتاثره بالحراره يمكن ان ينتج اغناء في حدود المنطقه المتاثره بالحراره ويشجع على ذوبان الحد الحبيبي. ويمكن ان يكون انتشار الحد الحبيبي سريع جدا مما يؤدي الى ان التدرج الحراري للمذيب الذي تم تكوينه بالتجمد في المنطقه المنصهره ممكن ان يشجع الانعزال على طول الحد الحبيبي الى المنطقه المتاثره بالحراره.



Schematic of pipeline diffusion across the fusion boundary.

Figure 3.44: Pipeline diffusion across the fusion boundary.

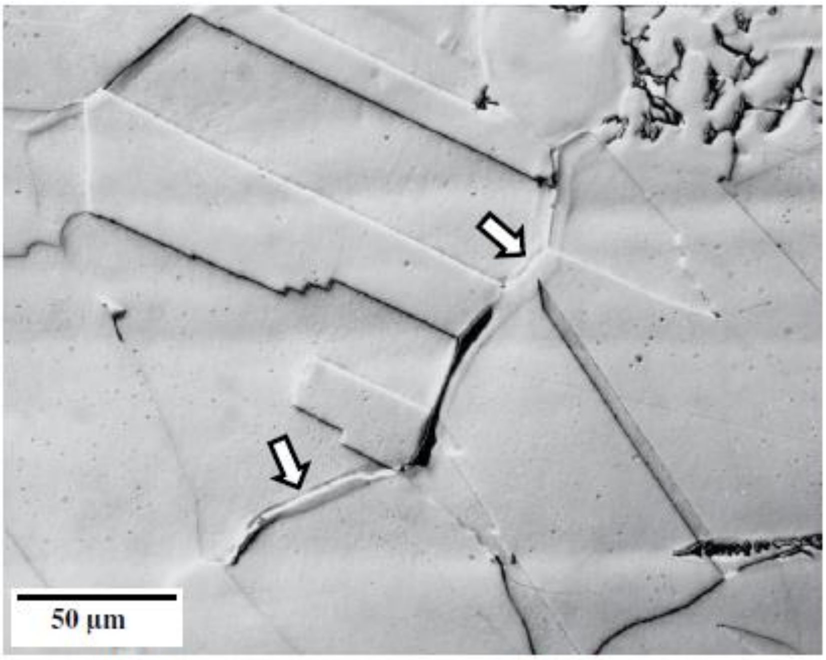
3.d.3 Examples of PMZ formation

Austenitic stainless steels can also form a PMZ, as shown in Figure 3.45. The arrows in the Figure indicate the presence of a liquid film that was present along the boundary at elevated temperature. This melting occurs due to the segregation of impurity elements (S and P) to the boundary.

الصفوف في شكل 3 تشير الى وجود طبقة سائله على طول الحدود في درجات الحراره المرتفعه. هذه الطبقه السائله الذائبه تحدث بسبب عزل عناصر الشوائب والتي هي الفسفور والكبريت الى الحد الحبيبي.

The formation of ferrite along these boundaries will suppress liquation in these alloys, since it is difficult for liquid films to wet austenite–ferrite boundaries.

تكون الفرايت على طول هذه الحدود الحبيبيه سوف يحصر السائل في السبائك لان من الصعب لطبقة السائل ان ترطب حدود الفرايت-اوستنايت.



PMZ formation in stainless steel, Type 304

Figure 3.45: Formed PMZ in stainless steel, Type 304.

3.e Heat Affected Zone (HAZ)

HAZ separates the PMZ from the unaffected parent (base material), Figure 3.4. All reactions in the HAZ occur in the solid state. No melting or liquation reactions occur in this region. Microstructure evolution in the HAZ is complex. (HAZ) undergoes to one or more of metallurgical process such as recrystallization, grain growth, phase transformation, dissolution/ averaging of precipitates, precipitate formation, residual stresses and stress relaxation. There are two types of (HAZ), wide and narrow regions.

المنطقه المتاثره بالحراره تفصل المنطقه المذابه جزئيا عن المعدن الاساس. كل التفاعلات في هذه المنطقه تحدث ضمن الحاله الصلبه. تتعرض الى واحده او اكثر من التفاعلات الميتالورجيه مثل اعادة التبلور, نمو الحبيبات, التحول الطوري, التحلل, تكون الرواسب, الاجهادات المتبقيه. ويوجد نوعان منها وهي المنطقه العريضه والضيقه

Microstructure of (HAZ) is affected by composition and thermal factors, such as material type, type of heat treatment condition prior welding, welding condition, e.g, amount of heat input and flow. Because during welding, rapid heating and cooling for metals which is dictated by the equilibrium phase diagram may cause formation new phases in the HAZ while disappear others not predicted in the phase diagram as a result of different reactions in this zone.

3.e.1 Factors Affect (HAZ) Width.

1- Heat input and heat flow conditions can influence the dimensions and nature of the HAZ.

2- (HAZ) dimensions are controlled by the temperature gradient from the fusion boundary into the surrounding base metal.

3-The nature of the metallurgical reactions that occur over that temperature range.

- If Heat Input is low and/or Heat Flow is Effective: a narrow HAZ will result, since less heat is introduced into the weld.
- If Heat Input is high and/or Heat Flow away from the weld is restricted, a wider HAZ will result.

3.e.2 Metallurgical Process in (HAZ).

The microstructure in (HAZ) undergoes three main process to change.

First process -Recrystallization and Grain Growth Processes, Figure 3.46, during the period of weld solidification, the microstructure of (HAZ) becomes softened. Recrystallization and grain growth in the (HAZ) occur in three stages:

First stage, Recovery: Re-arrangement of dislocations reduces the internal energy, result in formation a cellular dislocation structure that produces strain-free regions in the structure. The Strain-free regions act as nuclei for newly formed grains. Formation a cellular dislocation structure has a little effect on the strength or ductility of the material.

أعادة ترتيب الانخلاعات يقلل الطاقه الداخليه, منتجا تشكيل تركيب انخلاعات خلوي والذي بدوره ينتج مناطق حره الانفعال بتركيب الملحومه. هذه المناطق الحرة الانفعال تؤثركنويات لحبيبات متكونه جديده. تشكيل الانخلاعات الخلويه له تاثير على مقاومة ومطيلية الماده.

Second stage, Re-Crystallization: dislocations are prohibited as the strain-free nuclei grow. These nuclei become new grains and continue to grow and consume the previous, highly dislocated microstructure. This results in a dramatic decrease in strength and hardness, with a corresponding increase in ductility.

في هذه المرحله الانخلاعات يتم منعها لان النويات حرة الانفعال في حالة نمو. هذه النويات تصبح حبيبات جديده وتستمر بالنمو وتستهلك الحبيبه التي قبلها التي تمتلك تركيب مجهري ذو كثافة انخلاعات عالي التركيز. هذا يؤدي الى انخفاض سريع جدا في المقاومة والصلادة مع زياده مماثله في المطيليه.

Third stage, Grain Growth: continues with additional time or temperature leading to an increase in the grain size and hence, reducing grain boundary area, which produces reduction in the overall grain boundary energy. This process gradually slows down as the grains get larger. The increase in grain size beyond the recrystallization stage results in a further decrease in strength.

نمو الحبيبه يستمر مع مرور الوقت وزيادة درجة الحراره مؤديا الى زياده في حجم الحبيبه وبالتالي تقليل مساحة الحد الحبيبي, الذي ينتج نقصان في الطاقه لكامل الحد الحبيبي. هذه العمليه تتباطئ بالتدريج كلما أصبح حجم الحبيبات اكبر. الزياده في الحجم الحبيبي بعد مرحلة اعادة التبلور تنتج تناقص اكثر في المقاومه.

This is often referred to as the Hall–Petch effect, where yield strength (σy) is related to grain size by the following relationship:

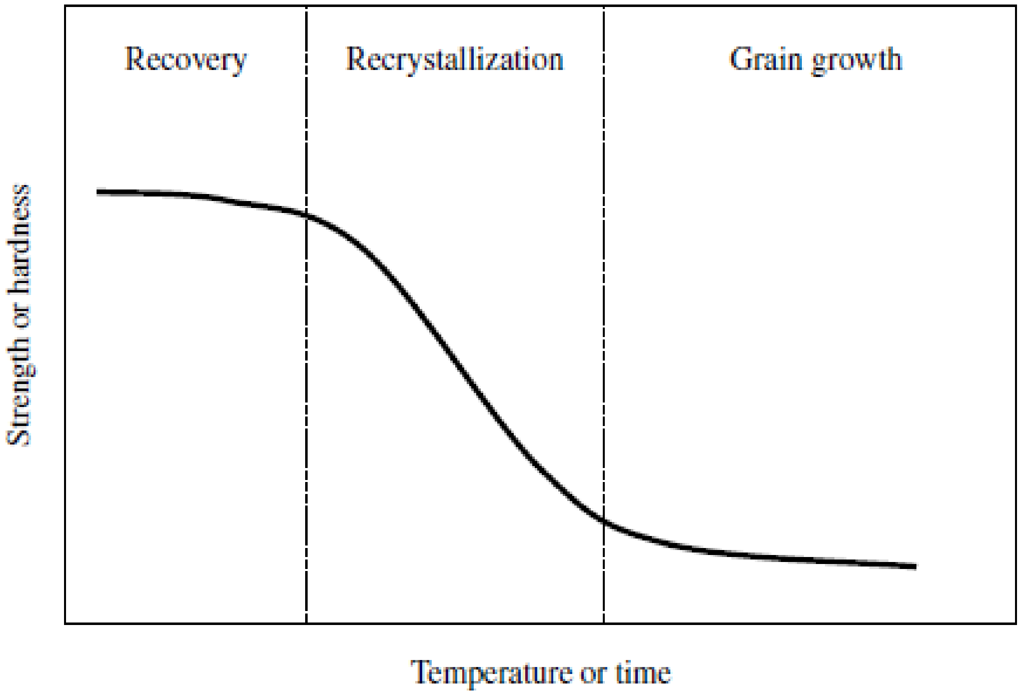
$$\sigma_y = \sigma_0 + k_y / d^{1/2} \qquad \dots\dots\dots\dots\dots\dots\dots 3..9$$

Where

σ0 : material constant for the starting stress for dislocation movement (or the resistance of the lattice to dislocation motion).

***k*y** : Strengthening coefficient (a constant unique to each material)

d : average grain diameter.



Change in strength (hardness) as a function of recrystallization and grain growth of cold-worked materials.

Figure 3.46: Recrystallization and grain growth in (HAZ).

Second process, Allotropic Phase Transformations, التحولات الطوريه المتغايره

Allotropy means that the metal could take on different crystallographic forms as a function of temperature. These differences in the crystallographic forms effect on material strength. A number of metals undergo allotropic transformations especially iron and titanium. When this type of metals subject to welding, this transformation would effect on HAZ spans. For example, in steels, because the HAZ spans a very large temperature range from the solidus to the lower critical temperature (A1), a variety of microstructures can result in these materials due to allotropic transformations.

للستيل: لان المنطقه المتاثره بالحراره يمتد الى مدى حراري كبير من درجة حرارة بداية الانصهار الى درجة الحرارة الحرجه الواطئه. تراكيب مجهريه مختلفه يمكن ان ينتجها هذا النوع من المعدن بسبب التحولات المغاير.

Also, Titanium alloys, the region of the HAZ heated above the alpha (hcp) to beta (bcc) transformation temperature (beta transus) will exhibit a microstructure very distinct from the base metal.

لسبائك التيتانيوم, المنطقه المتاثره بالحراره المسخنه الى اعلى من طور التحول من (الفا طور- بيتا طور) سوف تظهر تركيب مجهري مميز جدا من منطقة المعدن الاساس.

Other systems that undergo allotropic transformations include the duplex stainless steels and some copper alloys. Nickel and aluminium alloys are not allotropic(سبائك النيكل والالمنيوم ليست مغايرة التحول)

Third process: Precipitation Reactions,

Mechanism used for strengthening many types of engineering alloys, e.g., Al and Ni-base super-alloys.

هي اليه تستخدم لتقوية انواع عديده من السبائك الهندسيه مثل سبائك التي اساسها من ألمنيوم و النيكل.

During welding, these precipitated alloys are possible to dissolve or modify on heating in the region where HAZ is formed with cooling.

خلال لحام هذه السبائك المصلده بالترسيب هناك احتمال كبير في قابلية هذا الراسب للتحلل او ان يتغيرعند تعرضه للحراره في المنطقه التي تتكون بها المنطقه المتاثره بالحراره باستمرارالتبريد.

However, (HAZ) might soften due to averaging reactions, which results from growing the precipitated zone rather than dissolution below solvus temperature (critical temperature).

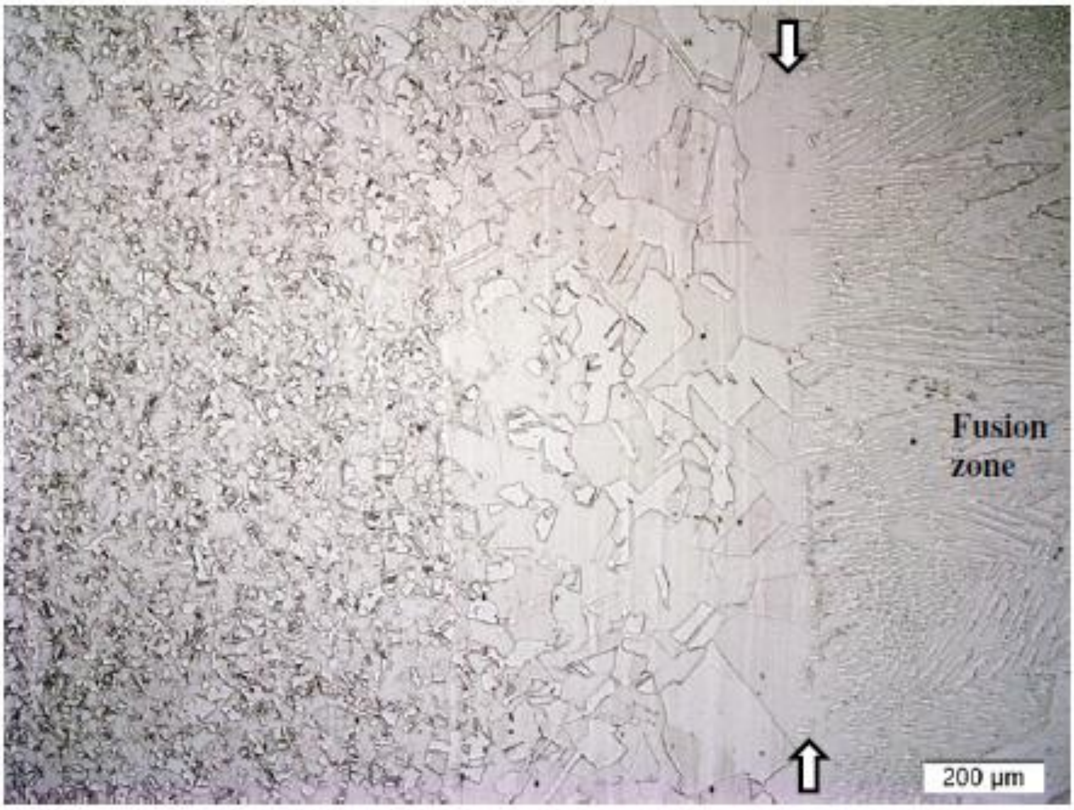
على اية حال, المنطقه المتاثره بالحراره ربما تصبح لينه بسبب تعرضها الى تاثيرا التعتيق التي تنتج من نمو المنطقة المتصلده بالترسيب بدلا من تحللها بدرجة حرارة اقل من درجة الحراره الحرجه.

Precipitation degree has effects on the (HAZ) properties such decreasing the strength. So, a PWHT heat treatment required to be given to the welds in order to recover the strength lost in the HAZ during welding. This can consist of a full solution heat treatment to dissolve all the precipitates and homogenize the structure, followed by aging or a simple aging treatment.

درجة الترسب لها تاثير على خصائص المنطقه المتاثره بالحراره مثل نقصان الصلاده. ولهذا يجب اجراء المعامله الحراريه ماقبل لحام المسبوكات لانواع المسبوكات التي تتعرض الى نقصان في صلادتها للتعويض عن الفقدان الحاصل في الصلاده. المعامله الحراريه هذه تتضمن دورات كامله لاذابة كل الرواسب ومجانسة التركيب متبوعا بالتعتيق الصناعي او الطبيعي (الاسهل)

3.e.3 Examples of HAZ Microstructure

In a fine – grained stainless steel Type 304L, the HAZ at grain growth stage, where the grains are larger than those of the base metal at about an order of magnitude as seen in Figure 3.47. Also, the HAZ is softer than the base metal and weld metal compared with the base metal due to the Hall–Petch effect. The fusion boundary is indicated by the arrows.

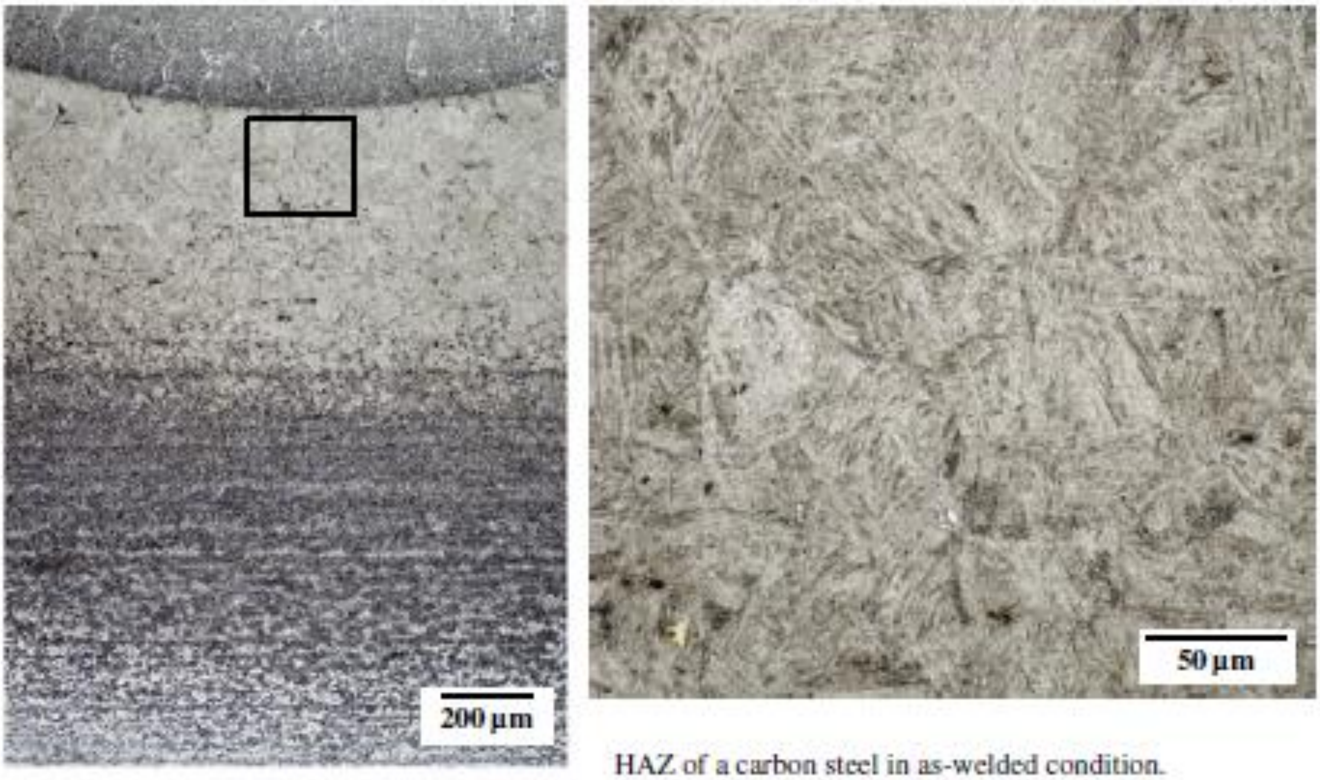


HAZ of GTA weld in a fine-grained austenitic stainless steel.

Figure 3.47: Microstructure HAZ in stainless steel Type 304L.

Figure 3.48 presents undergoing an even more dramatic change in the microstructure of HAZ of a carbon steel. The HAZ adjacent to the fusion boundary represents the CGHAZ and exhibits large prior austenite grain size and a microstructure consisting of a mixture of martensite and bainite, while the base metal consists of a mixture of ferrite and pearlite.

So, in as-welded condition, this microstructure would exhibit high hardness and would generally require a tempering heat treatment to restore ductility and toughness properties.



HAZ of a carbon steel in as-welded condition.

Figure 3.48: Microstructure of HAZ in carbon steel.

4. Welding Zones (Solid-State Welding).

The heating generates by producing friction through the parts need to weld. It requires a combination of heat and deformation to produce a sound weld between the parts need to weld at the interface. No occurrence for melting and solidification during solid-state welding.

Two distinct regions can be identified, which are (i) Heat and Deformation Zone, (ii) T-HAZ.

There are a number of non-fusion welding processes, e.g. friction stir welding (FSW), diffusion welding (DW), explosion welding (EW), Ultrasonic welding (UW).

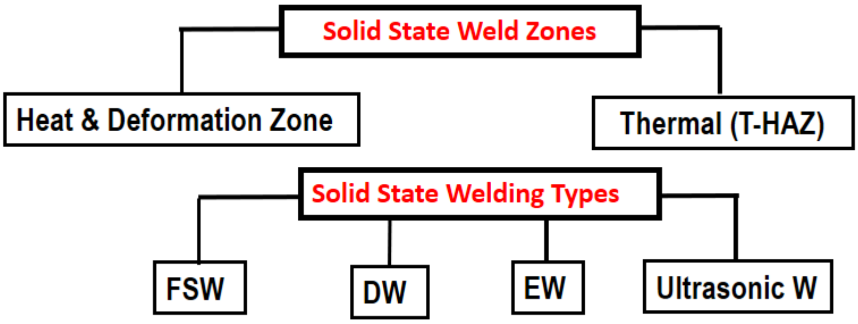


Figure 4.1: Sketch for solid state welding zones and types.

4.1 Friction Stir Welding

Bonding relies on the frictional heat of a tool rotating between the two pieces to be welded. The friction heats the material to a temperature where it flows easily and the butting pieces are joined by this metallic stirring action. No melting takes place and solid-state joint is formed with and a high integrity, Figure 4.2. Three distinct regions can be identified,

(i) Stir zone (weld nugget): the region that consumes the original joint. Metal is heated under the shoulder of the tool and is moved around the tool from front to back by the rotation of the tool. The end of the tool, called the pin (or probe), will sometimes have features machined into it that facilitate material flow in the stir zone.

وتمثل المنطقة التي تستنفذ الوصله الاصليه للحام, حيث يحدث تسخين للمعدن في هذه المنطقه تحت كتف العده التابعة للجهاز, ومن ثم يتم تسخين المعدن حول العده التابعه للجهاز من الأمام الى الخلف بالحركه الدورانيه للعده التابعه للجهاز.

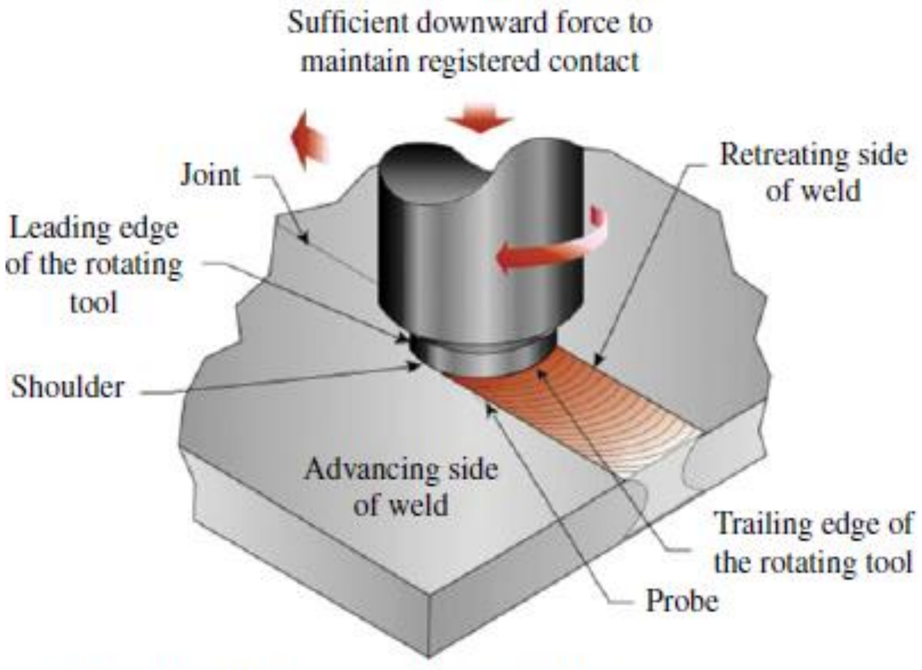
نهاية العده تسمى (المجس), ويمكن للمجس أن يحتوي على مميزات في طريقة تصميم شكله وبالشكل الذي يسهل انسيابية حركة الماده في المنطقه الدورانيه.

(ii) Thermomechanical affected zone (TMAZ): the region surrounding the stir zone where some metal flow occurs. Minor recrystallization is often observed in this region.

تمثل المنطقه المحيطه بالمنطقه الدورانية التحرك التي فيها يحدث أنسيابية للمعدن. في هذه المنطقه, يمكن معاينة عملية أعادة تبلور ثانويه.

(iii) HAZ of a FSW is analogous to that in a fusion weld—only the heat source is different. The HAZ of FSWs often exhibits the same metallurgical reactions as fusion welds.

المنطقه المتأثره بالحراره للحام الأحتكاكي الدوراني مشابه لتلك التي تعود للحام الأنصهاري. الفرق بين الحالتين فقط يعود الى المصدر الحراري المستخدم في عملية اللحام. المنطقه المتاثره بالحراره للحام الاحتكاكي الأنصهاري تعاني أو تواجه نفس التفاعلات الميتالورجيه التي تحدث في اللحام الانصهاري.



Schematic illustration of friction stir welding.

Figure 4.2: Friction Stir Welding (FSW).

4.1.a Parameters for successful Friction stir welding (FSW) welds.

(i) Determination the stir characteristics of the material used in (FSW). This is determined by material’s followability at elevated temperature, which facilitates the welding by (FSW).

*(ii)*Considering tool performance, which is always used in (FSW). This is determined by stirring temperature required to achieve welding. For example, requiring higher stirring temperatures to weld materials such as steels or stainless steels alloys could cause tool wear leading to significant changes in the microstructure of the stir zone, TMAZ, and HAZ relative to the base metal.

الاخذ بنظر الاعتبار أداء العده في اتمام اللحام الاحتكاكي. يتم حسابه اعتمادا على درجة الحراره الحركيه المطلوبه لاتمام اللحام. مثلا, الحاجه الى درجات حراره حركيه عاليه جدا للحام الستيل او سبائكه يمكن من ان يسبب سرعه في تاكل العده المستخدمه لاتمام اللحام ويؤدي بالتالي الى تغيرات ملحوظه في التركيب المجهري لمناطق اللحام الثلاث الناتجه.

4.2 Diffusion Welding.

Heating two components with long time to elevated temperature while in an intimate contact.

تسخين قطعتين بفتره زمنيه طويله وبدرجات حراره عاليه عند منطقة الالتقاء.

Conducted in vacuum or protective atmosphere to prevent oxidation at the interface.

تطبق في غلاف جوي محمي لتجنب الاكسده

Pressure is applied with sufficient magnitude to promote some local deformation at the interface.

يسلط ضغط بكميه كافيه لتشجيع احداث تشوهات موقعيه عند منطقة الالتقاء.

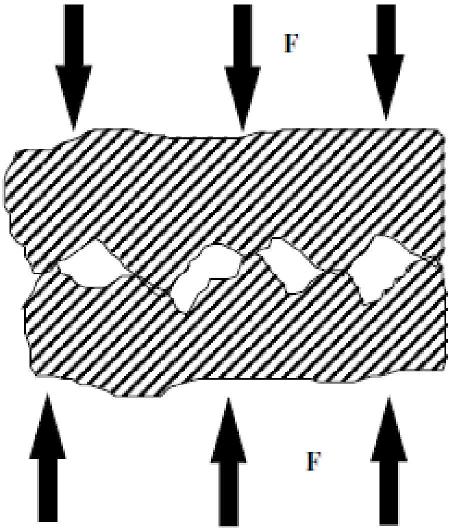
4.2.a Mechanism of Diffusion Welding.

The intimate contact has flat surfaces for both parts, while microscopically appears rough in the form of “Asperities” that limit complete interfacial contact, as shown in Figure 4.3.

السطح لمناطق الاقتراب يكون مستو تماما ولكن تحت المجهر يلاحظ ظهور حافات حاده او خشنه عليه. هذه الخشونه تحد من اتمام الاتصال البيني مابين السطحين المقتربين المراد لحامهما مع بعضهما.

This roughness undergoes high local stress when the two surfaces are subjected to a moderate load. This is because roughness area should support the entire applied load (*F*) due to stress concentrations phenomenon. As a result of this high local stresses, the roughness areas sustain elastic (temporary) and plastic (permanent) deformation. Once the material is plastically deformed, it would not be to return back to its original shape. So, welding would occur through plastic deformation.

المناطق الخشنه عند اقتراب سطحي المعدن المراد لحامهما تتعرض الى اجهادات موقعيه عاليه جدا مقارنه بالاجهادات المعتدله على السطحين باكمله. سبب الاجهادات العاليه هو ان المناطق الخشنه يجب ان تتحمل الحمل المسلط على السطحين بالكامل نتيجة ظاهرة تمركز الاجهادات حول هذا الجزء الخشن. بسبب هذه الاجهادات العاليه المسلطه على الاجزاء الخشنه فان هذه النتوءات الخشنه سوف تحتفظ ببعض التشوه المرن (المؤقت) والتشوه اللدن (الدائمي). وعند ذهاب التشوه المؤقت (المرن) والاستقرار على التشوه اللدن (الدائمي) فان اللحام بالانتشار سيحدث.



Microscopic features of a diffusion weld interface prior to bonding.

Figure 4.3: Diffusion welding mechanism.

4.2. b Conditions for A Satisfactory Diffusion Weld.

(i) Mechanical intimacy of the faying surfaces

التجانس الميكانيكي الحركي مابين سطوح الالتقاء للمعدن المراد لحامه بالانتشار

(ii) Disruption and dispersion of surface contaminants (oxides).

تشتيت الاكاسيد التي تسبب التلوث لسطوح الالتحام

This leads to no distinguishing features at the bond line would result, e.g. presence of some oxides at the bond line.

عند حدود الالتقاء لايوجد مؤشرات تشير الى الخط البيني الفاصل بين السطحين.

The presence of composition gradient at the inter-diffusion zone in- case of welding dissimilar metals. This may lead to the formation of intermetallic compounds.

التدرج في العناصرالسبائكيه المكونه عند السطح البيني الفاصل في حالة لحام مواد غير متشابه. هذا يؤدي الى تشكيل مركبات قويه سبائكيه.

This is achieved through the following stages, Figure (4.4):

Stage1. Deformation of roughness. It is temperature and time dependent(Creep).

Stage2: Boundary migration, recrystallization, and pore size reduction.

Stage3: Bulk diffusion phenomena includes oxide and contaminant dissolution and further pore size reduction.

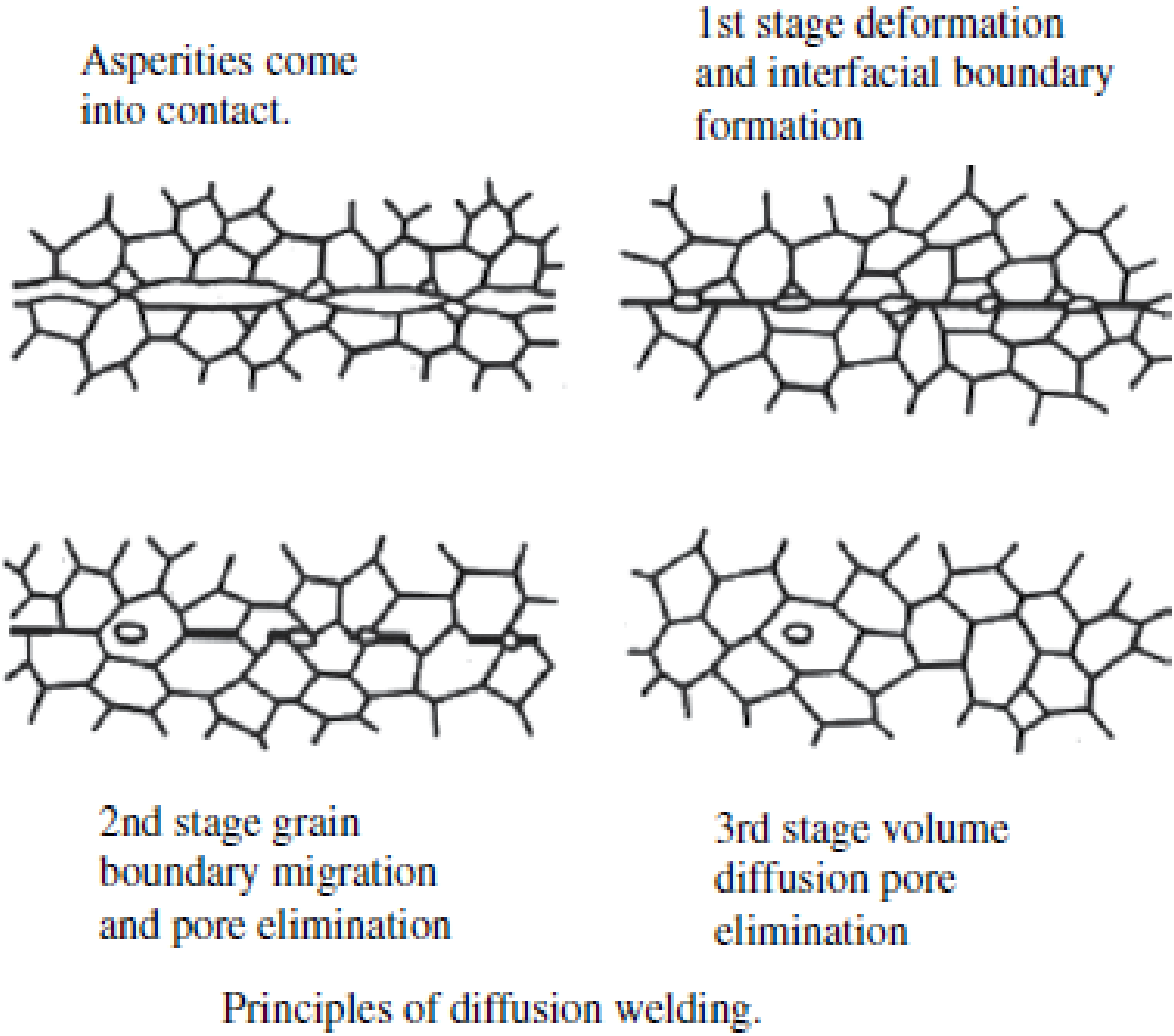


Figure 4.4: Conditions for Satisfactory diffusion weld.

4.3 Explosion Welding.

A form of impact (or collision) welding that can be used to join metallurgically incompatible materials and/or apply cladding to the surface of a material.

و هو نوع من انواع اللحام التصادمي الذي يطبق لربط المواد الغير متطابقه الخواص الميتالورجيه. ايضا يطبق لاغراض الطلاء السطحي للمواد.

The explosion weld forms almost instantaneously, meanwhile eliminate most metallurgical reactions, such as the formation of embrittling intermetallic phases.

اللحام الانفجاري هو لحام يحدث بشكل لحظي او فوري يؤدي الى ازالة غالبية التفاعلات الميتالورجيه, مثل التفاعلات الى تؤدي الى خلق اطوار سبائكيه هشه

4.3 a Mechanism of Explosion Welding.

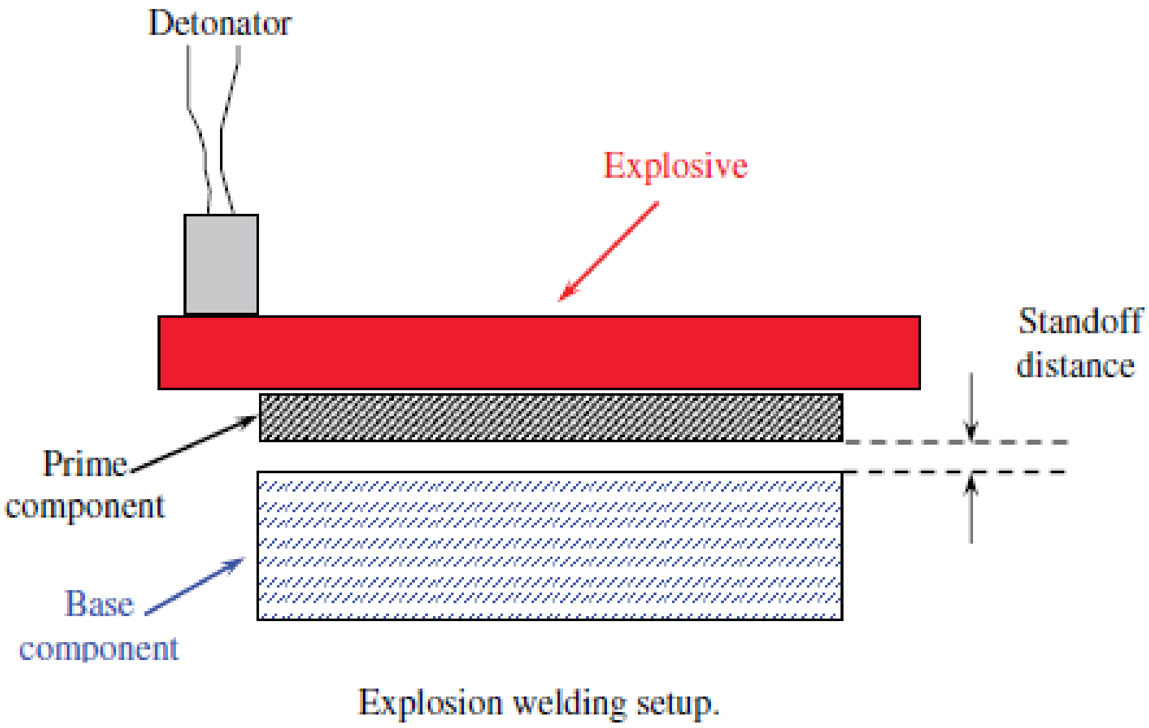


Figure 4.5: Explosion welding setup.

Figure 4.5 shows a typical setup for explosion welding. The collision between the components generates kinetic energy that produces local melting, vaporization, and possibly plasma formation.

التصادم بين المركبتين تولد طاقه حركيه تنتج فيما بعد ذوبان موقعي, تبخر, تشكيل طبقة البلازما.

Most of the liquid and vapor is expelled from the joint by a strong jet action at the interaction point.

بعض السوائل والبخار يطرد من الملحومه بواسطة تاثير الانبوبي القوي.

This “jetting” action removes oxides and other contaminants from the surface and produces metallurgically clean interfaces that are easily bonded.

التاثير الانبوبي يزيل الاكاسيد والملوثات الاخرى من السطح وينتج سطوح بينيه نظيفه ميتالورجيا وسهلة الربط للحام.

4.3.b Welding Zones in Explosion welding.

(i) Bond line of an explosion weld has a wavy appearance line can be seen using metallographic techniques. Melting region lies at the tip of the wave

حد الالتحام للحام الانفجاري له مظهر مموج. المنطقه الذابه تقع على قمة التموج.

(iii) The HAZ of explosion welds is extremely narrow and often undetectable. المنطقه المتاثره بالحراره ضيقه جدا

5. Weld Cracking

Occurs due to the metallurgical nature of the weldment. There are three types of cracking, hot cracking, warm Cracking, cold cracking. Figure 5.1 presents a schematic for the three types of cracking occur in weldment.

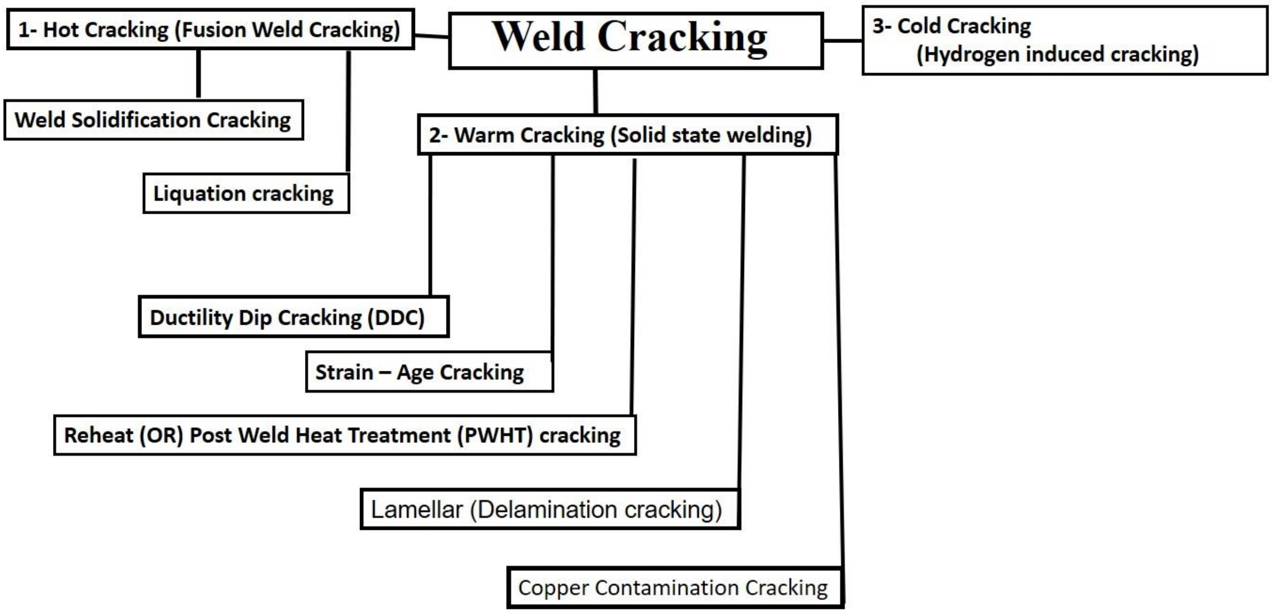


Figure 5.1: Schematic for the main three types of cracking occur in weldment.

5. 1 Hot Cracking (Fusion Weld Cracking).

Refers to the presence of liquid film in the microstructure of the fusion zone (FZ), (PMZ), and (HAZ) during fabrication. Liquid films is formed along grain boundaries (GB). The liquid films may be kept to temperatures below the equilibrium solidus temperature of the bulk alloy, thus extending the solidification range of the alloy to the “effective” solidus temperature.

طبقات السائل ربما يتم الاحتفاظ بها الى درجات حراره اقل من درجة حرارة بداية الانصهار المتوازنه للسبيكه بالكامل. و يمتد مدى التجمد للسبيكه الى الدرجه الحراره الفعاله لبداية الانصهار

Hot cracking has two profiles, which are weld solidification cracking and liquation cracking. See Figure 5.1.

5.1.a Weld Solidification Cracking.

Results from the thermal or mechanical imposed restraint (strain) and the crack susceptible microstructure. The crack-susceptible microstructure results from the persistence of liquid films along solidification boundaries in the weld metal. Cracking can often be eliminated by reducing the level of mechanical restraint. For example, joint geometries or weld parameter changes that alter the weld bead size and shape are often effective in eliminate cracking.

ينتج من الانفعال الميكانيكي المحبوس ومن تعرض التركيب المجهري للماده للتشقق. تعرض البنيه المجهريه للتشقق سببه اصرار بقاء طبقة السائل المحبوسه على طول حدود التجمد في منطقة اللحام. يمكن تقليص التشقق او ازالته بتقليل مستوى الانفعال الميكانيكي المحبوس. مثلا,الا ختيار الامثل للشكل الهندسي للوصلات الملحومه, التحكم بمعامل الملحومه الذي يبدل حجم قطرة اللحام وشكلها.

5.1.a.1 Reasons for Weld Solidification Cracking.

(i) accumulation non-uniform strains within the line of the grain boundaries of the structure leading to formation a bridge between solid-solid causing cracks or initiation of a crack point. These strains resulted from gathering high local strains over the bulk material while it is being solidified.

التشقق يحدث بسبب تجمع الانفعالات الغير المنتظمه ضمن خط الحدود الحبيبيه للجزء مؤديا الى تكوين جسر بين صلب واخر مسببا تشقق اونقطة بداية نشوء شق. هذه الانفعالات تنتج من تجمع انفعالات موقعيه عاليه على قوام الماده بالكامل اثناء تجمدها وهي تحت تاثير عملية اللحام.

(ii) Cracking occurs due to separation of liquid films at the SGBs along the grain boundaries causing formation dendritic cracking, flat cracking, or Inter-granular cracking, الخلايا الحبيبيه solid-state fracture.

بسبب انفصال طبقة السائل على طول الحدود الحبيبيه المتجمده مسببا اما تشقق شجيري, او مستو الشكل, او تشقق مابين الحبيبات, او الكسر الصلب.

(iii) Cracking occurs due to losing the material its ductility while subjects to a range of brittle temperatures resulted from thermal or mechanical stresses, or elevated temperature during welding, causing induced local strains.

بسبب فقدان الماده لمطيليتها وهي تتعرض الى مدى درجات حراره هشه ناتجه من اجهادات ميكانيكيه او حراريه, او بارتفاع درجة الحراره خلال اللحام, مسببا الحث على توليد انفعالات موقعيه.

(iv) Cracking occurs due to the dominant effect of composition metals or alloys on the solidification behavior of welds.

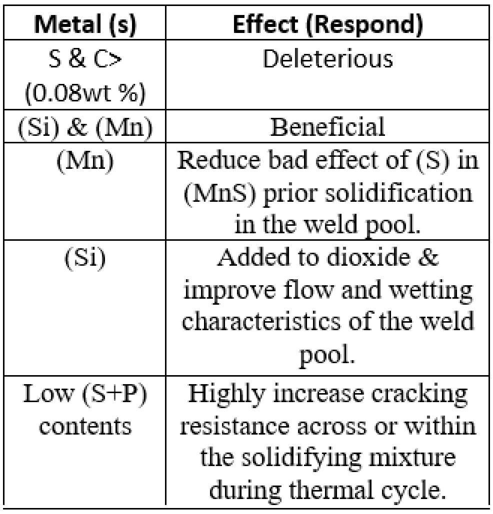
بسبب التاثير الغالب للتركيب العناصري للمعادن المراد لحامها او السبائك على سلوك تجمد الملحومات.

(v) Cracking occurs due to unavailability of sufficient amount of liquid film in the weld grain boundaries or within it required to wet grain boundaries lines during weld solidification. Liquid wetting characteristics in the structure during weld solidification encourage healing cracks, increase or decrease their amount.

بسبب عدم توافر او تواجد كميه كافيه من طبقة السائل في الحدود الحبيبيه الملحومه او بضمن خط اللحام. خصائص ترطيب السائل في الجزء خلال اللحام تشجع التئام الشق, او زيادته او نقصانه.

5.1.a.2 Factors Encourages Susceptibility to Weld Solidification Cracking.

(i) **Composition** affects directly on the behavior of weld solidification, initiation and elimination cracking. All the elements present in the mixture must be considered when attempting to predict weld solidification cracking susceptibility. An example shown in Table (5.1), shows the effect of composition on formation weld solidification cracking. For example, steel alloys have Sulphur with carbon content over (0.08wt %) have a deleterious effect, (Si) with (Mn) have a beneficial effect, (Mn) reduces the bad effect of (S) in the compound (MnS) prior solidification in the weld pool, (Si) is added as a deoxidizer, also improves the flow and wetting characteristics of the weld pool. And finally, low (S+P) contents, cracking resistance is high across the range of compositions.



Metal (s)	Effect (Respond)
S & C> (0.08wt %)	Deleterious
(Si) & (Mn)	Beneficial
(Mn)	Reduce bad effect of (S) in (MnS) prior solidification in the weld pool.
(Si)	Added to dioxide & improve flow and wetting characteristics of the weld pool.
Low (S+P) contents	Highly increase cracking resistance across or within the solidifying mixture during thermal cycle.

Table5.1: Composition effect on formation weld solidification cracking.

(ii) **Grain Boundary Liquid Films**, required to avoid possibly weld solidification cracking by wetting the boundaries. As the amount of liquid required to wet grain boundary increases, the susceptibility to cracking decreases and vice versa. Liquation grain boundary must be sufficient to wet the boundary at temperature below the bulk solidification temperature. Sufficient liquation grain boundary to avoid cracking depends on quantifying the boundary wetting characteristics. Quantifying the boundary wetting characteristics depends on the relative interfacial energies in alloys depending on the type of alloys’ systems.

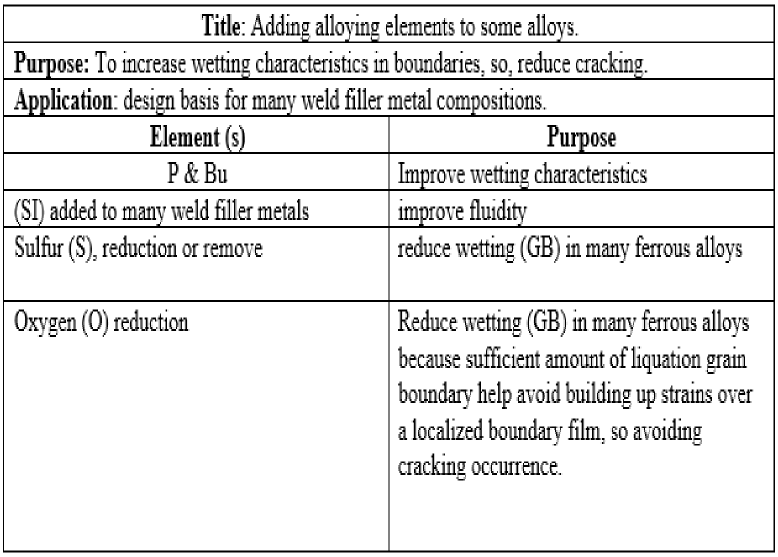
تقييس او التحديد الكمي لخصائص ترطيب الحدود الحبيبيه لخط اللحام تعتمد على الطاقات البينيه في السبائك اعتمادا على نوع النظام الذي تنتمي اليه السبيكه.

In some systems, adding some alloying elements to some alloys systems might help reduce cracking as it helps in controlling on boundary wetting characteristics. The purpose of those additions considered the basis for design many weld filler metal compositions.

الغرض من هذه الدراسه يعتبرالأساس في تصميم الكثير من معادن حشوات اللحام ذات التركيب العناصري الملائم لمنع التشققات في الملحومات الناتجه.

For example, Table (5.2) which highlights the importance of adding impurities such as Phosphorus (P) and boron (Bu) to improve the wetting characteristics, Silicon (SI) addition to many weld filler metals to improve fluidity, Sulfur (S) reduction, reduce wetting of grain boundary in many ferrous alloys, and Oxygen (O) reduction, reduce wetting of grain boundary in many ferrous alloys. Because, sufficient amount of liquation grain boundary help avoids building up strains over a localized boundary film, so avoiding cracking occurrence.

كميه كافيه من ترطيب الحد الحبيبي يساعد على تجنب زيادة حبس كميات عاليه جدا من طبقة الانفعالات الموقعيه. وبهذا يتم تجنب حدوث التشققات.



Title: Adding alloying elements to some alloys.	
Purpose: To increase wetting characteristics in boundaries, so, reduce cracking.	
Application: design basis for many weld filler metal compositions.	
Element (s)	**Purpose**
P & Bu	Improve wetting characteristics
(SI) added to many weld filler metals	improve fluidity
Sulfur (S), reduction or remove	reduce wetting (GB) in many ferrous alloys
Oxygen (O) reduction	Reduce wetting (GB) in many ferrous alloys because sufficient amount of liquation grain boundary help avoid building up strains over a localized boundary film, so avoiding cracking occurrence.

Table5.2: Effect of additions impurities on some alloys systems.

(i) **Effect of restraint(الانكماش) ,**occurs during weld solidification due to the negative volume change resulted from shrinkage, or contraction that occurs during the liquid-to-solid phase transformation, weld bead shape, properties of the surrounding HAZ and base material, the degree of controlling weld geometry, simple changes in weld geometry may be helpful in preventing cracking in materials that have marginal susceptibility to weld solidification cracking, Figure 5.2.

تحدث بسبب التقلص او نقصان حجم مادة اللحام اثناء التجمد. وهو يحدث عند التحول من طور سائل الى صلب للملحومه. ايضا مع شكل قطرة اللحام, خصائص المنطقه المتاثره بالحراره والمعدن الاساس, درجة السيطره على الشكل الهندسي للملحومه. تغيرات بسيطه في الشكل الهندسي للملحومه (بركة اللحام) ربما تكون عامل مساعد في تجنب حدوث تشققات التجمد للمواد التي تكون عرضه لهذا النوع من الفشل.

Qualitative Control on the weld restraint (Contraction) possible achieved by proper joint design, Fixturing, welding process and welding parameters, Material selection and preparation.

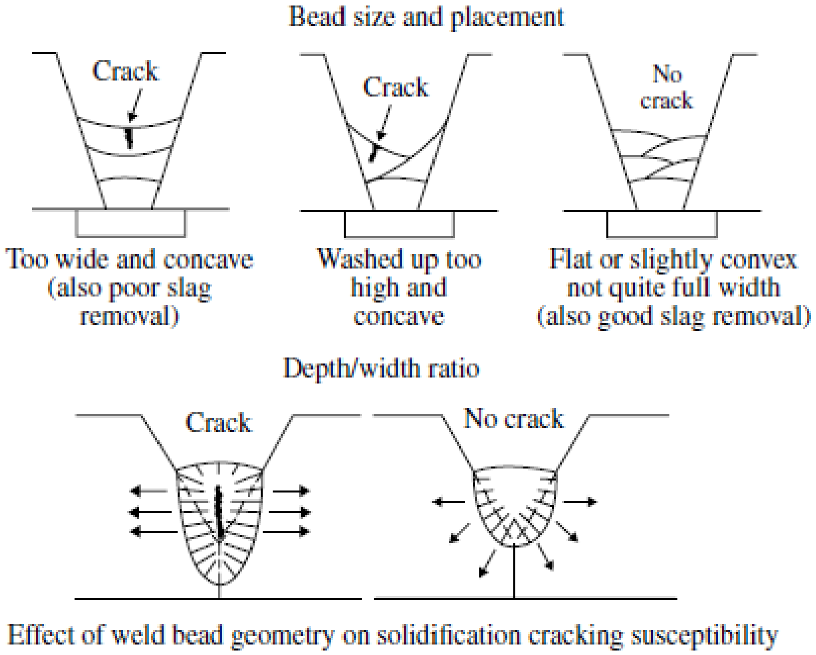


Figure 5.2: Effect of weld bead geometry on solidification cracking susceptibility.

5.1.a.3 Identifying Weld Solidification Cracking.

(i) by using **Metallographic Examination**, used for most materials cracking which occurs along SGBs straightforward. Unusual along sub-grain boundaries (cells or dendritic).

(ii) Using **Scanning Electron Microscopic (SEM-Fracto-graphy)**, at magnifications of 500 or higher/ Fracture surface. Used when no-evidence able to be provided by the metallographic examination and cracking is sever. For example, in structural steels and titanium alloys, where diffusion and elevated temperature transformations have removed any remnants of the solidification structure. The fracture surface of solidification cracks shows a cellular or dendritic morphology, often described as an “eggcrate” appearance. This results from the separation of opposing cellular or dendritic fronts along a thin liquid film at the end of solidification.

(iii) **Depending on the Fracture surface mode**, self-fracture manifestation. This is observed through a ductile or a brittle rupture fracture mode for the metal. This is used to observe the fracture surface on solid–solid bridging, the dendritic to flat fracture.

(iiii) **Phases Identification**, materials that solidify as austenite (fcc) are generally more susceptible to solidification cracking than those that solidify as ferrite (bcc).

5.1.a.4 Preventing Weld Solidification Cracking.

(*i*) Control of solidification behavior, in steel alloys, solidification as ferrite (bcc) rather than austenite (fcc), or reduction of impurity elements (S, P, and possibly B) is helpful to improve cracking resistance.

(*ii*) Control of the volume fraction and distribution of liquid films at the end of solidification, achieved by either minimizing the eutectic liquid films or increasing fraction eutectic to the level that crack backfilling can occur because these methods are not always straightforward. They are based on the composition of the base and filler metals.

(*iii*) Minimizing the solidification temperature range.

(iv) Controlling to Restraint phenomenon.

5.1.b Liquation Cracking.

It is a small cracking, located along grain boundaries (GB) in the PMZ region. It has a diameter equal to diameters of 3 grains before crossing HAZ. The cracks are inter-granular and normally are formed during cooling from peak temperatures above the effective solidus temperature of the material.

شقوق صغيره, واقعه على طول الحدود الحبيبيه في المنطقه الذائبه جزئيا قطرها يساوي مجموع حوالي ثلاث حبيبات باتجاه المنطقه المتاثره بالحراره خلف حد الانصهار. الشقوق تحدث بين الحبيبات وبصوره طبيعيه خلال التبريد من اعلى درجات حراره فوق درجة حرارة بداية الانصهار للماده.

There are two general mechanisms that have been proposed to explain the onset of liquation along these boundaries: Penetration mechanism, and Segregation mechanism. Figure 5.3.

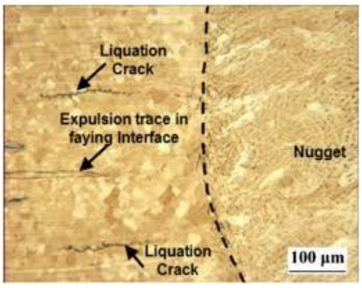


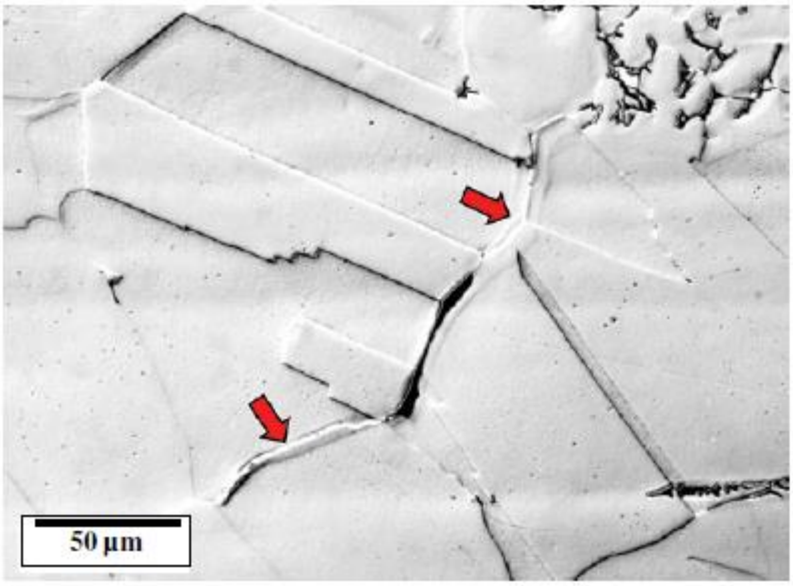
Figure 5.3: Liquation cracking defects.

5.1.b.1 (HAZ) Liquation Cracking.

(HAZ) liquation cracks are generally very small and undetected, occurs via the penetration mechanism. For some alloys above critical temperature, local liquation occurs in the microstructure in the region between fusion zone (FZ) and heat affected zone (HAZ), where grain growth along the grain boundary occurs through thermal driving force. The localized liquid start interacting with the grain boundary through the thermal driving force for grain growth. However, the liquid must be enough to wet or penetrate the grain boundary in order to make it susceptible to cracking. The penetration mechanism for grain boundary liquation requires both a liquation phenomenon and grain boundary motion. When the boundary encounters the liquated particle, it will be “pinned” and further motion inhibited. Depending on the wetting characteristics of the liquid/ boundary combination, the liquid may then penetrate along the boundary. This gives rise to grain boundary liquid films. The degree of penetration depends on the temperature field, the wetting characteristics, and the amount of liquid. An example of HAZ liquation cracking shown in Figure (5.4) in a Type 304L stainless steel. Grain boundary melting is evident by the widening of the boundary, as indicated by the arrows.

عند بعض السبائك وفي درجات حراره حرجه, السيوله الموقعيه تحدث في البنيه المجهريه في المنطقه الواقعه مابين المنطقه المنصهره والمنطقه المتاثره بالحراره, والتي عندها يبدا نمو الحبيبات على طول الحد الحبيبي من خلال القوه الحراريه الدافعه. السيوله الموقعيه تبدأ بالتفاعل الداخلي مع الحدود الحبيبيه من خلال القوه الدافعه الحراريه الخاصه بنمو

الحبيبات. السائل يجب ان يتغلغل او يرطب الحدود الحبيبيه بصوره كافيه حتى يجعلها متعرضه للتشققات. الية التغلغل لترطيب الحد الحبيبي تتطلب ظاهرة الترطيب وحركة الحد الحبيبي. عندما يواجه الحد الحبيبي اجزاء رطبه فانه سيقتطبها ويتم اعاقة حركتها. اعتمادا على خصائص الترطيب مابين الحد الحبيبي/السائل فان عملية التغلغل للسائل تحدث. درجة التغلغل تعتمد على المجال الحراري, خصائص الترطيب, كمية السائل.



HAZ liquation cracking in Type 304L stainless steel

Figure 5.4: (HAZ) liquation cracking in Type 304L stainless steel.

5.1.b.2 Weld Metal Liquation Cracking.

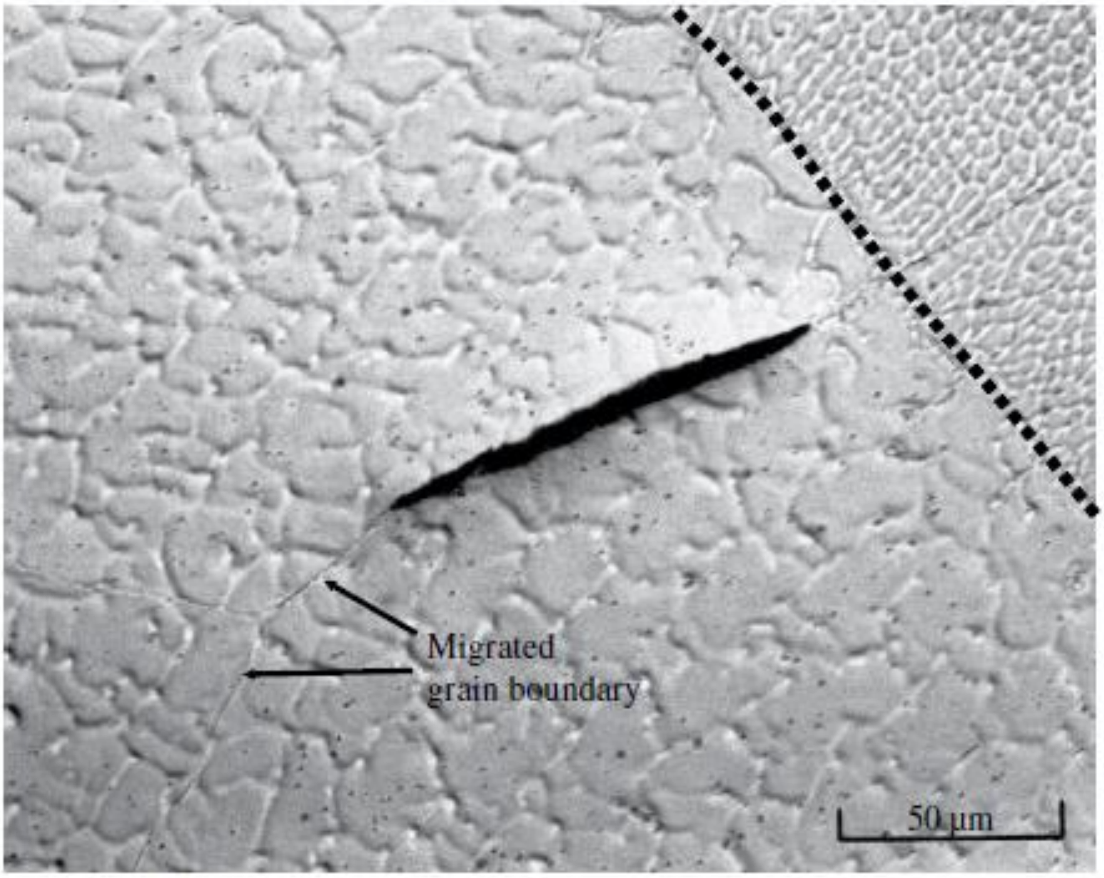
It is another form of liquation cracking that is specific to reheated weld metal (i.e., multi-pass welds). Cracks’ form in very close proximity to the fusion boundary. It is very short crack. These cracks are always inter-granular and may occur along both SGBs and MGBs in the reheated weld metal. Localized melting along SGBs results from the enrichment of alloy/impurity elements arising from partitioning during macroscopic weld solidification. The HAZ in multi-pass welds in effect contains segregated microstructure. Impurity segregation along MGBs is thought to promote liquation and potential cracking at these boundaries. An example of a weld metal liquation crack in fully austenitic stainless steel weld metal is shown in Figure 5.5. This crack is present along an MGB.

تمثل التشققات التي تحدث في الملحومه المتعدده اشواط اللحام.

الشقوق هي مابين الحبيبات وربما تحدث على طول الحدود الحبيبيه المتجمده والمتنقله خلال اشواط اللحام.

الذوبان الموقعي على طول الحدود الحبيبيه ينتج من تخصيب السبيكه بعناصر التسبيك خلال التجمد.

المنطقه المتاثره بالحراره في الملحومات متعددة الاشواط تحتوي على بنيه مجهريه ذات تراكيب معزوله والتي تتجمع على الحدود الحبيبيه المتنقله فتشجع على تجمع السوائل وبالتالي حدوث التشقق



Weld metal liquation crack along a migrated grain boundary in austenitic stainless steel weld metal.

Figure 5.5: weld metal liquation crack.

5.1.b. 3 Variables that Influence Susceptibility to Liquation Cracking.

First, **Composition**, the strongest influence, changes in composition are not a possible solution. Many base metals are already susceptible to HAZ liquation cracking due to elements that are intentionally added. Liquation cracking due to a segregation mechanism is often due to impurity segregation to grain boundaries. For example, (Table 5.3), the most important impurity elements in steel and Ni-base alloys are P and S and in some cases B (Boron). B has positive and negative effect, it improves the creep résistance, at the same time reducing it can affect badly on the service properties. Often, liquation cracking can be reduced or eliminated by reducing the level of impurity elements in the base metal or weld metal.

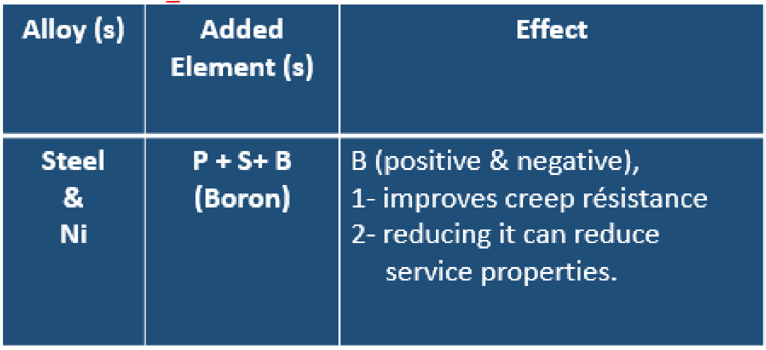
له تاثير كبير جدا في تعرض الملحومه الى التشقق السائله.

العديد من المعادن الاساس هي بطبيعتها عرضه لتشققات المنطقه المتاثره بالحراره بسبب العناصر المضافه لغرض ما.

تشققات السيوله يعزى الى الية العزل التي غالبا ماتحدث بسبب شوائب العزل على الحدود الحبيبيه.

الشوائب في الستيل والنيكل هي الكبريت والفسفور والبورون.

تشققات السيوله يمكن ازالتها بتقليل مستوى الشوائب في المعدن الاساس والمعدن الملحوم.



Alloy (s)	Added Element (s)	Effect
Steel & Ni	P + S+ B (Boron)	B (positive & negative), 1- improves creep résistance 2- reducing it can reduce service properties.

Table5.3: The most important impurity elements in steel and Ni-base alloys.

Second, **Grain Size**, grain size in the weld metal is controlled by weld heat input. As the grain size increases, HAZ liquation cracking susceptibility increases. This is because increasing grain size decreases the possibility to complete grain boundary wetting leading to reducing the area of grain boundary because of accumulation strain during welding and produce a weaker microstructure causing cracking. The reverse occurs in-case of small grain size. Small grain size with presence liquid film will also prevent strain localization and potential cracking.

Third, **Base Metal Heat Treatment,** base metal strength effects on accumulation localized strains in the HAZ during weld solidification. So, heat treatments are necessary for welds to release these accumulated strains before, during or after welding. Examples Types of Heat treatments required, Welding precipitation-strengthened materials, such as Ni-base super alloys. Solution heat treatment dissolves “constituent” particles that may subsequently liquate and also minimizes intrinsic restraint by reducing the strength level of parent material. Welding in the solution-annealed condition is also used to reduce weld solidification cracking. The side effect of this heat treatment represents by the possibility of increasing grain size that cause cracking susceptibility. So, balancing between the heat treatment required and controlling grain size required to solve this problem.

Fourth, **Heat Input and Filler Metal,**

(i) Heat input will influence the temperature gradient in the HAZ and subsequently control the extent to which liquation occurs. Since HAZ and weld metal liquation cracking occur over a fixed temperature range.

(ii) A steep temperature gradient in the HAZ (low heat input) can reduce the extent of grain boundary melting in the HAZ.

(iii) strength of the filler metal has effect on the strength of the HAZ. Since much of the restraint in the HAZ is associated with solidification shrinkage in the weld metal, lower-strength filler metals can generate less shrinkage stress that is translated to the HAZ or underlying weld metal.

5.1.b.4 Identifying HAZ and weld metal Liquation Cracks.

HAZ liquation cracks are always located along HAZ/PMZ grain boundaries, close to the fusion boundary or continuous across the fusion boundary into the fusion zone. They are formed during cooling from the peak temperature of HAZ. This is when strain accumulates in the system due to thermal contraction.

المنطقه المتاثره بالحراره عادة واقعه على طول الحدود الحبيبيه للمنطقه المتاثره بالحراره, وقريبه من الحد الحبيبي أو مستمره عبر الحد الحبيبي الى المنطقه المنصهره. هذه التشققات تتكون خلال التبريد من الدرجات الحراريه القصوى للمنطقه المتاثره بالحراره. هذا يحدث عند تجمع الانفعال بالسبيكه التي تتعرض للحام بسبب التقلص الحراري.

Metallographic ally, these cracks may be evident on the surface and in a weld cross section. They are usually very small and may escape detection by non-destructive testing techniques.

مجهريا, هذه التشققات تظهر على السطح, او خلال مساحة المقطع. تكون هذه التشققات صغيره جدا ومن الصعب الكشف عنها في الفحوصات الميكانيكيه اللاتدميريه.

The fracture surface appearance is inter-granular. Grain’s face has partially melted particles. The degree of melting particles dependent on liquation nature of grain boundary. The inter-granular fracture surface seems a very clean grain faces in alloys because the minimum amount of liquid.

ظهور سطح الكسر يكون بين الحبيبات. وجه الحبيبه ذائب جزئيا. درجة ذوبان الحبيبات يعتمد على طبيعة ترطيب الحد الحبيبي. سطح الكسر بين الحبيبات يبدو بوجه نظيف جدا بالسبائك بسبب الكميه القليله من السائل.

Two examples of HAZ liquation crack surfaces from SEM fracto-graphy are shown in Figures 5.6 and 5.7.

According to Figure 5.6,

Test name: Hot Ductility Test.

Test condition (temp): Nil ductility temperature.

Material name: Duplex stainless steel.

Fracture type: Inter-granular.

Distinct Evident: A clean fracture surface + Existence little amount of liquid film.

These steels are very resistant to HAZ liquation cracking, since grain boundary melting occurs over a narrow temperature range.

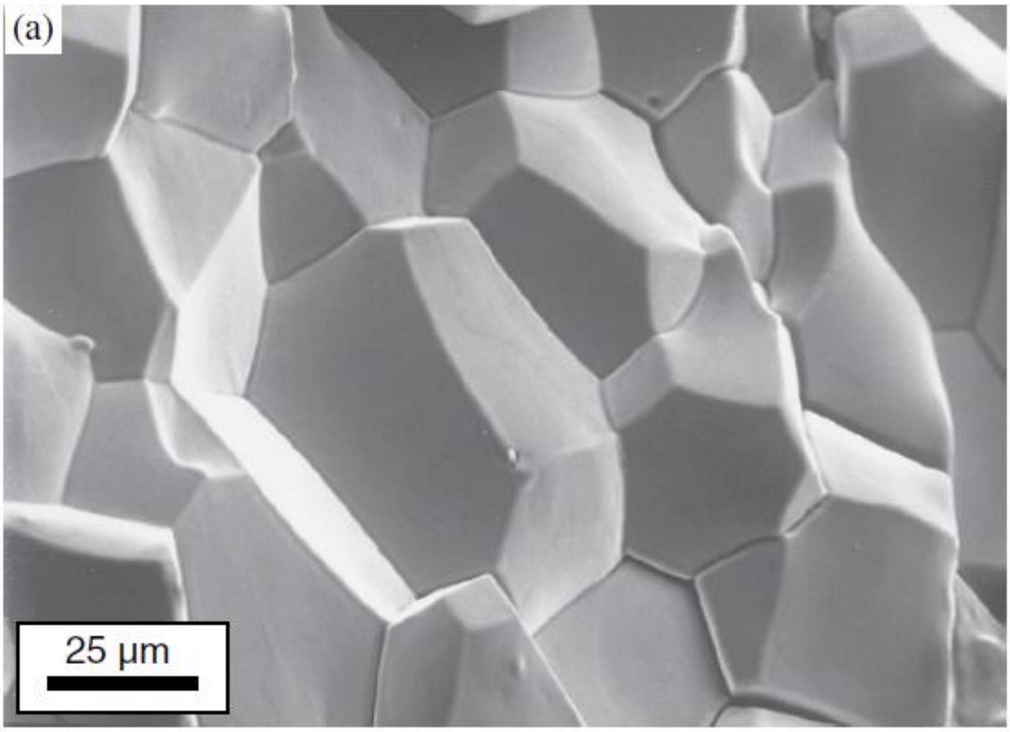


Figure 5.6: Fracto-graphy of HAZ liquation cracking: (a) duplex stainless steel

According to Figure 5.7,

Test name: Cladding Operation/ (Multilayer cladding operation).

Test condition: (Multi-pass weld) \ (Reheated weld metal)\

Material name: HSLA Steel

Fracture type:

1) fracture surface,
2) weld metal liquation cracks may Exhibit through:
   (i)an inter-granular appearance if cracking occurs along MGBs.

(ii)Dendritic appearance if the cracking occurs along weld metal SGBs. In some situations, both fracture modes may be observed on the same fracture surface indicating a transition from SGB to MGB fracture.

Distinct Evident:

(i)Re-solidified liquid film.

(ii)Cracking may occur either on heating or on cooling when heated above the liquation temperature, depending on how strain accumulates in the system upon reheating.

(iii)Cracking can be observed along both SGBs and MGBs and may be observed along both types of boundary in the same weldment.

(iiii)Has a much wider liquation temperature range than the duplex stainless steel, so cracking is expected.

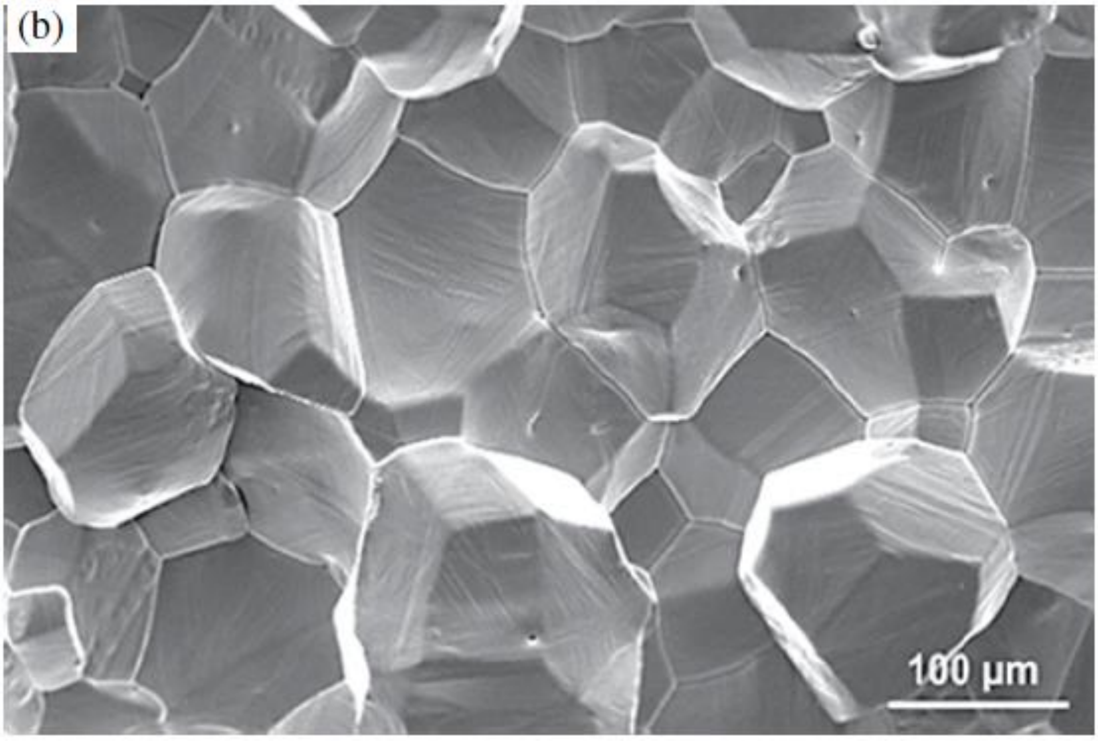


Figure 5.7: Fracto-graphy of HAZ liquation cracking.

5.1.b.5 Preventing Liquation Cracking.

Many of the same guidelines for preventing weld solidification cracking are applicable for HAZ and weld metal liquation cracking.

(i)Control of impurity levels in base and filler metals is always recommended. Base metals that contain constituent particles such as TiC and NbC in an austenite matrix can lead to constitutional liquation. Often, Ti and Nb are intentional alloy additions and, therefore, difficult to avoid in some alloys. Fully austenitic microstructures are the most susceptible.

(ii)The presence of some ferrite in the austenitic stainless steel HAZs and welds will minimize both HAZ and weld metal liquation due to its influence on wetting characteristics.

(iii)Minimizing grain size is beneficial, generally requires the use of low heat input.

(iiii)Manipulating orientation: grain boundary orientation to avoid miss-orientation.

(iiiii)Low-energy, “special” grain boundaries increase resistant to the formation of liquid films.

(iiiiii)Reducing restraint, it is possible to be applied for many high-strength, precipitation-hardened alloys such as (Ni-base super-alloys) by welding these types of alloys in the condition of solution heat-treated condition to reduce the internal restraint in the HAZ.

(iiiiiii)Weld metal liquation cracking can often be eliminated by using multiple small beads rather than large welds. This has both a metallurgical and restraint benefit.

5. 2 Warm Cracking (Solid State Cracking).

Solid state cracking occurs in the true HAZ or reheated weld metal for all types of materials such as steels, stainless steels, Ni-base alloys, Cu-base alloys, and Aluminium alloys. There are different types of solid –state cracking: Ductility-dip cracking (DDC), Reheat/post-weld heat treatment (PWHT) cracking, Strain-age cracking (SAC), Lamellar (or delamination) cracking, Copper contamination cracking, Hydrogen /Induced Cracking).

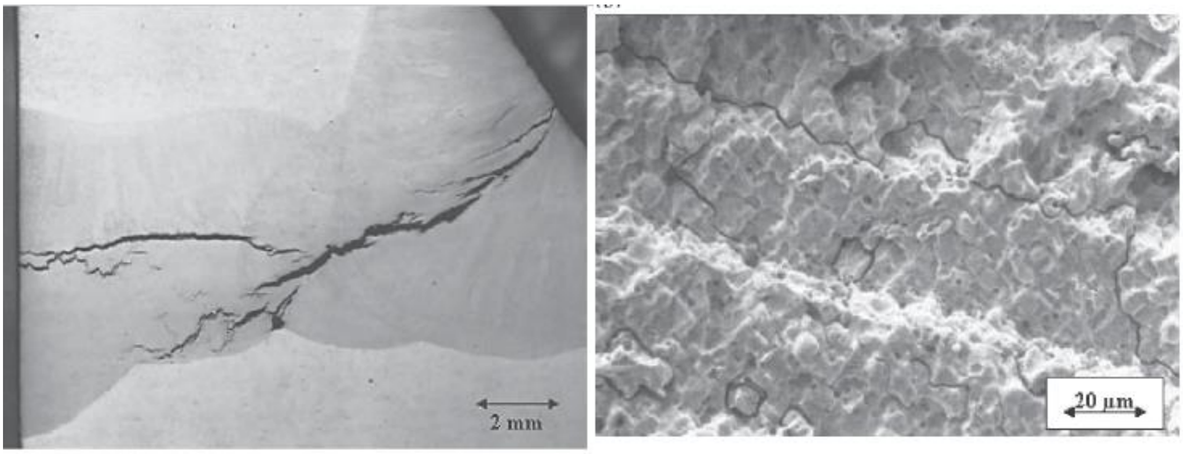
5.2.a Reheat cracking (Stress Relief Cracking).

It occurs due to accumulation residual stresses. Stainless Steels are the most materials which are susceptible to reheat cracking. To reduce the residual stress, PWHT or stress relief heat treatments following welding is recommended. This type of heat treatment helps temper martensitic microstructures, or reduce residual stresses, or both. It occurs during multi-pass welds, cladding of some pressure vessel steels.

5.2.a.1 Reheat Cracking in Stainless Steels.

Reheat cracking is observed in austenitic microstructure of stainless steels.

(i) *Stainless Steel type 347*, is susceptible to reheat cracking in the HAZ and fusion zone in the thick sections only. Because this type of steel is a stable grade of niobium which helps reduce susceptibility to corrosion. The mechanism for cracking in Type 347 is associated with the precipitation of NbC (كربيد النيوبيوم) during reheating cycle. During inter-granular precipitation of NbC, localized high strains concentrate at grain boundaries of the structure increasing grain growth in the HAZ, and promoting cracking, Figure 5.8.



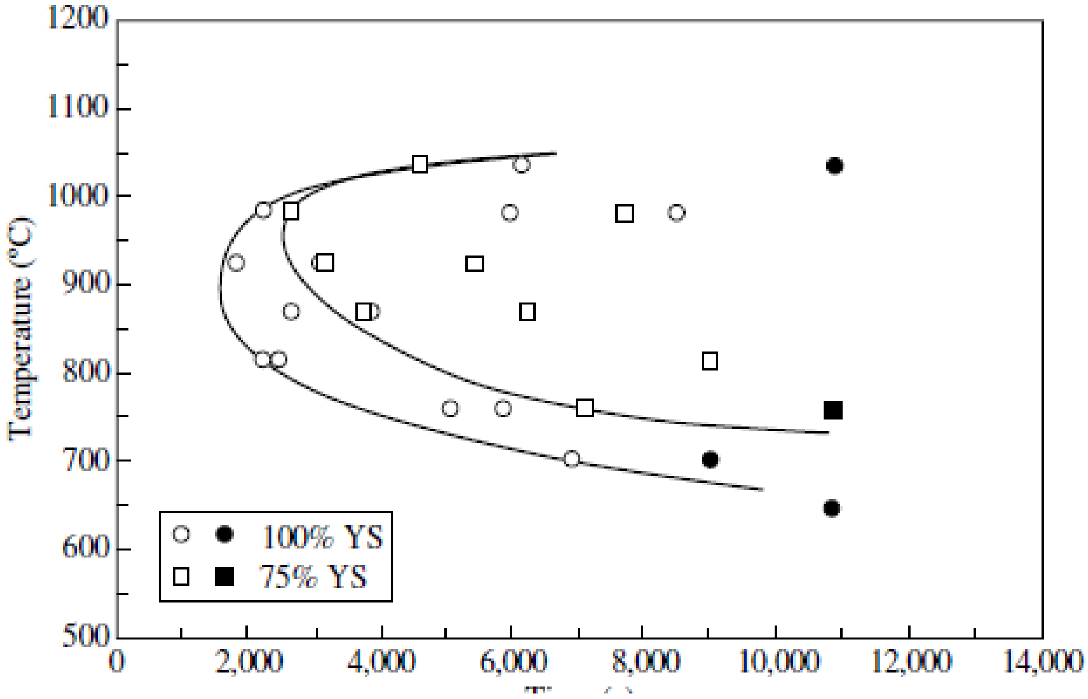
Example of reheat (stress relief) cracking in Type 347 stainless steel.

Figure 5.8: Reheat cracking in 347 stainless steel.

For example, reheat cracking in Type 347SS weld metal. The ASME code requirement for this type of alloy includes:

1) The structure be stress relieved in the temperature range from 850 to 900°C (1560 to 1650°F) before putting into service. This resulted in severe reheat cracking in the weld metal.

2) The fracture occurs along MGBs in the weld metal. The cracking susceptibility of Type 347 weld metal exhibits a C-curve cracking response, as shown in Figure 5.9. The two curves shown represent the onset of cracking when a weld metal sample of Type 347 was loaded to either 75% or 100% of its yield strength at a given temperature and held at that temperature until fracture occurs. By plotting the fracture time at a given temperature, the reheat cracking envelope can be determined. The cracking "envelope" described by these two C curves represents the precipitation temperature range of NbC in stainless steel. For example, at 900°C (1650°F), reheat cracking occurs within 2000 s when yield strength-level stresses are present.



Temperature–time cracking envelope for Type 347 weld metal under two stress conditions.

Figure 5.9: Temperature- time cracking envelope for 347 weld metal under two stress conditions.

(ii) **Alloy 800H (Ni-base alloy)**

Thick-section welds in Alloy 800H.

Chemical Composition: (Fe–20Cr–32Ni–0.5Ti–0.5Al–0.1C)

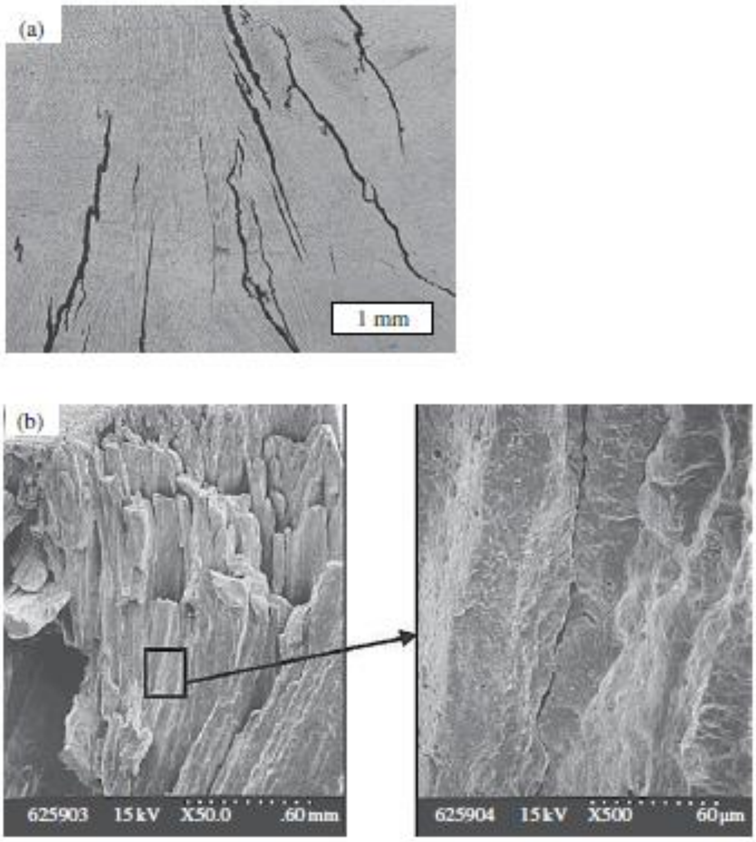
Used Electrode: Weld A (ENiCrFe-2) shielded metal arc electrodes.

Heat treatment required: PWHT following welding

The purpose: for stress relief and to avoid cracking in service

The nominal composition of Weld A is Ni–15Cr–8Fe–1.5Mo–**1.5Nb**–0.05C.

Stress relief was performed at 900°C (1650°F) and led to the cracking shown in Figure 5.10-a.



PWHT cracking in ERNiCrFe-2 (Weld A) weld metal after stress relief at 900°C.
(a) Cracking along weld metal migrated grain boundaries and (b) fracture surface morphology.

Figure 5.10: Reheat cracking in Alloy 800H (Ni-base alloy).

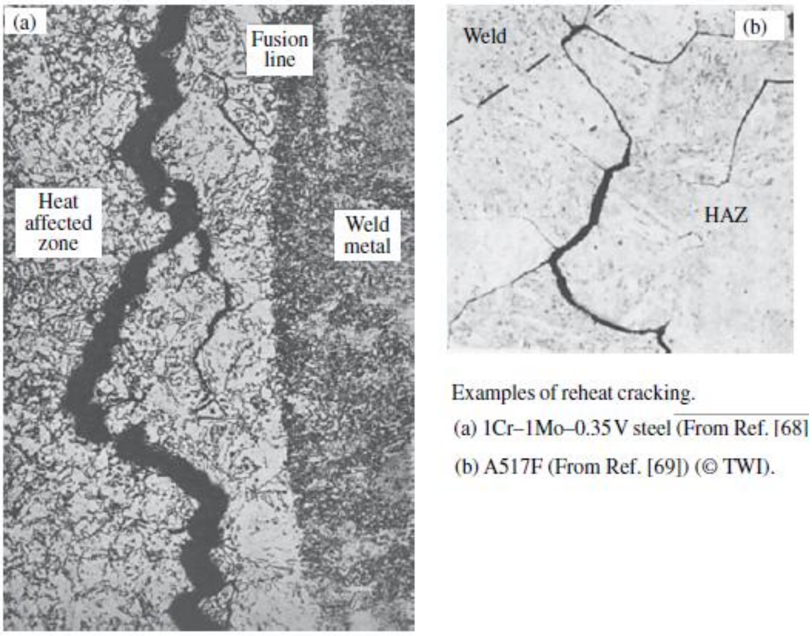
The cracking occurred in the weld metal rather than the Alloy 800H HAZ. Figure (5.10-b) the cracking occurs along MGBs in the weld metal. This is due to Nb presence in the filler metal resulted in the precipitation of NbC during PWHT and promoted cracking at the grain boundaries. The precipitation temperature range for NbC in this weld metal is very similar to that for Type 347, and thus, the time–temperature cracking envelope shown in Figure 67 is roughly the same for the Weld A filler metal.

5.2.a.2 Identifying Reheat Cracking.

(i) Composition, addition of Cr, Mo, and V to steel alloys could cause reheat cracking. This is because these elements form secondary carbides in the steel alloys. Using SEM/XEDS techniques reveal the presence of impurity elements such as

- (S +P): Associated with HAZ liquation cracking that may occur in steels**.**

And, (Cu +As+ Sn+ Sb): their presence on the fracture surface is a strong indication for reheat cracking.



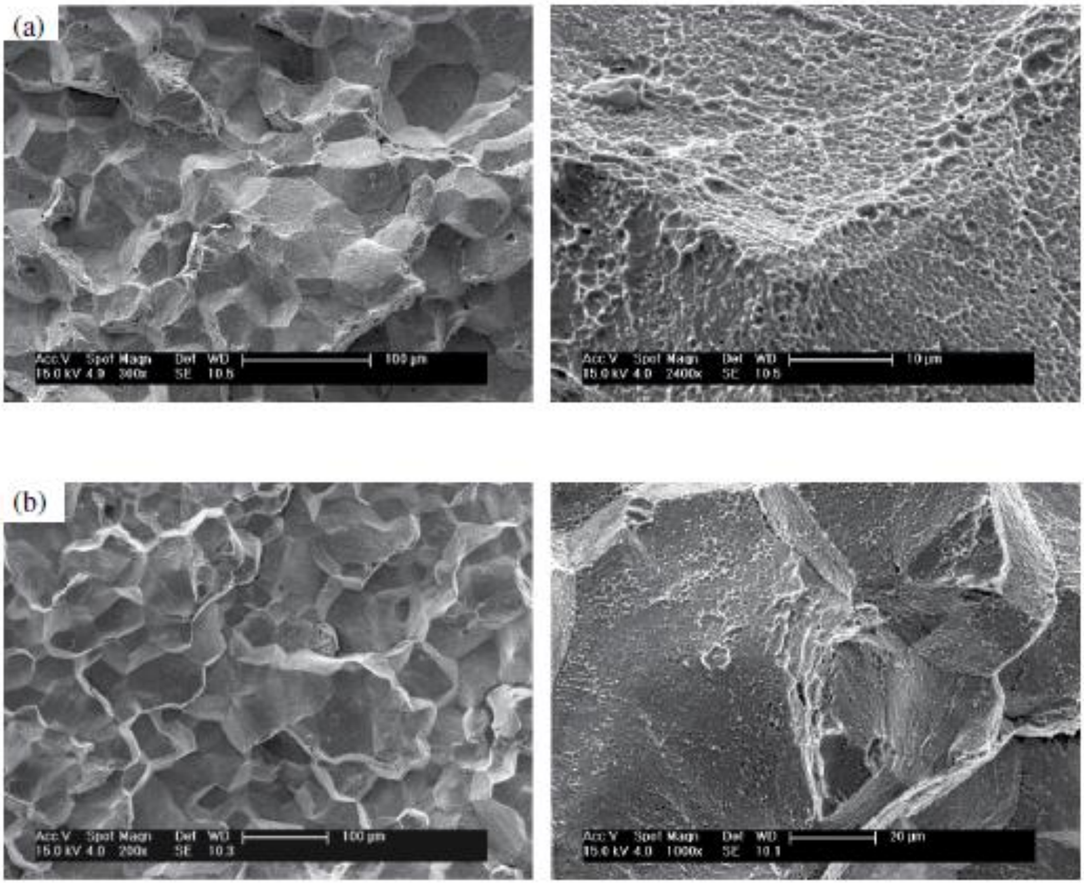
Examples of reheat cracking.
(a) 1Cr–1Mo–0.35 V steel (From Ref. [68]
(b) A517F (From Ref. [69]) (© TWI).

Figure 5.11: Effect of composition on formation reheat cracking.

(ii) Fracto-graphic Features, two general types of fracture or failure modes are associated with reheat cracking.

a) Failure mode 1: A classical IG fracture (flat and relatively grain faces) is generally associated with susceptible materials that fail at low temperatures and/or that have a relatively high impurity content.

b) Failure mode 2: a ductile IG mode (The IG dimples and associated with grain boundary precipitates of MnS) is generally associated with the susceptible materials that fail at higher temperatures (>500°C) or when the impurity content is low.



Fracture appearance of reheat cracks in low-alloy steels. (a) Ductile intergranular and (b) low ductility intergranular. Note difference in magnification (Courtesy of Katie Strader and Xiuli Feng, OSU).

Figure 5.12: Fracture appearance of reheat cracking for ductile and brittle low alloy steel.

5.2.a. 3Quantifying Reheat Cracking Susceptibility.

Quantifying reheat cracking susceptibility means measurements methods. It includes different type of tests on the weld used for the purpose to avoid reheat cracking. There are different methods for this purpose such as By using externally applied load (or strain), The Lehigh restraint test, Y-groove test, Modified implant test, and BWRA test. All the tests above require Sectioning after testing to determine if reheat cracks are present.

5.2.a. 4 Preventing Reheat Cracking.

(i) Composition control, generally as the secondary carbide former content and carbon content increase, the material becomes more susceptible to reheat cracking. Impurities could contribute to formation reheat cracking through diffusion mechanism to grain boundaries and lowering the boundary cohesive strength. Reducing impurity content can improve cracking resistance in most of the susceptible materials.

(ii) Effect of welding conditions, minimize weld heat input in order to reduce HAZ grain size because in both steel alloys, the larger grains in the HAZ the more susceptibility to reheat cracking. Also, less grain boundary area results in higher-strain localization at the boundaries. Finer grains help to better distribute the strain and minimize void formation and/or boundary sliding.

(iii) Control of residual stresses, is associated with thick-section weldments where the level of residual stress following welding is quite high—approaching the yield strength of the base or weld metal. By many techniques such as, (a) Control of bead size and (b) placement and welding sequence, (c) Selection filler metal with strength matches that of the base metal. This help concentration the restrains in the weld metal rather than the HAZ during cooling.

(iiii)Effect of stress concentration: This includes elimination of slag intrusions at the weld toe, grinding or blending the weld toe, or use of other material removal techniques to eliminate stress concentrations. Since cracking usually initiates in the HAZ very close to the fusion boundary, attention to this area of the weldment is very important. Welds with partial penetration, lack-of-fusion, or other process-related defects can also greatly increase stress concentration. Defects of this type that are open to the surface are the most damaging. "Peening" technique is suggested to apply to avoid stress concentration. Peening technique: means generate local compressive stresses on the weld surface and potentially mitigate initiation of reheat cracks.

5.2.b Lamellar Cracking\ Delamination Cracking.

Lamellar cracking (تشقق رقائقي) occurs in HAZ region usually associated with plain carbon or low-alloy steels depending on material cleanliness. For example, Impurities such as sulphur and oxygen promote formation of intermetallic inclusions during steel processing that serve as the initiation sites for lamellar cracks.

على سبيل المثال,وجود شوائب مثل الكبريت والاوكسجين يمكن ان يشجع تكوين متضمنات سبائكيه خلال عملية انتاج الستيل والتي تكون نقطه لنشوء الشقوق الرقائقيه.

Lamellar cracking results from the local separation in between the intermetallic stringers in the HAZ.

تنتج التشققات الرقيقه من الانفصال الموقعي بين الجزيئات السباكيه في المنطقه المتاثره بالحراره

Generally, it occurs in the rolled plate material welds when their section thickness exceeding one inch.

تحدث عامة في الملحومات المصنوعه من مواد ذات الواح مدرفله.

5.2.b.1 Mechanism of Lamellar Cracking.

Occurs due to:

(i) Low ductility in the transverse direction of the parent alloy (rolling direction). المطيليه الواطئه بالاتجاه العرضي للمعدن الاساس (المعدن الأساس)

(ii) Using thick plate which leads to gathering restraint

أستخدام الالواح السميكه التي تؤدي الى تجمع الانفعالات

(iii) High volume fraction of inclusions in the welds which generate Stresses (ارتفاع حجم الجزيئات الغريبه في الملحومه التي تولد اجهادات), welding stresses are high enough to exhaust the ductility through thickness of the base metal and HAZ. An example of a configuration where high stresses can lead to lamellar cracking is shown in Figure 5.13.

التشقق الرقائقي سوف يحدث عندما تزداد نسبة اجهادات اللحام الزائده الى الحد الذي تجهد فيه مطيلية المعدن الاساس باتجاه السمك وباتجاه المنطقه المتاثره بالحراره. كما في المثال الموضح.

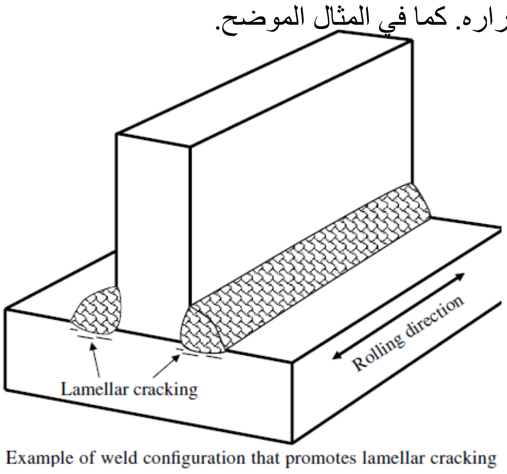


Figure 5.13: Example of weld configuration that promotes lamellar cracking.

Failure occurs due to the availability of (C-Mn) alloying elements in (HAZ) of low alloy steels or low carbon steel alloys. So, the fracture would start from ferritic–pearlite matrix and elongated stringers or inclusions resulting a de-cohesion at that interfaces between the stringers and the matrix.

الفشل يحدث بسبب وجود (كربون-منغنيز) في المنطقه المتأثره بالحراره لسبائك الستيل الواطئة الكربون. وبهذا, الفشل سوف يبدأ من المنطقه مابين محتوى فرايت-بيرلايت والجزيئات الغريبه الطوليه الممتده على اتجاه الدرفله مسببة الأنفصال عند السطح البيني بين المحتوى والجزيئات الغريبه.

Stringers (Inclusions): they are the remnants of the ingot solidification and subsequent deformation processes. Stringers represented by sulphur, oxides, silicate.

المتضمنات: هي جزيئات متبقيه ناتجة من تجمد المصبوبات ومن عمليات التشوه اللدن المتتابعه. الجزيئات الناتجه متمثله بالكبريت والاكاسيد والسيليكا.

For example, failure by sulphur stringers occurs due to formation (Manganese sulphide/ MnS) along the rolling direction oriented via the deformation or (rolling process). The sulphur came from rejecting it along grain and sub-grain boundaries during solidification. So, the sulphur either to be formed like bands with the same rolling direction or distributed uniformly as discrete particles over the grain boundaries line.

مثال: الفشل بسبب جزيئات كبريت تحدث نتيجة تكون كبريتيد المنغنيز على طول اتجاه الدرفله عن طريق عملية الدرفله (حيث يحدث فيها تشوه اللدن). خلال دورة التجمد سوف يرفض الكبريت من على طول الحدود الحبيبيه أو شبه الحبيبيه. يحدث رفض الكبريت بانفصاله عن ذرات المنغنيز. ولهذا, الكبريت يتكون اما على شكل شرائط او اجزاء متقطعه على امتداد خط الحدود الحبيبيه.

A Metallographic image (Figure 5.14) describes the lamellar cracking locations.

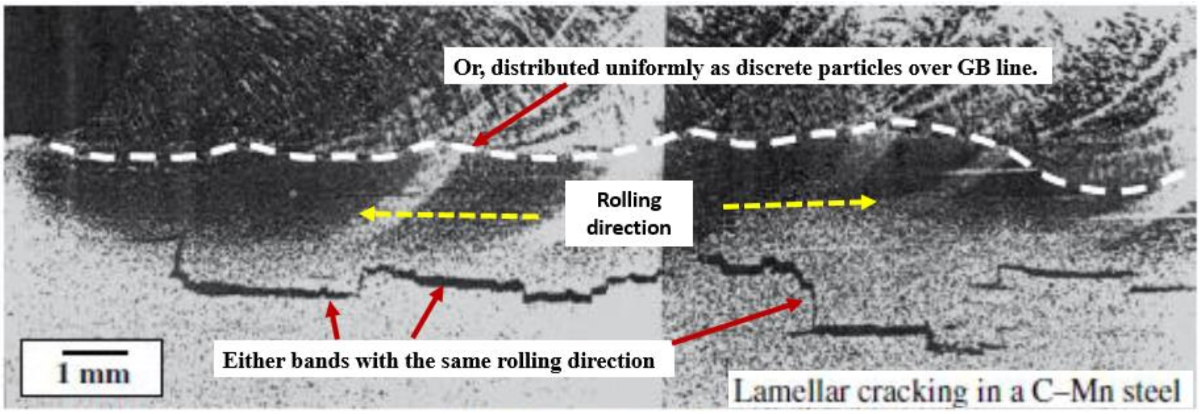


Figure 5.14: Lamellar cracking in a C- Mn steel.

By looking at Image in Figure 5.14, the dot line is fusion boundary (FB), the stair step fashion propagation in untransformed region of HAZ represents Lamellar cracking, Located at some distance from the fusion boundary. Crack initiation point (crack's tip) considers the region of presenting plastic strain causing fracture surface with a ductile tearing. This ductile tearing encourages connecting individual cracks which are located at different levels to each other taking the appearance of ''stair step or terraced'' lamellar cracking.

نقطة نشوء الشق (قمة الشق) تعتبر منطقة تواجد الانفعال اللدن الذي يسبب التمزق المرن. التمزق المرن يشجع على ربط الشقوق الفرديه المتناثره والواقعه بمستويات مختلفه مع بعضها البعض متخذة المظهر الموصوف بالتشقق (ذا الخطوات المدرجه).

The terraced appearance represents de-cohesion at the stringer/matrix interface and the ligaments joining. See Figure 5.15.

المظهر المدرج يمثل الأنفصال مابين السطح البيني للنسيج البنيوي/المتضمنات و الاربطه.

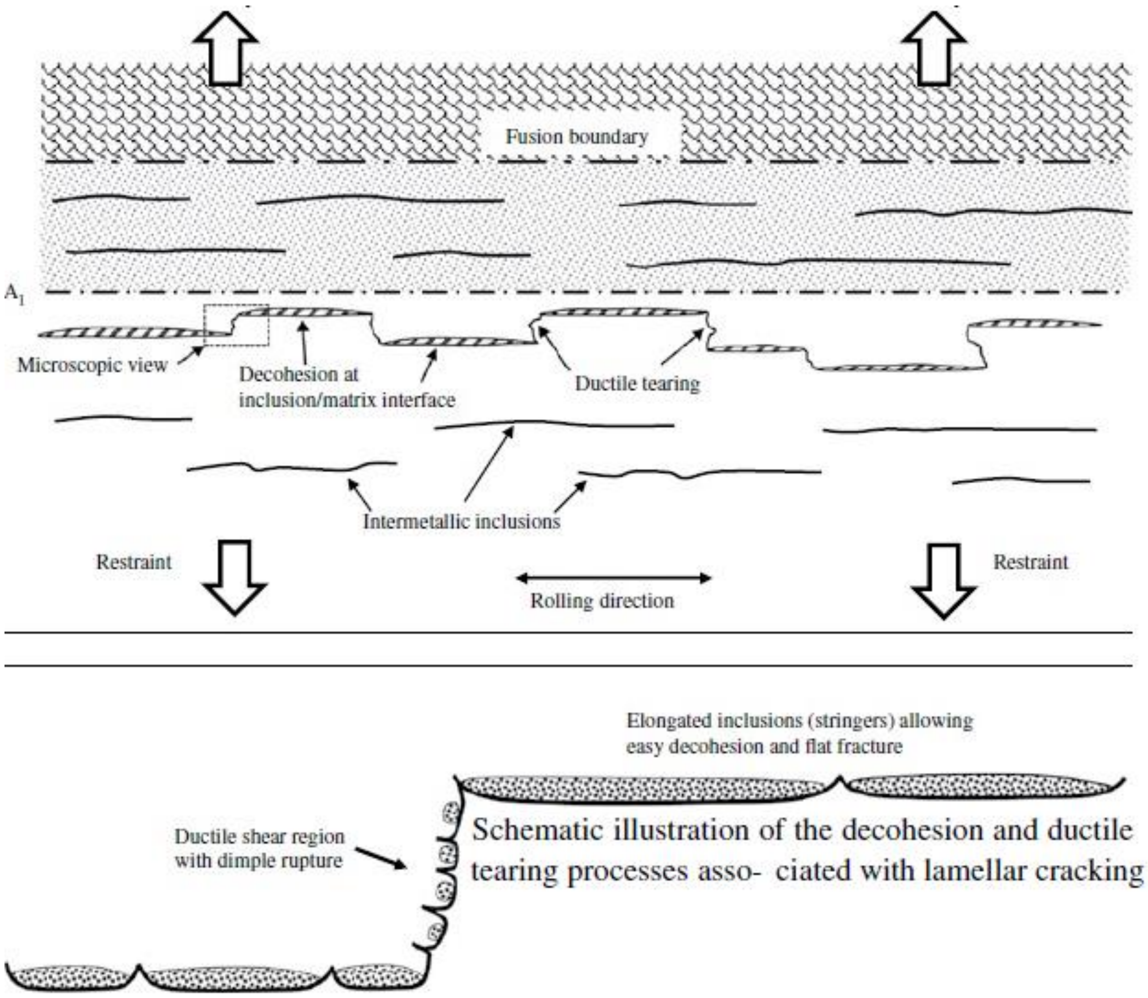


Figure 5.15: A schematic of the de-cohesion and ductile tearing process.

5.2.b.2 Identifying Lamellar Cracking.

(i) Cracks normally exhibit an irregular, “stair step” appearance.

(ii) Lamellar cracks normally located in the HAZ.

(iii) Metallographically, the cross section appears in either the etched or un-etched (as-polished) conditions.

(iiii) The fracture surface usually consists of a number of plateaus or terraces.

(سطح الكسر دائما يحتوي على عدد من الهضاب والتدرجات)

(iiii) Ductile tearing is typical in the segments connecting the plateaus.

(التمزق المطيلي هو قطع شرائحيه تربط الهضاب مع بعضها البعض)

(iv) Fracture mode on the plateau (representing the stringer/matrix interface) may vary from flat fracture to microscopic dimpled rupture

نموذج سطح الكسر للهضبه (السطح البيني مابين النسيج والمتضمنات) يمكن ان يتراوح مابين سطح كسر مستو او سطح كسرمنقر.

5.2.b.3 Preventing Lamellar Cracking.

(i) Selection the clean steel alloys, which include the lower levels of sulphur and oxygen reduce the formation of intermetallic inclusions in the form of stringers along the rolling direction

اختيار السبائك النظيفه التي تتضمن اقل الكميات من الكبريت والاوكسجين يقلل من تكوين المتضمنات السبائكيه بشكل اجسام غريبه على طول اتجاه الدرفله

2) Selection steels with additions of rare earth elements such as ‘’**cerium**’’. Because cerium element reacts with sulphur element in the steel to produce **a spheroid zed sulphide** which control on inclusions morphology. So avoid formation elongated sulphide stringers.

اختيار الستيل الذي يحتوي على عناصر خامله مثل السيروم لان السيروم يتفاعل مع الكبريت في الستيل لينتج كبريت كروي الشكل والذي بدوره يساعد في تنعيم شكل سطح المتضمنات. وبهذا سوف يساعد على تجنب تكون متضمنات الكبريت الطولية.

3) Substituting castings or forgings process instead of rolling process. Because rolling encourage lamellar cracking while forging or casting able to break the inclusions in the structure which encourage formation lamellar cracking.

استبدال عملية السباكه والطرق بدلا من الدرفله في انتاج الستيل لان الدرفله تشجع على التشقق الرقائقي بينما الطرق والسباكه تشجع على تكسير المتضمنات التي تشجع تكوين الشقوق في البنيه.

4) Selection the appropriate design for weld joint that minimize generation stresses in the weld.

اختيار التصميم المناسب للملحومه والذي يقلل من تولد الاجهادات داخل الملحومه

5) Changing the weld pass sequence and the size of the individual weld beads to reduce the weld stresses that lead to cracking.

تبديل عدد مرات اللحام (اشواط اللحام) وحجم كرية اللحام لتقليل الاجهادات بالملحومه التي تؤدي الى التشقق الرقائقي.

6. Weld Failure Concept.

Welded structures that are essentially free of defects may be susceptible to failure under certain environmental and loading conditions. Forms of failure in welded structures are possible due to changes in a microstructure relative to the base metal, stress concentration, and the pre-existed fabrication defects. This leads to incidences of catastrophic in welded structures such as bridges, ships, and large storage tanks. To identify the failure reasons, there are two main concepts, Figure (6.1) should be studied.

First: Characterization (Identification) weld Fracture Surface morphology through advanced techniques, such as scanning electron microscope (SEM) devices.

Second: applying the critical stress intensity factor (K) approach to determine if weld induced flaws (defects) were responsible for failure or whether design deficiencies were at fault.

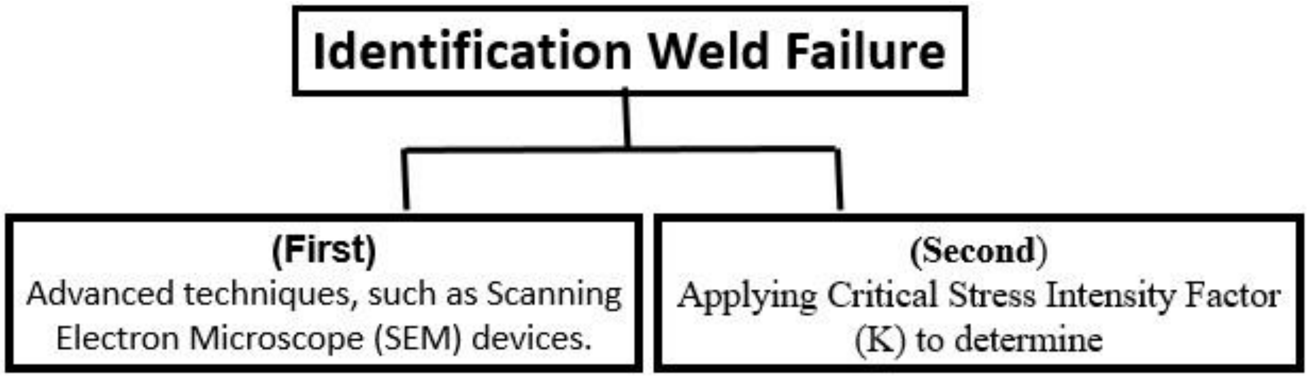


Figure 6.1: Main concepts to identify weld fracture.

6.1 Weld Fracture Surface Morphologies.

Using scanning electron microscopy (SEM) technique helps identify the defects and characterize their types, e.g. cracks types. This course highlights the steps for identification three types of cracks through using (SEM) as an example. This identification represents a completed picture for sections: (5.1.a Weld Solidification Cracking), (5.1.b Liquation Cracking), and (5.2.a Reheat cracking). See Figure 6.2.

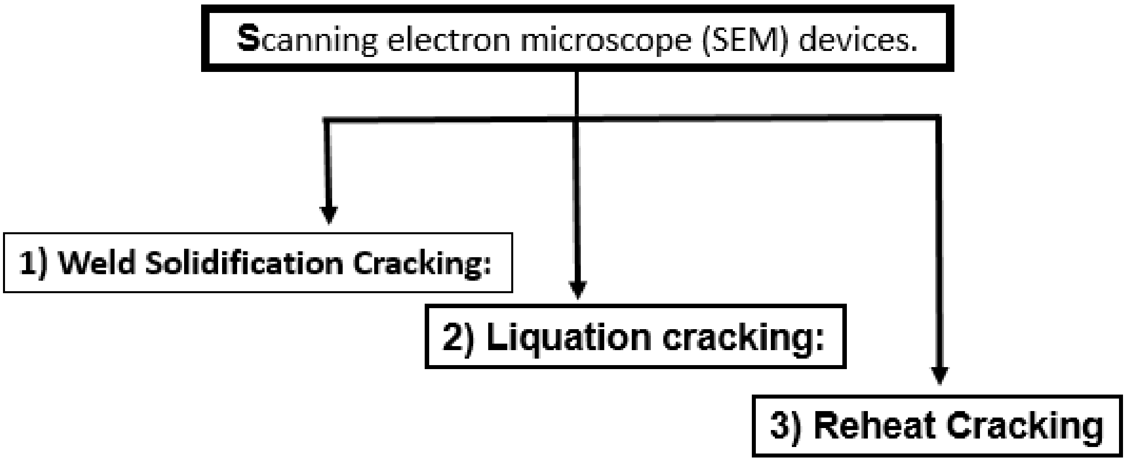


Figure 6.2: Sketch for cracks' types identified by (SEM) technique.

6.1.a Weld fracture surface morphologies in weld solidification cracking.

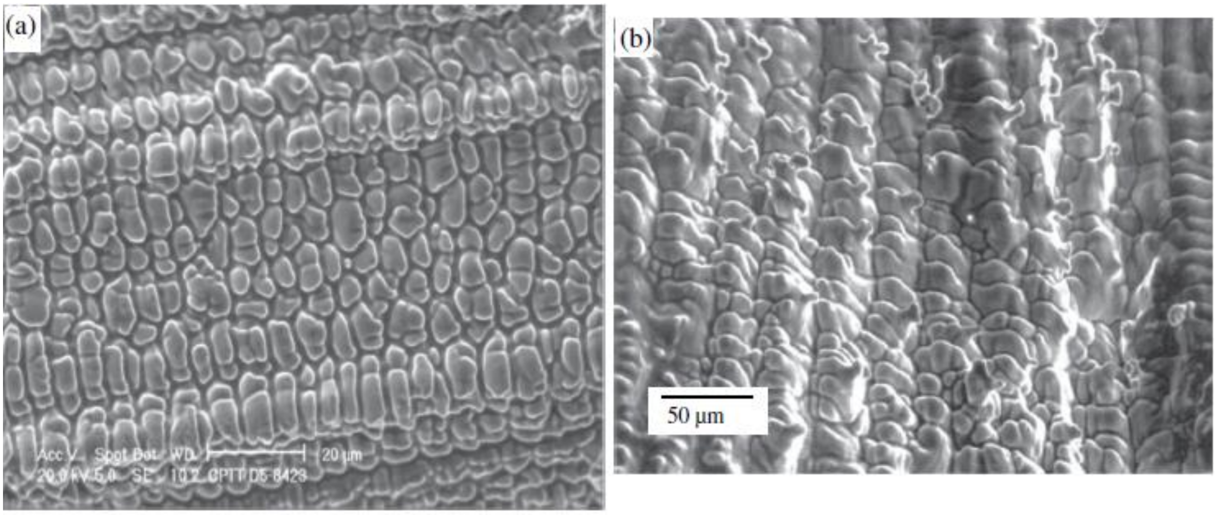
(i) Solidification cracking usually occurs along solidification grain boundaries (SGB), see Figure (3.13).

(ii) The fracture surface is smooth, with liquid presence and have an ‘’egg crate’’- type appearance due to exposing the tips of solidification dendritic cells to fracture surface. This is classified as an observed fracture. Examples, occurs in Ni-base alloy, duplex stainless steel, and aluminium alloy weld metals, Figure 6.3.

(iii) Have a flat appearance (FA) crack surface morphology due to cooling down the weld metal below the solidus temperature which causes change in the nature of the solidification grain. Occurs in some alloys (Ni-base alloys and austenitic stainless steels).

(iiii) Solidification cracking having the possibility to transform from a dendritic morphology to a ductility-dip crack (DDC) with a flat fracture appearance. Mostly occurs in Ni-base alloys and fully austenitic stainless steels. This is not observed fracture.

(iiiii) Solidification cracking have a decoration of the dendrite surface with a second phase due to eutectic reactions that occur during the terminal stages of solidification. An example, Figure (6.4) of this for a Nb-bearing Ni-base alloy. In this case, the eutectic reaction that occurs at the end of solidification results in the presence of NbC on the dendrite surface.



Solidification crack fracture surfaces. (a) Ni-base alloy, (b) duplex stainless steel,

Figure 6.3: Fracture surface morphology in different alloys.

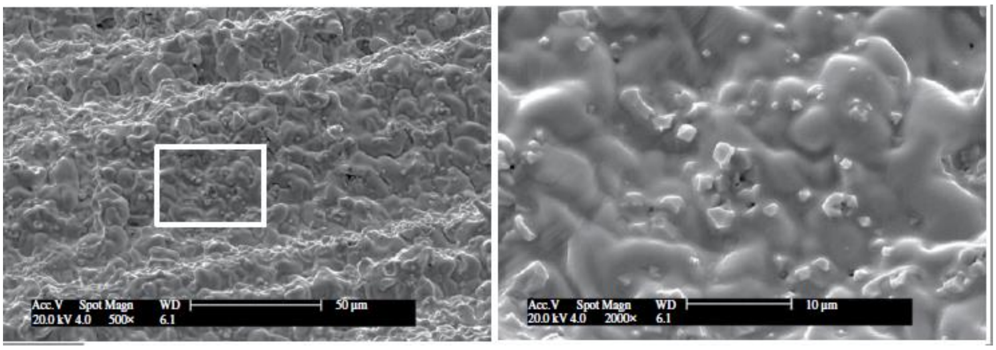


Figure 6.4: The dendrite surface with presence of NbC.

6.1.b Weld fracture surface morphologies in liquation cracking.

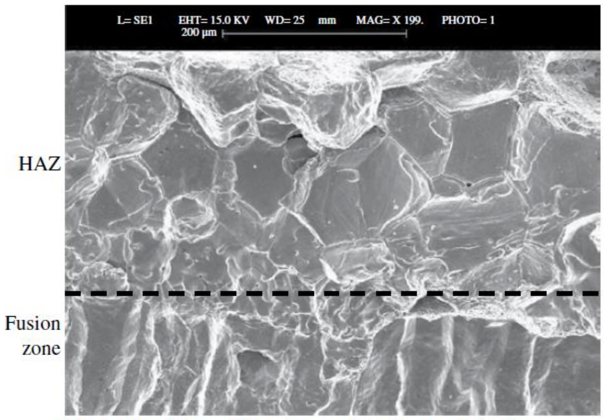
Occurs in HAZ or weld metal and results from local melting along grain boundaries (GB).

(i) In the base metal HAZ, this melting occurs along grain boundaries closed to the fusion boundary (FB).

(ii) In the weld metal, liquation during reheating of previously deposited weld metal can occur at either solidification grain boundaries (SGB) or migrated grain-boundaries (MGB).

6.1.b.1 Examples of Fracture Surface Morphology of HAZ Liquation Cracking.

The actual failure in a weld **steel forging** alloy is due to liquation crack, which propagated into both the fusion zone and HAZ. The HAZ fracture surface is IG along prior austenite grain boundaries, while the fusion zone fracture surface shows columnar features typical of solidification growth. As characterized by Figure 6.5.



HAZ and weld metal liquation cracking in a steel forging

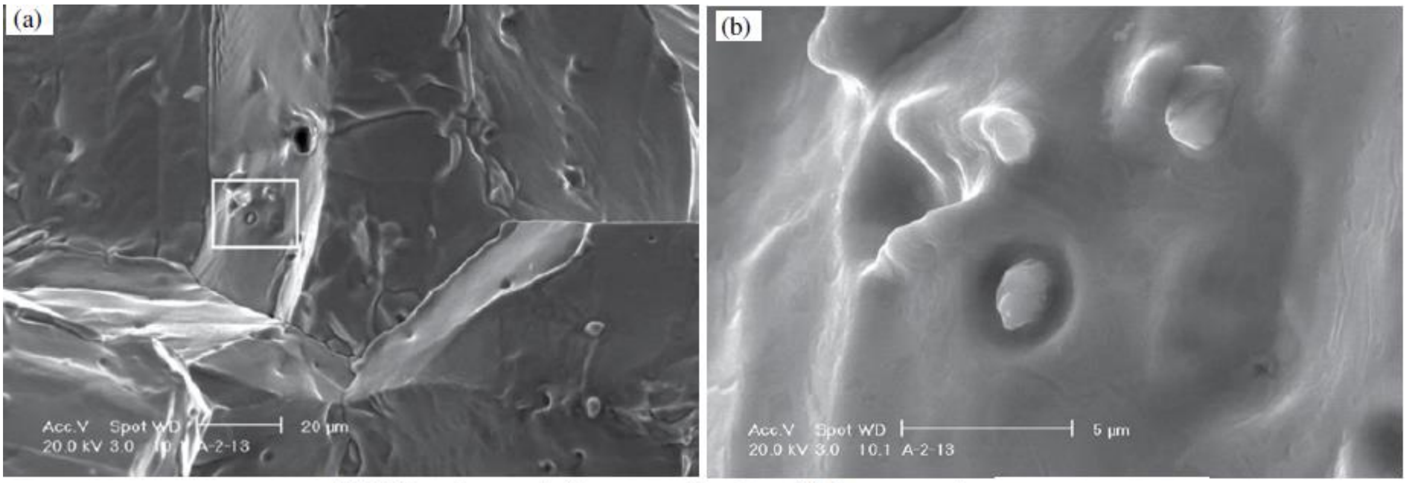
Figure 6.5: Liquation cracking profile in steel forging.

The actual failure in a weld Ni-super alloys is due to HAZ liquation crack, which characterized by the following tips:

(i) Grain’s faces are not clean, which means presence of liquid film at the time of failure.

(ii)The fracture surface reflects the presence of liquid film along the grain boundaries.

(iii) The liquid film represents a constitutional liquation on the fracture surface represented by TiC particles resulted from local melting at the interface with the matrix. See Figure 6.6.



HAZ liquation crack fracture surface in a Ni-base superalloy
(a) Intergranular fracture with liquid grain boundary liquid films and
(b) inset from (a) showing constitutional liquation of TiC particles

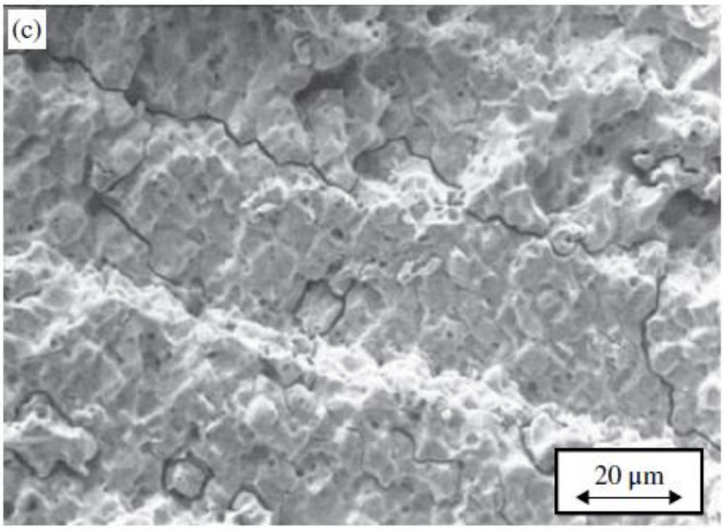
Figure 6.6: Liquation cracking profile.

6.1.c Weld fracture surface morphologies in reheat cracking.

(i) Usually associated with low-alloy steels that contain Cr, Mo, and V and stabilized austenitic. stainless steel alloys (such as Type 347).

(ii) This form of cracking usually occurs during PWHT. Failure occurs at or near the grain boundaries (GB).

(iii) The fracture surfaces appear clearly IG. The IG fracture can be flat and may exhibit micro-ductility (ductile IG). See Figure 6.7.



Reheat cracking fracture surfaces. (c) Type 347 weld metal.

Figure 6.7: Reheat cracking morphology in weld metal type 347.

6.2 Stress Intensity Factor (*K*).

describes the magnitude of the elastic stress field surrounding a crack or structural discontinuity. This factor is the basis for linear-elastic fracture mechanics (LEFM) and, thus, describes the stress intensity in materials that are essentially brittle. Thus it is used for description the linear-elastic behaviour in brittle material where the region of plasticity that exists at the tip of an existing flaw under load is extremely small and vice versa for ductile materials which has elastic-plastic behaviour to describe stress toughness. The purpose is to understand the relationship between materials behaviour, design, with joining method effect, e.g. welding process. This gives expectations about the reasons for pre-failure in welds, which should be avoided, and determine the magnitude (length) of cracks or discontinuities that can be tolerated in welds for a given design stress level. The general expression for (*K*) is

$K = \sigma (\pi a)^{1/2} Y$……………………………(6.1)

Ơ: applied stress

a: crack length

Y: dimensionless geometric factor

K: stress intensity factor.

6.2.a Preventing Brittle Fracture.

(i) Material toughness, the ability of a material to carry a load or deform plastically in the presence of a crack, notch, or discontinuity.

(ii) Crack size, all brittle fractures must initiate from a crack or discontinuity of finite size. These discontinuities can vary from small to large defects, such as cracks or fatigue cracks. The critical crack (or flaw) size needed to cause brittle fracture is dependent on the material toughness.

(iii) Stress level, tensile stresses are necessary for brittle fracture to occur. These stresses may be residual from the fabrication process, imposed in service, or, in general, a combination of both.

(iiii)Secondary factors that influence the three primary factors listed above to some degree and hence lead to susceptibility to brittle fracture including temperature, loading rate, stress concentration. See Figure6.8.

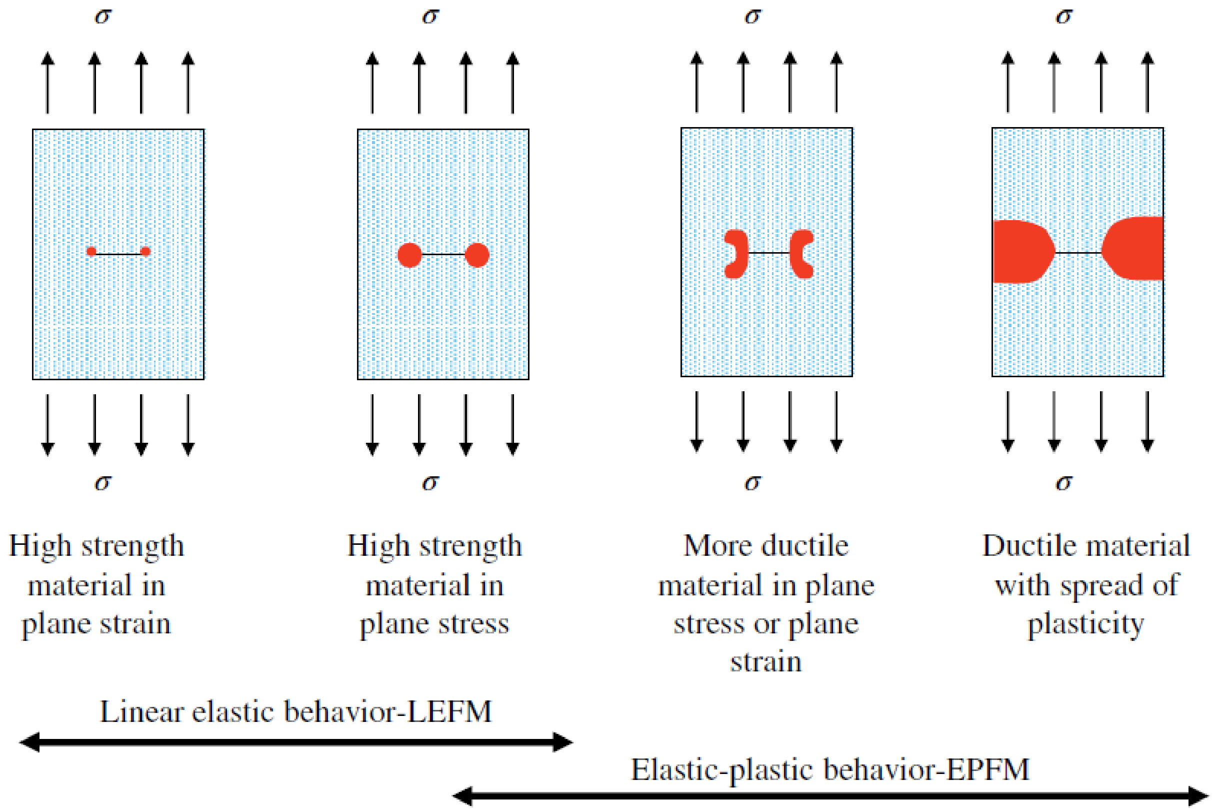


Figure 6.8: Schematic illustration of linear-elastic and elastic-plastic fracture mechanics.

6.2.a.1 Effect of Material Toughness on Propagation Crack Under Temperature Effect.

The general effect of temperature on fracture resistance (toughness) in a variety of structural materials is illustrated in Figure 6.9. Toughness of austenitic stainless steels increases as the temperature decreases. The fracture energy for low- and medium-strength steels showed a strongest effect with increasing temperature, while rapid decrease in fracture resistance below “transition” temperature. The dramatic transition in fracture resistance for low and medium steels with temperature is called transition temperature. For steels, this is usually termed the ductile-to-brittle transition temperature (DBTT). When the ambient temperature dropped below the transition temperature, the resistance to fracture of these structures was extremely low.

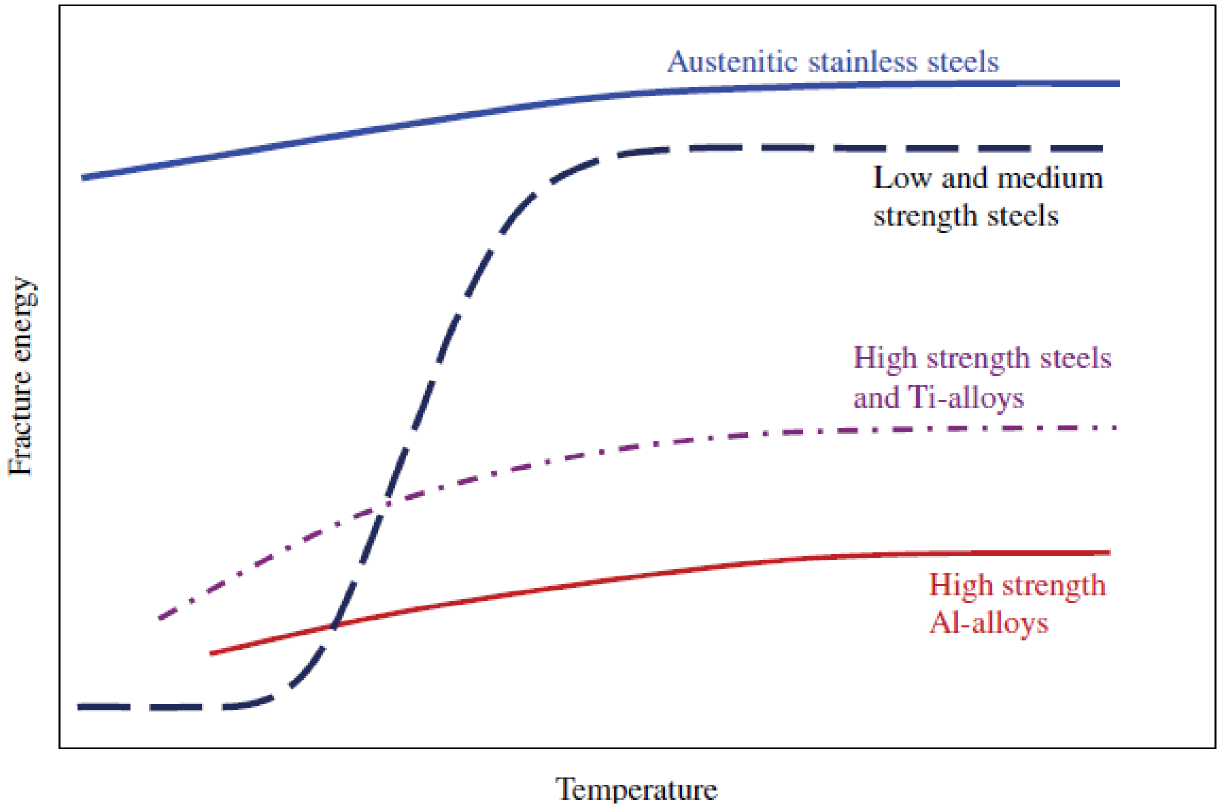


Illustration of toughness as a function of temperature for several materials.

Figure 6.9: Toughness for several materials as a function of temperature.

7. Dissimilar Metal Welding.

joining two metals have different core properties, but might have same name sometimes. For example, welding two austenitic steel metals together, but they may still be different enough to be considered dissimilar. This joining possess different chemical or mechanical properties, and so aren’t necessarily a natural fit for each other. The purpose behind studying welding dissimilar metals is due to an achieve a combination of their advantages to improve properties of products to meet the needs of automobile industry, aerospace, and chemical industry.

7.1 Factors should be considered before Welding Dissimilar Metals.

(i) Solubility, refers to metal’s ability to dissolve in a solvent. Both metals must be able to dissolve together.

(ii) Intermetallic compounds, occur in the transition zone (TZ) during the welding process, and exhibit metallic bonding.

(iii) Weld-ability, based on the solubility and intermetallic compounds of two metals.

(iiii) Thermal expansion How much the shape of your metals will change when a temperature is applied.

(iiiii) Melting rates, the point at which metals will melt.

(iiiiii) Corrosion – If two metals are extremely different on the electrochemical scale, then corrosion could occur.

(iv) End-service conditions What are the conditions that your dissimilar metals will be operating within?

7.2 Mechanism and Welding Methods Applied for Welding Dissimilar Metals.

During welding dissimilar metals, brittle intermetallic compounds (IMCs) is easily formed at the interface, such as Fe-Ti IMCs and Mg-Al IMCs.

Different welding techniques are able to be used to weld dissimilar metals, but it was not possible to completely avoid the formation of brittle IMCs in weld metal, such these type of welding are:

(i) Solid-state processes which possess comparatively low temperature, such as diffusion bonding and friction stir welding, results are a welded joint with relatively high bonding strength.

(ii) Diffusion Bonding is a typical solid-state technique that makes the material surface contact, deform, and diffuse under the high temperature and pressure. Then, pores at the interface are gradually closed to achieve a good connection.

(iii) Friction Stir Welding is a solid-state joining technique that may offer some advantages in the suppression of the formation of cracks, holes, and brittle IMCs.

(iv) Laser Welding has several advantages, such as high energy density, high cooling rate, and production of a narrowed heat-affected area.

Laser welding can effectively improve the flexibility and adaptability of welded joints of dissimilar metals.

(v) Electron beam welding: makes the kinetic energy of electrons transform to heat by impact of electron beam on the material. The electron beam welding possesses production of a narrowed heat-affected area, and rapid cooling rate.

(vi) Other Welding Techniques such as gas tungsten arc welding, resistance spot welding, and cold metal transfer welding are also used in dissimilar metals' welding.

7.3 Hinders Faces Welding Dissimilar metals.

The main difficulty in connecting dissimilar metals is easy to produce brittle IMCs which leads to increase the embrittlement of welded joints. By the action of external stress, the brittle IMCs will become weak area in weld metal and cracks will be easily produced in this area. Then, cracks continue to extend resulting rapid fracture of welded joints, which weakens the mechanical properties of welded joints.

7.4 Enhancement of Dissimilar Welded Joints Qualification.

Addition intermediate interlayers in dissimilar metals welding, to avoid formation of excessive brittle IMCs in weld metal. This intermediate layer could effectively:

(i) Inhibit the formation of brittle IMCs.

(ii) Minimize thermal expansion mismatch between the substrates during welding.

8. Weld-ability of Materials.

According to American Welding Society (AWS), it is the capacity of a metal to be welded under the fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended service. The purpose of studying weld-ability of metals is to create a joint that is free of cracks and able to withstand the stresses placed on it, also help improve the quality of welds through understanding the heating and cooling cycles inherent to most forms of welding, which possible to create strains and stresses in the welds. These strains and stress affect physically, chemically, and metallurgically causing changes in the welds, such changes make a metal prone to poor weld-ability. Stainless steels are chosen because of their enhanced corrosion resistance, high temperature oxidation resistance or their strength. The unique properties of the stainless steels are derived from the addition of alloying elements, principally chromium and nickel, to steel. The four grades of stainless steel have been classified according to their material properties and welding requirements to: austenitic, ferritic, martensitic, and austenitic-ferritic (duplex).

8. a.1 Welding Characteristics of Austenitic Stainless Steel.

(i) Austenitic stainless steels have about (16-26) % chromium (Cr), and (8-22) % (Ni). Commonly used alloy for welded fabrications is Type 304 which contains approximately 18%Cr and 10%Ni. These alloys can be readily welded using any of the arc welding processes, because they are non-hard-enable on cooling, they exhibit good toughness and there is no need for pre- or post-weld heat treatment.

(ii) Imperfections, although austenitic stainless steel is easily welded, weld metal and HAZ cracking can occur. Weld metal solidification cracking is more likely in fully austenitic structures which are more crack sensitive.

(iii) To avoid, the presence of 5-10% ferrite in the microstructure is extremely beneficial, due to its capacity to dissolve harmful impurities which encourage form low melting point segregates and inter-dendritic cracks. In addition, the choice of filler material composition is crucial in suppressing the risk of cracking.

8. a.2 Welding Characteristics of Ferrite stainless steel.

(i) Ferrite stainless steels have (11-28) % Cr. These alloys a non-harden-able, they can be easily fusion welded. But, a coarse-grained HAZ will have poor toughness.

(ii) Avoiding weld imperfections, the main problem when welding this type of stainless steel is poor HAZ toughness. Excessive grain coarsening can lead to cracking in highly restrained joints and thick section material.

(iii) Necessary Precautions, In thicker material, it is necessary to employ a low heat input to minimise the width of the grain coarsened zone and an austenitic filler to produce a tougher weld metal. Also, by Preheating between (50-250) °C, which reduces the HAZ cooling rate, maintain the weld metal above the ductile-brittle transition temperature and may reduce residual stresses.

8. a.3 Welding Characteristics of Martensitic stainless steel.

(i) Martensitic stainless steel Has a moderate chromium content, 12-18% Cr, with low Ni and a relatively high carbon content, have hard HAZ martensitic structure and the matching composition weld metal.

(ii) Welding Precautions: Avoid cracking in the HAZ, especially in thick section components and highly restrained joints.

(iii) Avoid weld imperfections, high hardness in the HAZ makes this type of stainless steel susceptible to hydrogen cracking. Precautions include:

- Using low hydrogen process (TIG or MIG) and ensure the flux or flux coated consumable are dried.

- Justifications among welding parameters such as time, temperature, chemical composition, carbon content.

- Thicker section and higher carbon (> 0.1%) material need preheat and post-weld heat treatment. The post-weld heat treatment should be carried out immediately after welding to temper (toughen) the structure, and to enable the hydrogen diffusion away from the weld metal and HAZ.

- Thin section and low carbon material are able to be welded without preheat, providing that a low hydrogen process is used, the joints have low restraint and attention is paid to cleaning the joint area.

8. a.4 Welding Characteristics of Duplex Stainless Steels.

(i) Duplex Stainless Steels Has a two phase structure of almost equal proportions of Austenite and Ferrite. The composition about Cr, Ni and Mo.

(ii) Normally, it is weld-able, but need restricted following –up for the heat input range to obtain the correct weld metal structure.

(iii) Weld Imperfections, avoid low heat input welding procedures, controlling temperature, selection the appropriate filler metal which has a small amount of nitrogen or shielding gas which itself may contain nitrogen. This is in order to compensate hydrogen loss. The main aim for that is to produce a weld metal structure with a ferrite-austenite balance to match the parent metal.

8.b Weld-ability Factors.

(i) Selecting the correct shielding gas for the application in the right quantity can minimize the chance of weld defects. For example, copper and aluminium require a gas to shield them from atmospheric contaminants during welding.

(ii) Selecting the right Welding Process that match type of metal need to weld.

(iii) Choosing the wrong filler metal can cause defects in the weld, such as cracks and porosity.

(iiii) Preheat and Post-heat: Brittle metals are prone to cracking during welding. Heating the metal prior to welding and afterward can reduce the risk of this problem.

(iiii) Welding Procedure: Weld quality can be dependent on the number of welds, their length, and the size of the weld bead. Several small welds can be more effective than a few large welds.

8.c Weld-ability Testing.

Used for fabric-ability assessment of materials by various welding processes and to determine the service performance of welded construction. The standardized mechanical tests for testing the weld-ability of weld joints made from different materials are tensile, fatigue, fracture toughness and hardness tests.

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