Solidification Mechanisms

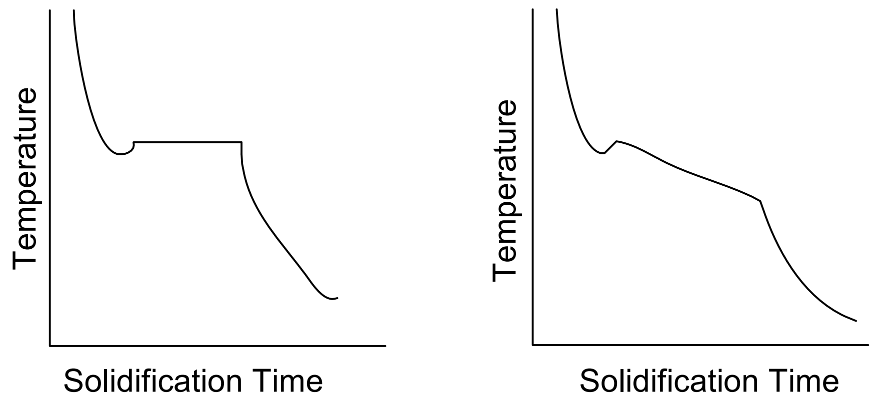
This chapter presents common solidification mechanisms observed in weld metal and different modes of solidification. Influence of welding speed and heat input on the grains structure of weld has been explained. Further, fundamental mechanisms used for grain refinement of weld metal and common methods of grain refinement have been described.

Keywords: Weld solidification, epitaxial solidification, actual temperature gradient (G), growth rate (R), axial and columnar grains, macrostructure, inoculation grain refinement, arc pulsation

Fundamentals of solidification of metals

During the solidification of the liquid metal fast moving disordered atoms get arranged in a definite order to form crystal lattices such as BCC, FCC, and HCP etc. As soon as heat source moves away, gradually heat is lost to the base metal. Rate of heat loss depends on temperature of weld metal, weld pool size, thickness and thermal properties base metal etc.

On cooling, liquid metal losses energy in the form of latent heat and so the temperature is lowered which in turn decreases the average inter-atomic distance between mobile & disordered atoms. On further cooling, attractive forces between atoms prevent them moving away from one another and eventually completely liquid to solid transformation takes place. Solidification of pure metals begins with temperature arrest and then continues to take place at a constant temperature as shown in Fig. 33.1 (a) while alloys solidify over a range of temperature. The arrest in temperature is attributed to evolution of the latent heat of solidification on transformation from the liquid metal to solid state.



a) b)

Fig. 33.1 Schematic of cooling curve for a) pure metal and b) alloy during the solidification

Total energy of the molten metal reduces during solidification. On the formation of a small nucleus e.g. cubical shape having side of length "a" two changes in free energies takes place a) free energy lost during the solidification and b) free energy required for creation of new surfaces of the cubical shape solid.

The freezing energy lost : $\Delta G_{LS} = a^3\ \Delta G_{LS}^*$

The surface energy needed for creation of new surfaces for a cube is : $6a^2\ \Delta G_I^*$

Where change in free energy per unit volume is ΔG_{LS}^* (on liquid to solid state transformation) and a is side of the cube. Therefore, volume of cube would be a^3. Where interfacial energy per unit area is ΔG_I^*

Thus, total change in free energy is the algebraic sum of above two energies $\Delta G = -a^3\ \Delta G_{ls}^* + 6a^2\ \Delta G_I^*$

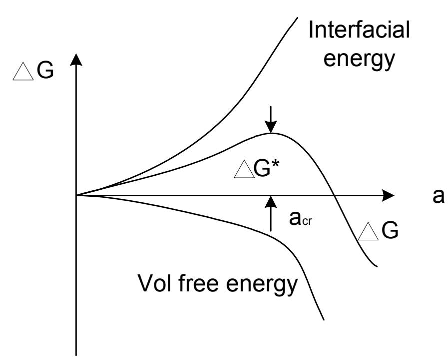


Fig. 33.2 Free energy vs grain size during the phase transformation

Above equation shows that total change in free energy will vary with change in size of nucleus (Fig. 33.2). There is a critical size a_{cr} for a nucleus to be stable, below which nucleus (called embryos) gets re-dissolved in the liquid metal. Figure (33.2) shows that reduction in free energy caused by liquid to solid phase transformation is more than increase in free energy due to creation of the new surfaces. This is the reason why under-cooling below the equilibrium transformation temperature is required, so that the condition of reduction in total energy is satisfied. Greater is the under cooling temperature smaller is the critical size. This explains the dependence of nucleation rate on under cooling temperature.

If liquid metal is already carrying solid particles then it will begin to crystallize on them at equilibrium temperature without under-cooling. This phenomenon forms the basis for the heterogeneous nucleation. Heterogeneous nuclei are physically and chemically different from the freezing liquid metal. Surface bonding and crystalline similarity for various particles in the liquid metal, are important factors to act as heterogeneous nuclei.

These particles may or may not be wetted by liquid metal depending upon the interface forces between them. Experimental investigations have established that two conditions should be satisfied by the heterogeneous particles to be an effective nucleant 1) crystalline similarity between the particles and solidified liquid metal and 2) difference in lattice size of two crystals should not be greater than 20%. However, these are not the only conditions for particles to be an effective nucleant.

Kinetics of liquid-solid interface is described by the ratio thermal gradient (G) and travel speed of liquid solid interface (R). Value of G and R are generally found in range of 100-1000K/m and 10^{-3} to 10^{3} m/s. Solidification mode generally varies as per prevailing G & R value for given solidification conditions. There can be four modes of the solidification (as per G and R value) namely a) planar (high G and low R), b) cellular, c) columnar dendritic, and d) equaixed dendritic (low G and high R). These four modes are shown in Fig. 33.3. Ratio of G and R determines the mode of solidification and product of two (G, R) indicates the cooling rate so these two parameters decide the fineness grain structure (Fig. 33.4).

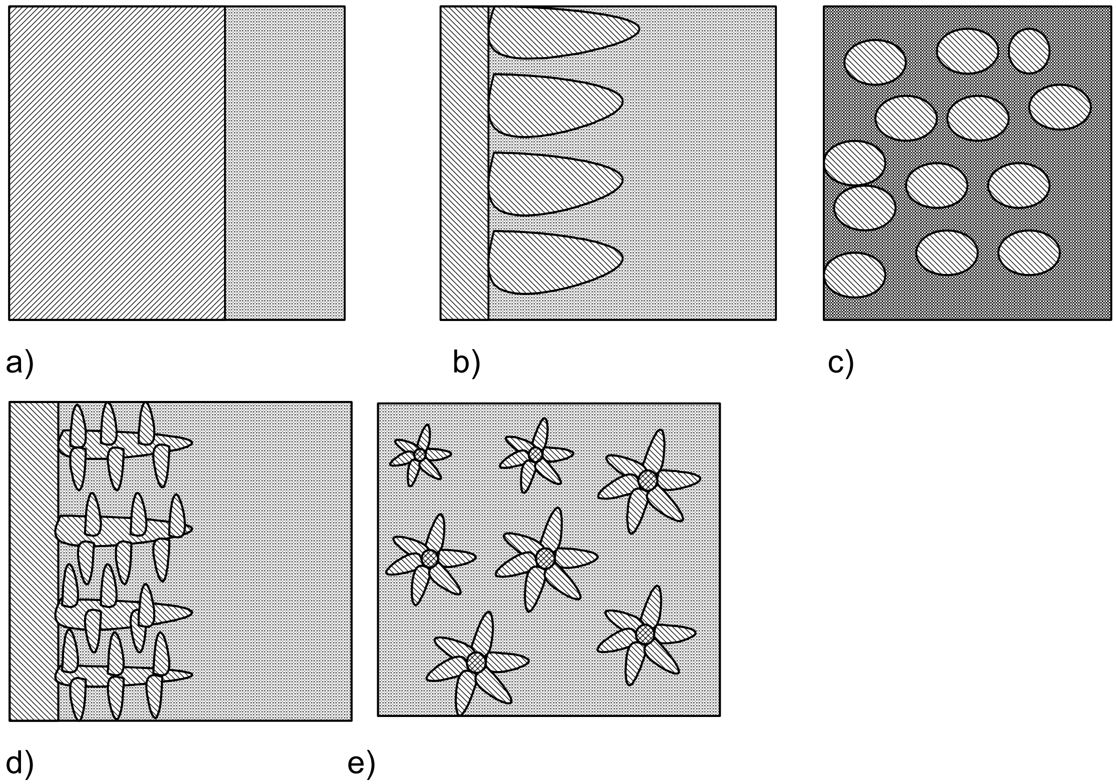


Fig. 33.3 Schematic of modes of the solidification a) planar, b & c) cellular, d) columnar dendritic and e) equiaxed dendritic

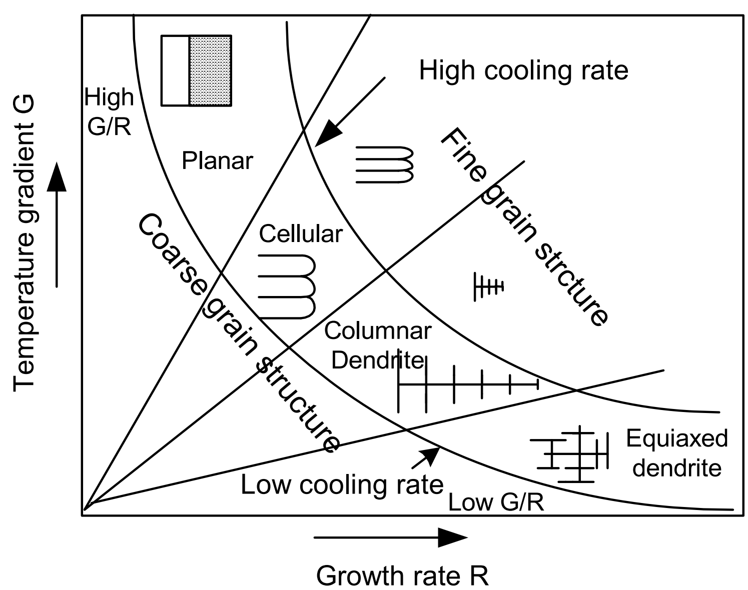


Fig. 33.4 Influence of G & R on mode of solidification and grain structure

Solidification of the weld metal can take place two ways a) epitaxial and b) none-epitaxial depending up on the composition of the weld metal. In a weld pool, temperature gradient is observed right from the center of the weld pool to fusion boundary of the base metal and iso-thermal temperature lines exist around the weld. These isotherms determine the boundaries of heat affected zone, mushy zone and liquid weld metal zone (Fig. 33.5). The peak temperature is found at the center of the weld and then decreases gradually on approaching towards weld fusion boundary. Grains grow from the fusion boundary towards the weld center. The growth generally occurs at a faster rate in the direction perpendicular to the fusion boundary and opposite to that of the heat flow than other directions.

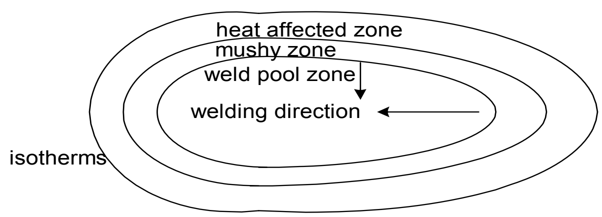


Fig. 33.5 Schematic showing different zones

33.1 Epitaxial solidification

The transformation of the molten weld metal from liquid to solid state is called solidification of weld metal and it occurs due to loss of heat from weld puddle. Generally, solidification takes place by nucleation and growth mechanism. However, solidification of weld metal can occur either by nucleation and growth mechanism or directly through growth mechanism depending upon the composition of the filler/electrode metal with respect to base metal composition. In case, when composition of the filler/electrode is completely different from the base metal, solidification occurs by nucleation and growth mechanism e.g. use of nickel electrode for joining steel. And when filler/electrode composition is similar to the base metal, solidification is accompanied by growth mechanism only on partially melted grain of the base metal which is commonly known as epitaxial solidification (Fig. 33.6). The growth of grain on either newly developed nuclei or partially melted grain of the base metal, occurs by consuming liquid metal i.e. transforming the liquid into solid to complete the solidification sequence.

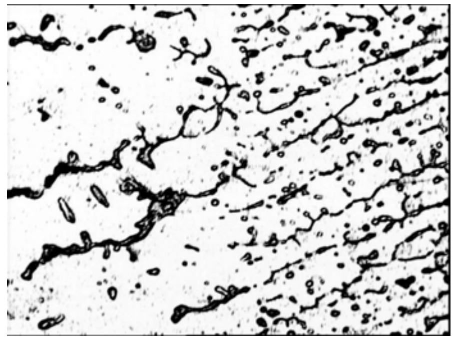


Fig. 33.6 Typical micrograph showing epitaxial solidification in Al weld joint

33.2 Modes of solidification

The structure of grain in growth stage is governed by mode of solidification. There are four type of grain commonly observed in solidified metal namely planar, cellular, dendritic, equiaxed corresponding to the respective modes of the solidification (Fig. 33.7). Moreover, the mode of solidification in weld depends on composition and cooling conditions experienced by weld metal at a particular location during the solidification. Thermal conditions during solidification are determined by heat transfer in weld pool affect the temperature gradient (G) at solid-liquid metal interface (^{0}C/mm) and growth rate of solidification front (R) as indicated from growth rate (mm/sec) of solid-liquid metal interface.

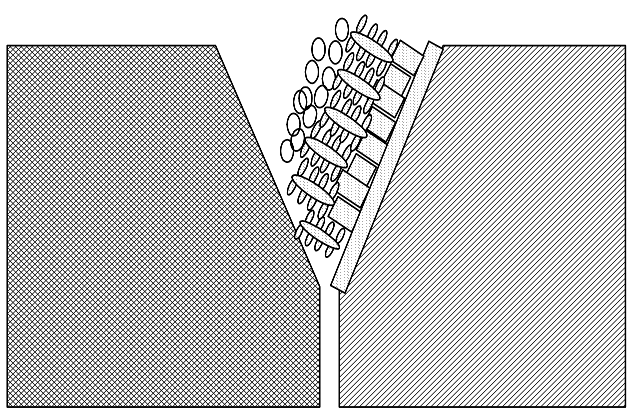


Fig. 33.7 Different modes of solidification a) planar, b) cellular, c) cellular, d) dendritic and e) cellular structure

The shape of solid-liquid metal interface determines morphology of microstructural features of the weld metal. A stable plane solid-liquid metal interface results in planar solidification. The condition for stability of plane solid liquid metal interface is given by $(G/R)>(\Delta T/D)$. Where G is the temperature gradient in liquid near solid liquid metal interface, R is growth rate of solidification front, ΔT is the solidification temperature range for a given composition and D is the diffusion coefficient of solute in liquid metal (Fig. 33.8).

Moreover, the stability of the solid-liquid metal interface is governed by thermal and constitutional supercooling condition prevailing in the liquid metal near the solid- liquid metal interface. Destabilization of solid-liquid metal interface results in the growth of interface in cellular or dendritic form. The constitutional super-cooling for instability of plane solid liquid metal interface is expressed by following relationship: $(G/R)>(\Delta T/D)$.

A combination of high actual temperature gradient (G) and low growth rate (R) results in planar solidification i.e. where liquid-solid interface is plane. A combination of low actual temperature gradient (G) and high growth rate (R) results in equiaxed solidification as shown in Fig. 33.8. A combination of intermediate G and R values results in cellular and dendritic mode of solidification. Product of G and R indicates the cooling rate. A high value of G.R produces finer grain structure than low G.R value. During welding, weld pool near the fusion boundary experiences high value of G and low value of R which in turn results in planar solidification and at the weld center reverse conditions of G and R exist which lead to the development of equiaxed grains. In fact, G and R varies continuously from the weld fusion boundary to the weld center therefore all common modes of the solidification can be seen in weld metal structure in sequence of planar at the fusion boundar, cellular, dendritic and equiaxed at the weld centre. In general, equiaxed grain structure is the most favourable weld structure as it results in best mechanical performance of weld. Therefore, attempts are made to achieve the fine equiaxed grain structure in the weld by different approaches namely inoculation, controlled welding parameters and application of external force such as electromagnetic oscillation, arc pulsation, mechanical vibrations etc. In following sections, these approaches will be described in detail.

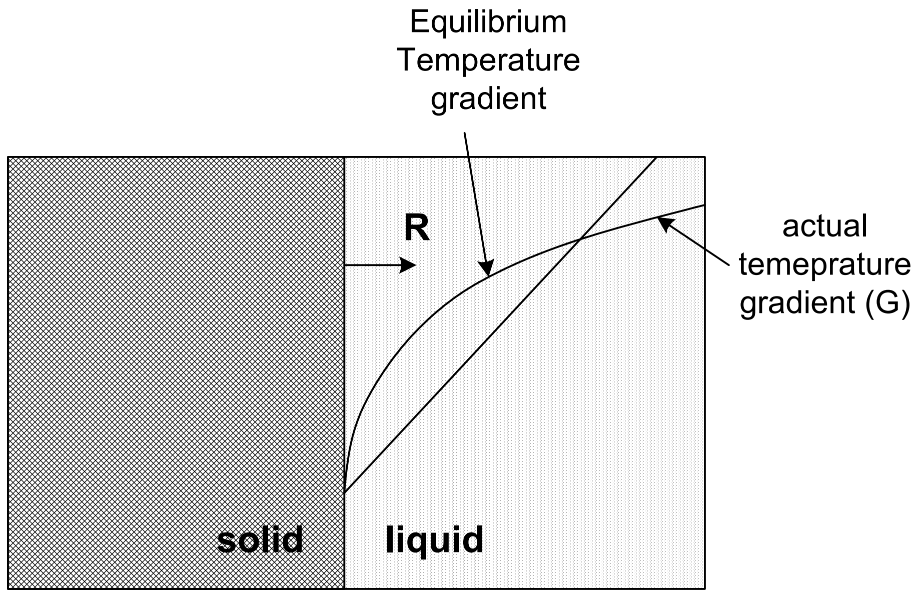


Fig. 33.8 Schematic of temperatures distribution during solidification near solid-liquid metal interface

In addition to microstructural variations in the weld, macroscopic changes also occur in weld, which are largely governed by welding parameters such as heat input (as determined by welding current and arc voltage) and welding speed. Macroscopic observation of the weld reveals of the two types of grains based on their orientation a) columnar grain and b) axial grain (Fig. 33.9). As reflecting from their names, columnar grains generally grow perpendicular to the fusion boundary in direction opposite the heat flow while axial grains grow axially in the direction of welding (Fig. 33.9). The axial grains weaken the weld and increase the solidification cracking tendency therefore effort should made to modify the orientation of axial grains.

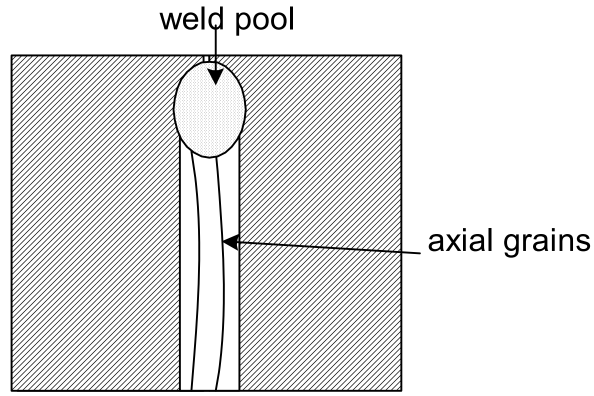


Fig. 33.9 Schematic of axial grain in weld joints

33.3 Effect of welding speed on grain structure of the weld

Welding speed appreciably affects the orientation of columnar grains due to difference in the shape of weld puddle. Low welding speed results in elliptical shape weld pool and produces curved columnar grain with better distribution of low melting point phases and alloying elements which in turn lowers solidification cracking tendency of the weld than weld produced using high welding speed (Fig. 33.10). At high welding speed, the shape of the trailing end of weld pool becomes like a tear drop shape and grains are mostly perpendicular to the fusion boundary of the weld. In this case low melting point phases and alloying elements are mostly segregated along the weld centerline,

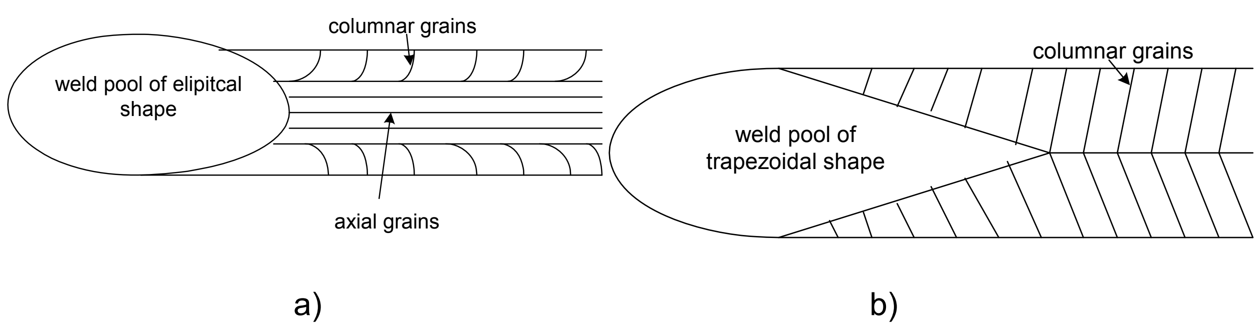


Fig. 33.10 Effect of wending speed on shape of weld pool and grain structure at a) low speed and b) high speed

33.4 Common methods of grain refinement

33.4.1 Inoculation

This method is based on increasing the heterogeneous nucleation at nucleation stage of the solidification by adding alloying elements in weld pool. These elements either them-self or their compounds act as nucleants. Increased number of nucleants in the weld metal eventually on solidification results in refinement of the grains in the weld (Fig. 33.11). It is understood that elements having a) melting point higher than the liquidus temperature of the weld metal and b) lattice parameter similar that of base metal can perform as nucleants. For aluminium, titanium and boron based compound as such TiB_2, TiC, Al-Ti-B, Al-Zr are commonly used as grin refiner. Addition of grain refiners in molten metal can lower the surface energy to facilitate the nucleation even with limited under-cooling. Increase in the nucleation rate facilitates the grain refinement. For steel, Ti, V and Al are commonly used grain refiners.

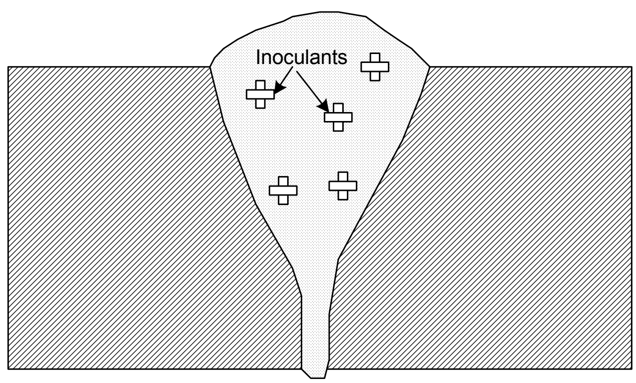


Fig. 33.11 Schematic of grain refinement by inoculation

33.4.2 Arc pulsation

The gas metal arc and gas tungsten arc welding process generally use constant voltage and constant current power source. Moreover, these processes sometime use a DC power source which can supply varying current called base current and peak current. Base current is the minimum current primarily used to have stable arc and supplies least amount of the heat to the weld; and solidification of the weld is expected to take place during the base current period (Fig. 33.12). While peak current is maximum current supplied by the power source to the weld arc to generate the heat required for melting of the faying surfaces. The cycle of alternate heating and cooling results in smaller weld puddle and so rapid cooling of the weld metal which in turn results in finer grain structure than the conventional welding i.e. without arc pulsation (Fig. 33.13). It is believed that abrupt cooling of the weld pool surface during base current period can also lead to development of few nucleants at the surface which will tend to settle down gradually and so making make their distribution uniform in the molten weld pool in the settling process. Increased availability of nucleants due to surface nucleation will also be assisting to get finer grain structure in weld.

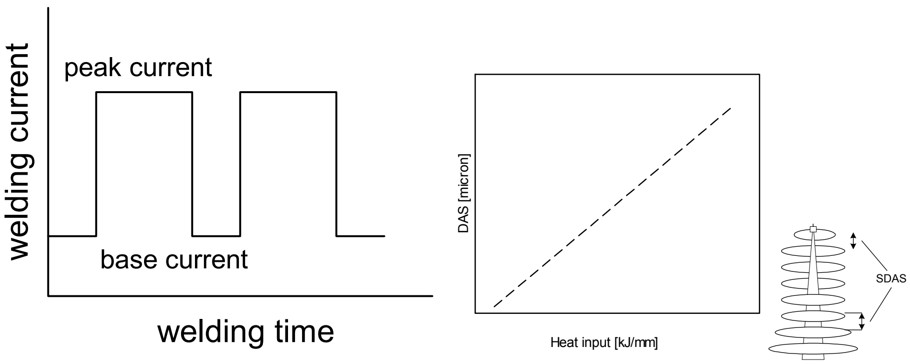
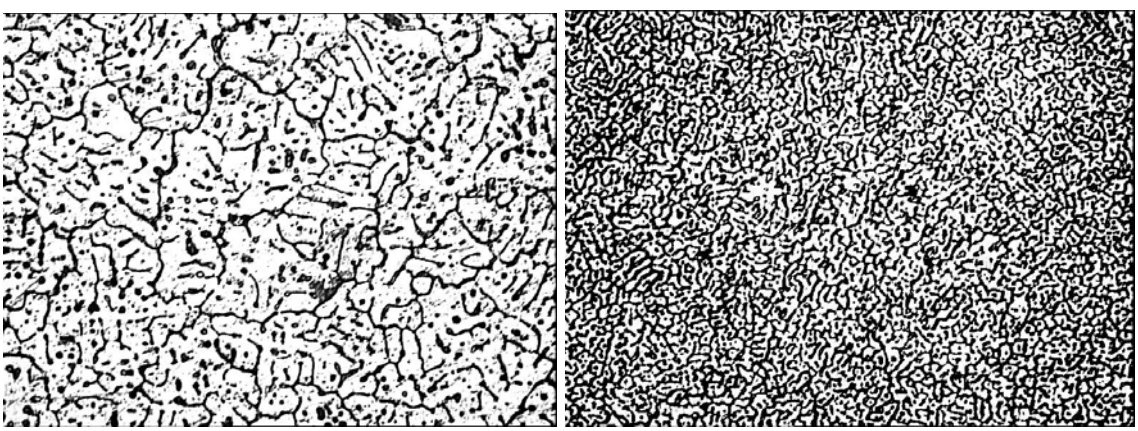


Fig. 33.12 Schematics of a) pulse current vs time welding and b) effect of heat input on dendrite arm spacing



a) b)

Fig. 33.13 Microstructure of aluminium weld developed a) without arc pulsation using 160 A current and b) arc pulsation between 120 and 160 A (200X)

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