where θ is the angle between the normal to the interface and the pull direction and is close to 90°. The low interface growth rate, in turn, reduces the need for the high interface temperature gradients required to maintain growth stability in vertical ribbon growth. The gradients in the vertical methods are the cause of high thermoelastic stresses and set practical productivity limits when low defect densities and flat ribbon are required. Details on the process limits affecting the horizontal growth techniques may be found in other publications [45, 46]. We next give a description of each of the techniques listed in Table 6.3.

WEB. WEB is grown directly from melted silicon in a crucible with no shaping device (Figure 6.21) [47]. A dendritic seed or button is lowered into a supercooled melt. The seed spreads laterally to form a button. When the seed is withdrawn, two secondary dendrites propagate from the ends of the button into the melt, forming a frame to support the freezing ribbon. The dendrites grow into the melt that has been supercooled by several degrees. Very accurate melt temperature control is required in order to maintain the supercooled interface condition and prevent "pull-out", whereby the growth terminates by voiding of the meniscus. The width of the ribbon is controlled by the position of the two dendrites that support the liquid film. The growth velocity is determined by the rate of removal of the latent heat into the ribbon and of the heat conducted through the melt through the meniscus. Typical growth rates are from 1 to 3 cm/min.

In vertical ribbon growth, the meniscus contains the suspended melt volume that connects the bulk melt to the growth interface and crystal. Its shape and the heat conduction taking place within it critically affect impurity segregation and the crystallisation

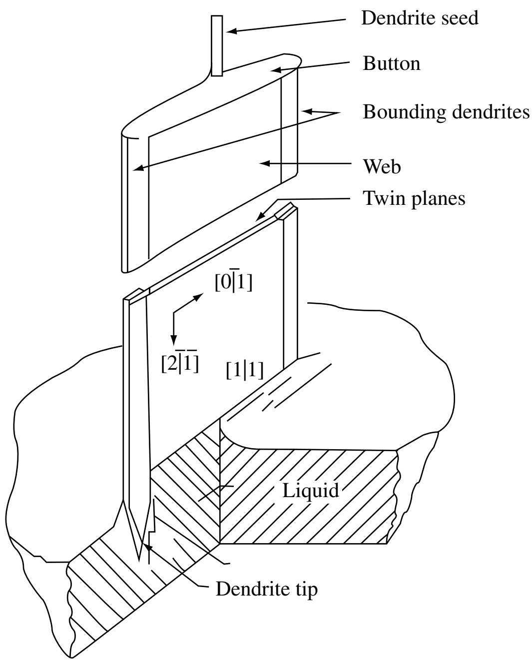

Figure 6.21 Schematic of Dendritic Web (WEB) growth process for ribbon