MICROSTRUCTURES OBTAINED THROUGH RAPID SOLIDIFICATION

As discussed in some detail in section 2.8, an increase in the rate of heat extraction (cooling rate) results in gradual departure from equilibrium up to global and interface non-equilibrium. As the rate of heat extraction increases the microstructure length scale of solidified alloys decreases. Eventually solidification without crystallization may occur.

Crystallization must occur via a process of nucleation and growth. If nucleation is suppressed (for example through the imposition of high undercooling on the system), the liquid will solidify without crystallization as an amorphous material also termed glass. Thus, condensed matter can be classified into three categories, as listed in Table 12.1. Liquids are stable above the fusion temperature, $T_f$, crystalline solids are stable under the solidification temperature $T_S$, and glasses are stable at a temperature lower than the glass transition temperature, $T_g$.

<table>
<thead>
<tr>
<th>Condensed matter</th>
<th>Temperature range</th>
<th>Thermal condition</th>
<th>Atomic configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>$T &gt; T_f$</td>
<td>stable</td>
<td>disordered</td>
</tr>
<tr>
<td>Solid - Crystal</td>
<td>$T &lt; T_S$</td>
<td>stable</td>
<td>ordered</td>
</tr>
<tr>
<td>Solid - Amorphous (glass)</td>
<td>$T &lt; T_g$</td>
<td>metastable</td>
<td>disordered</td>
</tr>
</tbody>
</table>

The glass transition temperature is defined as the temperature at which the material exhibits a sudden change in the derivative thermodynamic properties, such as heat capacity and expansion coefficient, from crystal-like to liquid-like values. This is illustrated in Figure 12.1. When the cooling rate is low phase transformation occurs at $T_f$ with formation of a crystalline solid. When the cooling rate is high, the property changes continuously and the extrapolation method (broken lines) is used to determine $T_g$.

Thus, depending on the solidification velocity and the degree of interface nonequilibrium, rapidly solidified materials may exhibit a crystalline or amorphous microstructure.
12.1 Rapidly solidified crystalline alloys

The term rapid solidification is normally applied to casting processes in which the liquid cooling rate exceeds 100K/s (Boettinger, 1974). This definition may be outdated in light of recent work on bulk metallic glasses. While different alloys respond differently to high cooling rates, some microstructures observed in rapidly solidified alloys can be achieved by slow cooling when large liquid undercooling is achieved prior to nucleation.

The following techniques are used to produce rapidly solidified alloys:

- melt spinning, planar flow casting, or melt extraction, which produce thin (~25 to 100µm) ribbon, tape, sheet, or fiber;
- atomization, which produces powder (~10 to 200µm);
- surface melting and re-solidification, which produce thin surface layers

Some examples of such techniques are presented in Figure 12.2. These methods may be considered casting techniques where at least one physical dimension of the final product is small. Consolidation is used to yield large products from rapidly solidified alloys. This consolidation often alters the solidification microstructure of the final products. Yet, many features of the solidification structure can remain in the final product.

At ‘normal’ rates of cooling the tip radius of the dendrite decreases as the solidification velocity increases (Figure 12.3). However, as the cooling rate increases in the rapid solidification range the tip radius increases. This is accompanied by a decrease in branching. The equiaxed dendrite becomes globular/cellular. Typical examples of the evolution of the microstructure as a function of the solidification velocity are given in Figure 12.4. Figure 12.4a shows a transverse section of a fine