expected to remain as intact, ellipsoidal particles after milling. The contribution of cocoa starch to the properties of chocolate is largely unknown.

The majority of the world's current cocoa harvest is milled using agitated ball mills (Niediek, 1994). Ball size, ball charge, agitator velocity, height to diameter ratio, feed rate and feed direction all have an effect on the mill efficiency and particle size distribution. Where large quantities of cocoa mass are being processed, it may be more efficient to use a series of ball mills, each successive mill with a smaller ball size beginning with 15 mm (0.6 in) and ending with 2–5 mm (0.1–0.2 in). As ball size is reduced, agitator speed may also be increased (Niediek, 1994). Equipment wear of 20–100 g per 1000 kg of cocoa mass can be expected in ball mills, but staging ball mills also tends to reduce contamination from the grinding media. Ferrous materials can be removed from the finished cocoa mass by magnets located at the mill exit, but non-ferrous contaminants like ceramics are not easily removed. Contamination from grinding media increases subsequent chocolate refiner wear.

The triple mill employs three successive pairs of corundum discs for fine grinding cocoa nib. For each pair of discs, one rotates while the other is stationary. Their capacity is similar to commercial stirred media mills used for grinding cocoa nib, that is 1000–2000 kg h^{-1} (1–2 t h^{-1}). Although operating costs, such as energy and maintenance, may be lower than for agitated ball mills, capital costs are generally greater for disc mills (Niediek, 1994), and temperature control is more difficult. Unlike the agitated ball mill, the feed material may be solid or liquid, although pre-grinding is customary. Figure 9.4 illustrates a typical triple disc mill.

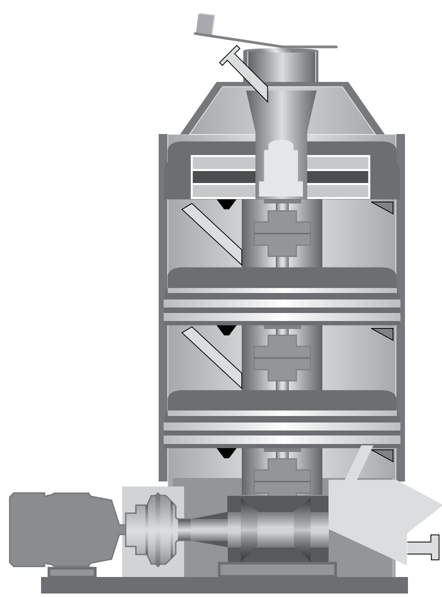

Figure 9.4 Schematic diagram of a triple disc mill (Lehmann).

Unroasted cocoa nib is more difficult to grind than roasted nib, due to a greater proportion of shell and a higher moisture content. This is related to the plasticising effect of moisture on the cellular material. Grinding energy increases with moisture content. Alkalisation of the nib usually makes it easier to grind (Niediek, 1994).

9.5 Chocolate refining

The particle size of the dispersed phase of chocolate, particularly that of the largest particles, must be sufficiently small so that the chocolate does not feel gritty when eaten. Although traditionally continental European chocolate has been described as having a fineness of 15–22 μm (6–9 × 10^{-4} in) and that in North America as being 20–30 μm (8–12 × 10^{-4} in; Jackson, 1994), with the increased globalisation of the industry traditional differences begin to blur and specifications become much more product specific. For example, dark chocolate is generally ground finer than milk chocolate, and chocolate for cookie drops can be coarser than solid eating chocolate, since the texture of the cookie will mask that of the chocolate. However, eating quality is not determined by particle size alone, and many other factors, such as fat content, determine the overall texture (see Chapters 20 and 21). In a comparative study of chocolates from the United States and continental Europe, we found the size of the larger particles (d_{90}; i.e. 90% finer than this size, as measured by laser light scattering, which approximates to a micrometer reading) ranged from 20 to 37 μm. To our surprise, both the finest and the coarsest were from the United States.

Provided the cocoa mass has been properly milled, the primary purpose of chocolate refining is to grind the sugar and, for milk chocolate, the solid milk particles. Crystalline sugars behave as brittle materials under mechanical stress. In studies where sucrose–cocoa butter mixtures have been roll refined, chipping and abrasion contributed significantly to the breakage pattern (Aguilar and Ziegler, 1992). This may not be surprising given the jagged, irregular shape of milled sugar. Whole milk powders (28% fat) roll refined with cocoa butter showed a log-normal breakage pattern, characteristic of brittle fracture when ground below their glass transition temperature (Figure 9.5).

Although spray-dried whole milk powder contains 25–29% fat, this fat is trapped in a matrix of glassy (amorphous) lactose as emulsified droplets (Figure 9.6). Milk protein is similarly distributed, principally as casein micelles. The glassy lactose matrix, like window glass, normally behaves as a brittle material during roll refining. This has been confirmed by Bouzas and Brown (1995). While the fat does not plasticise the lactose matrix, these inclusions, along with trapped air, do reduce the hardness of the particle, making whole milk powder easier to fracture in comparison to crystalline sugar. Therefore, when refined together, the milk powder is broken preferentially. Reducing the size of spray-dried whole milk particles liberates fat in a manner similar to reducing cocoa nib, but the effect this has on flow properties is not as obvious (Bouzas and Brown, 1995).