Aerated Confections

11

11.1 Introduction

The class of aerated confections encompasses a wide range of candy, from the highly aerated marshmallow to the lightly aerated (dense) taffy. Nougat, sponge candy and fruit chews are also found in the category of aerated candies. Aeration is also used to modify texture of other candy categories, including hard candy, brittles, and chocolate. Various types of aerated confections, categorized according to their typical density, or specific gravity, are seen in Table 11.1.

Specific gravity is the relative weight of a specific volume of candy compared to the weight of the same volume of water. One gram of water at 4 °C (37 °F) occupies 1 cm^3 of volume. One gram of aerated candy typically occupies a much greater volume, although several factors can affect specific gravity. Specifically, the nature of the dissolved solids (sugars, proteins, etc.) and the presence of particulates (emulsion droplets, inclusions, etc.) can affect density over and above the air phase. Due to the dissolved sugars, typical unaerated candy syrups may have specific gravity of 1.2–1.5, depending on solids concentration. Aeration causes a significant reduction in specific gravity, to as low as 0.2 in some highly aerated confections, and a subsequent increase in volume. Specific gravity may be measured by simply comparing the weight of a known volume of candy to the weight of the same volume of water. A simple way to estimate specific gravity is to weigh a cup filled with the aerated confection (completely filled so there are no air pockets, but without packing) and divide by the weight of the same cup filled with water.

The main ingredient that characterizes aerated confections is, of course, air. The continuous phase of the candy contains dissolved sugar (among other ingredients), but the presence of small air cells distributed throughout the sugar phase gives a unique texture and appearance to aerated candies. In addition to increasing volume (and lowering density), aeration causes an increase in the viscosity and a decrease in fluidity of the candy mass during processing and, ultimately, modifies the appearance, texture and sensory properties of the finished product. Finely dispersed air cells give a somewhat short texture, similar to that imparted by sugar crystals although not nearly as profound. Air also leads to a reduction of stickiness and cold flow, a lighter mouthfeel, a decrease in sweetness, and a lightening of color.

In order to stabilize air cells in confections, a stabilizing agent (i.e., gelatin, soy protein, dairy protein or egg albumin) is typically used. The presence of these stabilizing proteins during aeration promotes formation of bubbles and prevents their coalescence. The result is a foam made of finely dispersed air bubbles within a sugar candy matrix (the continuous phase). Other stabilizing agents include modified starches, gum arabic, agar, and alginates. Each stabilizing agent imparts

R.W. Hartel et al., *Confectionery Science and Technology*, DOI 10.1007/978-3-319-61742-8_11

Table 11.1 Approximate densities and water contents of typical aerated confections

Candy type	Approximate density (g/mL)	Water content (%)
Taffy	0.9–1.1	7–13
Fruit chews	0.9–1.1	5–7.5
Nougat	0.8–1.0	8–11
Marshmallow		5–18
Extruded	0.25–0.35	
Deposited	0.5–0.7	
Grained		5–10
Ungrained		15–18
Frappé	0.2–0.4	20–25
Vacuum puffed[a]	0.8–0.9	1–2

[a] Malted milk balls

a unique characteristic texture to the confection (for example, the elastic nature of marshmallow is due to the characteristics of gelatin).

Formation of all aerated candies generally follows the same process, although some differences exist for the different types. First, the sugar mass that forms the continuous phase is mixed and cooked to the desired water content. Typically, the stabilizing agent is added after the sugar mass has cooled slightly since denaturation and/or degradation of the proteins used as stabilizing agent can occur if temperature is too high. Numerous aeration technologies exist; aerated confections can be extruded with air injection, whipped in mixing bowls, pulled on taffy hooks, or aerated chemically. The viscosity during aeration and the intensity of agitation determine the nature of the air cells (e.g., bubble size distribution). For certain stabilizers (e.g., gelatin), temperature control is also important to ensure proper solidification. Following aeration, additional ingredients may be added to give the desired color, flavor, and texture. Forming candies from the aerated mass can be done (1) by depositing either in starch or plastic molds, (2) by extrusion through a forming die, (3) in batch rollers to form ropes of candy that are formed and cut into the desired shape, or (4) spreading the candy mass into a sheet for scoring and cutting. A few candies, like malted milk balls and some puffed hard candies, are aerated through vacuum expansion.

The texture of aerated confections is governed to a large extent by the air phase, although the nature of the continuous sugar phase also imparts certain characteristics. Taffy and ungrained marshmallow contain higher amounts of glucose syrup than sucrose, so the sugar all remains in the liquid (or amorphous) state. These candies have a chewy texture since there are no sugar crystals to break up the strands of amorphous sugar phase even though the presence of air bubbles provides some short character to these candies. Sugar crystals, as found in grained marshmallow and most fruit chews, also impart a shorter texture, with the short texture increasing with the amount of sugar crystals present.

The moisture content of the finished product can vary from as low as a few percent for dried marshmallow and vacuum puffed candies to as high as 25% for frappé (Table 11.1), with hardness generally increasing as water content decreases. This water content gives a water activity of between 0.4 and 0.75, meaning that many aerated candies are susceptible to drying out under normal storage conditions. Hardening over time due to moisture loss typically signals the end of shelf life for aerated confections.

11.1.1 Aerated Confections

A wide range of products fall in the category of aerated confections. Typical formulations for marshmallow, nougat, fruit chews and taffy are shown in Tables 11.2, 11.3, 11.4, and 11.5.

11.1.1.1 Marshmallow

Marshmallows come in a wide variety of shapes, sizes and textures, depending on the intended application. Marshmallows can vary in specific gravity from highly aerated products, about 0.25 specific gravity, to much denser products, with specific gravity of 0.7 or higher. Water content can vary from over 20% for fluid marshmallows to less than a few percent for dried marshmallows (often found in cereal products). Furthermore, the sugar phase of marshmallows may either be ungrained or partially grained to provide a short texture. For the most part, marshmallows are

Table 11.2 Typical formulations (in %) for deposited and extruded marshmallow

		Extruded marshmallow	Deposited marshmallow
Sucrose		30–40	30–45
Glucose syrup (62 DE)		35–45	30–45
Water		10–15	10–15
Hydrated gelatin		6–11	4.5–9.0
Gelatin (250 bloom)	33.3		
Hot water	66.7		
Flavor		0.2–0.5	0.2–0.5
Color		0.02–0.5	0.02–0.5

Table 11.3 Typical formulations (in %) for chewy and grained nougats

	Chewy nougat		Grained nougat	
Syrup phase		65–80		65–80
Sucrose	30–45		40–55	
Water	8–12		12–18	
Glucose syrup (42 DE)	43–60		32–45	
Salt	0.2–0.5		0.2–0.5	
Frappé		15–30		10–25
Protein	5–10		6–12	
Water	10–30		30–55	
Glucose syrup (42 DE)	60–80		0–10	
Sucrose	0–10		35–50	
Fat		2–5		2–5
Vanilla		0.2–0.4		0.2–0.4
Powdered sugar		–		4–6
Nuts		2–4		2–4

Table 11.4 Typical formulation (in %) for fruit chew candy

		Fruit chew
Sucrose		25–40
Glucose syrup (42 DE)		30–55
Water		6–12
Fat		6–9
Hydrated gelatin		1–3
Gelatin (250 bloom)	33.3	
Warm water	66.7	
Lecithin		0.1–0.25
Fondant		0–10
Citric acid		0.7–1.2
Flavor		0.2–0.5
Color		0.05–0.1

Table 11.5 Typical formulation (in %) for salt water taffy

	Salt water taffy
Sucrose	25–35
Glucose syrup (42 DE)	50–60
Water	8–12
Evaporated milk	0–5
Fat	2.5–5
Frappé	0–4
Mono- and diglycerides	0–0.25
Lecithin	0–0.25
Salt	0.1–0.3
Flavor	0.1–0.3
Color	0.05–0.15

stabilized with gelatin to give a gummy-like, elastic texture, although other stabilizers may be used to give different textures.

There are several different variations of marshmallow. Marshmallow is typically either extruded or deposited, and either type may be grained or ungrained. The formulation and process conditions are slightly different, depending on the desired texture and characteristics. Gelatin is the most common stabilizer used for classic marshmallows, although soy or egg proteins (or even starch) may be used, either individually or in combination with gelatin. In ungrained marshmallow, the sugar syrup must contain more than 50% glucose/corn syrup solids to inhibit formation of sugar crystals during processing or storage. Ungrained marshmallow may be formed by depositing (often in dried starch) or extruding into the desired shapes. Ungrained marshmallows may simply be dusted in starch for consumption ("jet-puffed" marshmallows), coated with sugar or enrobed with chocolate. Typical formulations for deposited and extruded marshmallows are provided in Table 11.2.

Grained marshmallow typically contains higher levels of sucrose than glucose syrup to create a supersaturated state in the sugar syrup phase of the confection. Graining is often induced through seeding with either powdered sugar or fondant prior to forming, which is usually accomplished by depositing in dried starch or extruding. A common example of a grained marshmallow is the banana-flavored circus peanut, which is deposited into dried molding starch to form the dimpled surface (mold side). Extruded, grained marshmallow may be dried to low (a few percent) moisture content, a product that is often found in breakfast cereals or hot cocoa mixes.

An ungrained form of marshmallow often used for inclusion in other foods or confections is frappé, also known at times as mazetta, egg whip or nougat créme. Frappé is often mixed into confectionery bases to make aerated products like cream centers, caramels and fudge, or nougat. In this respect, frappé is sometimes considered a sugar syrup-based carrier of air to provide aeration in other products. Frappé may be made by whipping a sugar syrup containing sucrose, glucose syrup and/or invert sugar at about 20–25% water content with a hydrated stabilizer (egg albumin is common for frappé) to low (0.25–0.35) specific gravity. The specific ingredients chosen are determined by the desired characteristics of the frappé, from light and fluffy to a more firm and robust product capable of withstanding higher agitation. Commercial frappé often contains a starch to help stabilize the aerated mass.

11.1.1.2 Nougat

The original nougat, with its origin in either France or Italy (depending on whose claim is believed), is an aerated confection made of honey, egg white and almonds. Egg protein is the main stabilizer in this type of nougat. However, nougat, like marshmallow, comes in a wide range of product characteristics, from an ungrained, extremely chewy product to grained nougat with a short texture from substantial crystallization. Nougat may be found as a distinct candy item, but in the United States is most often found in candy bars, whether grained or ungrained, and often in combination with caramel and enrobed in chocolate. Divinity or sea foam candy is basically a softer grained version of nougat.

As with marshmallow, the primary difference in grained and ungrained nougat is the relative content of sucrose and glucose syrups. Ungrained nougat must have higher levels (at least 50%) of glucose syrup solids to inhibit graining, whereas grained nougat contains more sucrose to generate a supersaturated state in the syrup phase. Graining in nougat may be promoted by seeding the cooled candy mass with powdered sugar or fondant, by agitating the candy mass at the appropriate point in the process or crystals may be allowed to form spontaneously (even during storage). Typical formulations for chewy and grained nougat are provided in Table 11.3.

11.1.1.3 Chewy Candies and Taffy

Fruit chews and taffy are typically slightly aerated, often by pulling, to give a specific gravity close to 1.0. Gelatin is often used in chewy candies, whereas the stabilizers most typically used for taffy include egg protein or starch. Chewy candies generally contain a slight level of crystalline sugar (5–10%) to provide a slightly short texture, whereas taffy generally is ungrained. The addition of a small amount (5–10%) of fat to chewy candies decreases the stickiness on processing equipment, wrappers and teeth. Tables 11.4 and 11.5 provide typical formulations for fruit chews and salt water taffy, respectively.

11.1.1.4 Vacuum-Expanded Confections

The main confection in this category is the malted milk ball, although some hard candies may also be vacuum-puffed.

In the vacuum process, small air bubbles are introduced into a cooked candy mass (4–6% moisture) through pulling or some other aeration method. After the candy is formed, often by sheeting and passing it through drop rollers to form small balls, it is placed in a type of vacuum oven. Reducing pressure while the candy is still somewhat fluid (warm, but not hot) causes expansion of the bubbles (ideal gas law) through the amorphous matrix to promote aeration (increase volume). When the puffed candy is cooled (still under vacuum), the sugar matrix solidifies into the glassy state, trapping the bubbles in their expanded state within a hardened, crunchy sugar matrix.

11.1.1.5 Aerated Hard Candy

Hard candies are often aerated to provide unique textures and colors. Aeration of hard candy is covered in detail in Section 8.3.2.2.

11.1.1.6 Aerated Chocolate

Chocolate can also be aerated, again to provide unique textures. Aeration of chocolate is covered in Section 15.6.5.

11.2 Formulations and Ingredients

The main components of aerated confections, besides air and stabilizer, are sugar and glucose syrup (Tables 11.2, 11.3, 11.4, and 11.5). Numerous other ingredients may be added to provide modified functionality, texture and/or nutritional characteristics. For example, humectants are often added to control water activity and shelf life, fats may be added to provide lubricity, emulsifiers may be added to help disperse the fat phase into a fine emulsion, and texture modifiers like starch may be added to impart specific physical properties. Colors and flavors are added to suit, as desired.

11.2.1 Air

Although the simplest (and cheapest) ingredient in aerated confections, air is also arguably one of the most important. Air should be clean, dry and free from all contaminants, including particulates, microorganisms, odors and oil droplets. When a candy is aerated by pulling (whether taffy, nougat, fruit chews, hard candy, etc.), the air in the manufacturing facility is incorporated into the mass by the continual folding and refolding. Typically, there are no concerns in regard to such aeration processes as long as good air handling facilities maintain fresh air circulation and the humidity is not too high. If humidity is above approximately 50–60%, the moisture in the air may cause problems within the candy itself and dehumidification may be necessary. If compressed air is used in pressure aeration, it must be treated to ensure that no contaminants enter the candy. Specifically, compressed air should be filtered to less than 0.3 μ prior to injection into the candy mass to remove contaminants like small oil droplets, undesired particulates and bacteria. The air should also be free from odors and any oils used in the compressors should be food grade.

Although air is the primary gas whipped into aerated confections, there are times when other gases might be used. For example, nitrogen gas might be considered for fat-based products (nougat) to minimize lipid oxidation. However, commercial use of gases other than air is rare.

11.2.2 Sweeteners

Sucrose and glucose/corn syrups are the primary sweeteners used in aerated confections, although versions of these candies can be made with other sweeteners like invert syrups and polyols. The ratio of sucrose to glucose syrup determines the likelihood and extent of graining. Higher levels of sucrose (up to 70% of sugar solids) promote graining and lead to a short texture; higher levels of syrup solids (as high as 70%) inhibit graining and give chewier candies. In some candies, such as fruit chews or grained marshmallows, fondant may be added to provide the seed for grain.

Typically, 42 DE glucose syrup is used in aerated confections, although different textures can be obtained from using other glucose syrups. Use of 63 DE glucose syrup gives a slightly softer texture, whereas high-maltose glucose syrup imparts a slightly chewier texture. Addition of a small amount of invert sugar syrup can be used to give a softer texture and to provide humectant properties by reducing water activity and inhibiting moisture loss during storage.

Sugar-free marshmallows can be made with a range of polyols. Maltitol and HSH or polyglycitol syrup (see Section 1.8.1) can be used together in exactly the same manner as sucrose and glucose syrup. Other polyols that can be used in sugar-free aerated confections include sorbitol and isomalt.

11.2.3 Stabilizers

To attain very low specific gravity in marshmallow, a stabilizer is needed. Whipping sugar syrup without a stabilizer may result in slight aeration; whereas, whipping in the presence of a stabilizer allows air to be incorporated and maintained in the candy by preventing air bubbles from coalescing during and after aeration. In many aerated confections, especially highly-aerated marshmallows, the stabilizer is a protein that orients at the air-serum interface to provide stabilization by preventing newly formed bubbles from recombining. Gelatin is by far the most common stabilizer in marshmallow, but egg albumin, dairy protein, and soy protein may also be used.

When proteins are used for aerated confections, their temperature must generally be kept below the denaturation temperature to minimize degradation. Egg, dairy and soy proteins are subject to denaturation if held at high temperatures for too long. Typically, these proteins begin to denature at about 68–70 °C (about 155–160 °F). However, denaturation is a kinetic process, meaning that the longer time it spends at temperatures above the denaturation point, the greater the extent of denaturation. Gelatin also degrades or breaks down at high temperature, with the extent of degradation proportional to time and temperature. Once the protein is denatured or degraded, it no longer provides the same level of aeration. For this reason, proteins are often added to the cooked sugar mass after it has cooled to a temperature safe from degradation. Also, since water is added with the hydrated stabilizer, the sugar syrup candy must be cooked to higher temperature accordingly to offset the addition of water back to the candy.

The choice of stabilizer is made based on the desired attributes of the final product and other factors (cost, ease of processing, religious concerns, etc.).

Each stabilizer imparts a different texture to the aerated confection. The albumens (egg, soy and dairy), typically used at levels of 1–1.5%, impart a soft, short texture. Agar (1–2%) also imparts a soft, light texture. Gum arabic (used at 20–30%), on the other hand, produces a candy with a tough, chewy texture. Alginates, used at 1.5–3%, also produce a tough texture. Modified starches may also be used in aerated confections. They produce a tough texture when used at 7–11%. Stabilizers may also be used in combinations to create unique textures and commercial blends are available for specific applications. A description of the different textural attributes of each stabilizer, along with typical usage levels, is given in Table 11.6.

Table 11.6 Stabilizers used in aerated confections

Stabilizer	Usage level (%)	Texture characteristics
Gelatin	2.0–6.0	Elastic
Egg albumin	1.0–1.5	Soft, short
Soy protein	1.0–1.5	Soft, short
Whey protein	1.0–1.5	Soft, short
Gelatinized starch	7.0–12.0	Firm, chewy
Agar	1.5	Light, soft
Gum arabic	20.0–30.0	Tough, chewy
Alginates	0.5–3.0	Tough

Data from Groves 1995

Gelatin is the most common stabilizer in marshmallows since it gives a unique elastic texture, one that can be moderated by choice of gelatin bloom strength (see Section 5.2.3.1) and the amount of gelatin used. In ungrained marshmallow, low bloom (125) gelatin used at higher levels (4–6%) gives a chewy texture, whereas high bloom (250) gelatin used at lower levels (2.5–4%) gives a shorter texture. In grained marshmallow, low bloom gelatin is used at levels of 2.5–4%.

Most stabilizers for aerated confections must be hydrated prior to use. Complete hydration is necessary to ensure that the stabilizer is fully active and the maximum results are obtained. Certain stabilizers may be very difficult to hydrate; thus, it is critical that this step be given sufficient time. Some stabilizers are prone to clumping. This can be minimized by dispersing the powders in sugars or a syrup before hydrating or dispersing with a high shear mixer. Also, an excess of water must generally be used to allow complete hydration; this water must be accounted for in the formulation for the aerated confection. Table 11.7 summarizes the minimum amount of

Table 11.7 Hydration requirements for stabilizers used in aerated confections

Stabilizer	Minimum water required	Hydration time (min)
Egg, soy, whey protein	1.0[a] (50%[b])	30
Gelatin	1.5 (60%)	30
Gum arabic	1.25 (55.6%)	45
Gelatinized starch	3.0 (25%)	–[c]
Agar	30.0 (96.8%)	–[c]
Alginates	99.0 (99%)	30

Data from Groves 1995

[a] Parts water required per 1.0 part of dry powder stabilizer

[b] % water in hydrating solution

[c] Must be fully cooked

water needed and minimum times required for hydration of different stabilizers.

11.2.4 Humectants

To moderate texture and prevent moisture loss during storage, humectants such as sorbitol, glycerol and invert sugar syrups are sometimes added to aerated confections. Addition of 1–2% humectant gives a softer product with a lower water activity that retains moisture during storage. If invert sugar syrup is used as a humectant, the total level in the candy (from addition and inversion during processing) should remain below about 4%, otherwise the candy will be excessively sticky. Addition of glycerol or sorbitol causes a significant reduction in water activity (replacement for water), which helps prevent the candy from drying out during storage while also softening the texture.

11.2.5 Fats

The addition of fats to chewy candy (nougat, chews and taffy) provides lubrication during both processing and consumption. Fats added at 3–8% of the candy mass promote easier processing (less sticking to process machinery) and lead to less stickiness on the teeth during consumption. However, fats have a negative effect on aeration since they migrate towards the air interface and cause breakdown of air bubbles. Thus, their addition must be carefully controlled, particularly in nougat, to ensure that aeration is not inhibited or lost.

Typically, fats are not added in marshmallow formulations since fats tend to depress whipping ability. Marshmallow is intended to have a low density and high air content, which precludes the addition of fat. In nougats, less aeration is desired and the highly viscous continuous sugar phase tends to hold air bubbles, so some fat can be accommodated in the formulation, particularly if added late in the process, without losing texture characteristics. Liquefied fat is often blended into the warm aerated mass, with as little shearing as possible, as one of the final process steps prior to forming. When the nougat is cooled, the fat globules become semi-crystalline and provide the desired lubricity without affecting aeration. In chews and taffies, the extent of aeration is sufficiently low that the negative effect of fat is not a problem and the fat can be added at the beginning. This is particularly true for candy that is pulled since the high viscosity of the candy matrix on the pulling machine (or hook, if pulling is by hand) stabilizes the air cells incorporated by folding and re-folding.

Typically, the fats used in chewy candies are modified vegetable fats, chosen primarily for their low price, melting properties, and resistance to oxidation. Fats typically add little in the way of flavor to these products; however, their physical attributes are important to finished product characteristics. They should be semi-solid at room temperature to provide stand-up properties and prevent oiling off, with a melting temperature less than mouth temperature so there is no waxy mouthfeel. A melt point of 33–35 °C (91–95 °F) is generally considered best for fats used in taffy, although higher melting points, 35–40 °C (95–105 °F), may be more appropriate in warmer environments.

Since the fats are exposed to air within the candy itself, lipid oxidation (see Section 4.2.3) is a problem that can result in rancid off-flavors. Often, nonlauric fats (palm, soy, cottonseed, etc.) modified to have the appropriate melting properties are used since lauric fats (e.g., coconut, palm kernel) oxidize readily to produce soapy off-flavors. Palm fats (or certain of its modifications) may be used to minimize *trans* fat content.

11.2.6 Emulsifiers

The addition of fats to aerated chewy candies (nougat and taffy) generally dictates that an emulsifier be added to help disperse and stabilize the fat globules during processing (see Section 4.6), particularly when the candy mass is still fluid. However, the viscosity of the continuous sweetener phase generally prevents fat globules from coalescing and prevents oil separation; thus, emulsifiers are not necessarily needed to stabilize the emulsion.

When used, lecithin is the most common emulsifier found in aerated confections, although glycerol monstearate (GMS) and sugar esters can also be used. GMS in particular helps to reduce stickiness of nougats and chewy candies. Levels of emulsifier use are generally low, between 0.1% and 0.2%.

11.2.7 Texture Modifiers

Low levels of texture modifiers may be used to influence physical properties and eating characteristics, particularly in chewy candies (nougat and taffy). Starch, dextrin, gums, pectin, and gelatin may be added to provide specific textural effects. The use of starch in taffy, for example, helps improve stand-up properties (reduces cold flow) and imparts a slightly shorter texture to the candy piece. In some cases, a portion of the starch used in taffy may be added after the cook (but before pulling). The presence of intact starch granules helps prevent cold flow and provides a shorter texture. High molecular weight saccharides, like dextrins, also enhance chewing characteristics in fruit chews and taffy.

The addition of fondant or powdered sugar to aerated candies is a form of texture modification in that the crystals provide a shorter texture to the candy. The extent of short texture characteristic depends for the most part on how much of the sugar is in crystalline form (also a function of water content and sucrose to glucose syrup ratio). Highly grained candies (as in some marshmallows) can have an almost crumbly texture, grained nougats with intermediate crystal content have a short and soft texture, and lightly grained candies (like fruit chews) are somewhat short but still retain a significant chewy and elastic texture.

11.2.8 Fruit Juice

To appeal to a more health-minded consumer, many fruit chews are now formulated with fruit juice and/or concentrate. Since fruit juice concentrates typically contain high glucose content, the other sweeteners must be chosen carefully to provide a balanced saccharide profile lest the candy be excessively soft and sticky. Another consideration with fruit juices added prior to cooking is that they lose a substantial amount of flavor through volatilization at boiling temperatures and thus, other flavorings are still typically required. Some juices (for example, black carrot juice concentrate) may also be considered colorants.

11.2.9 Organic Acids

It is common to add organic acids to complement fruit-flavored chewy candies (fruit chews and taffy). As in other candies, acids added at a low level, less than 1%, bring out the fruit flavors. In some chews, higher levels (1–2%) of organic acids, including citric, malic, tartaric, fumaric or ascorbic acid, may be added, for example, to provide a sour experience. Often the best flavor pairings happen when the organic acid matches the base flavor. For example, lactic acid matches with dairy flavors, citric acid with citrus flavors, and malic acid with strawberry flavors.

11.2.10 Flavors

Water, glycol and alcohol-based flavors are best suited for aerated confections. Oil based flavors should not be used for highly aerated products like marshmallow since they might cause a loss in aeration. For this same reason, low fat cocoa powder should be used instead of chocolate liquor because of its lower fat content.

Flavors should be stable when aerated and verified that they do not react with the whipping proteins to cause denaturation. Flavor usage is greatly dependent upon the strength of the flavor and customer expectations. Flavor usage is often in the 0.2–0.5% range.

11.2.11 Colors

As with flavorings, it is prudent not to use oil-based dyes in highly aerated confections, although they may be acceptable in low aeration confections such as pulled taffies. Consistency in color is easier with a predispersed dye than with a dye powder, which can cause speckling. Usage levels (especially for dark color shade) tend to be higher than in other confections since aeration imparts whiteness.

11.2.12 Gelation Aids

In some types of marshmallows such as sugar free or standard marshmallows where quick setting of the gelatin is required for the production process, a gelation aid may be added to the formulation. Sodium hexametaphosphate and metal salts such as calcium chloride help promote rapid gelation by forming an ionic bridge between gelatin strands. Rapid setting of gelatin is needed for extruded marshmallow since the marshmallow rope would flatten out as it leaves the extruder and is transferred to the conveyor belt.

11.2.13 Active Ingredients

Lightly aerated chewy candies are good carriers of active ingredients and various health-promoting products can be found on the market. For example, a chewy nougat product contains calcium carbonate to promote bone strength in certain individuals. Other types of active compounds that might be found in such candies include vitamins, caffeine, proteins, essential oils, and other extracts (e.g., lutein).

11.2.14 Inclusions

Of the aerated candies in this category, nougat is the one most likely to contain inclusions. In nougat, it is common to find nuts and fruit pieces; in fact, the original nougat from France and Italy contained nuts and perhaps fruit as well. The inclusions are typically chopped into fine pieces and blended into the candy mass just prior to cooling, solidification and forming. Inclusions increase the overall specific gravity of the piece, although the nougat phase remains highly aerated, and provide a unique contrast between the dense solid inclusion and the lighter, more aerated nougat.

11.3 Processing

Manufacture of all aerated candies, except those that are vacuum expanded, generally follows the process shown schematically in Figure 11.1. Differences in method of cooking and aeration are based on the nature of the product. After the sweeteners have been mixed together, the sugar syrup is cooked to the proper temperature to give the desired moisture content in the finished product. The stabilizing agent may be added either before cooking or after, depending on the process. The batch is then cooled and aerated to produce a candy with reduced density. The method and order of ingredient addition, the aeration step, and forming processes are steps that depend to some extent on the type of aerated products.

11.3.1 Dissolving and Cooking

As with most candies, the sweeteners are mixed together and heated to dissolve any crystalline materials. The syrup mixture is then cooked to the specified temperature to obtain a candy mass with the desired moisture level. Typical cooking temperatures are in the range of 107–110 °C (225–230 °F) for marshmallow, 123–129 °C (253–264 °F) for nougat, and 121–132 °C (250–270 °F) for fruit chews and taffy. It is important to control the cook temperature in order to control

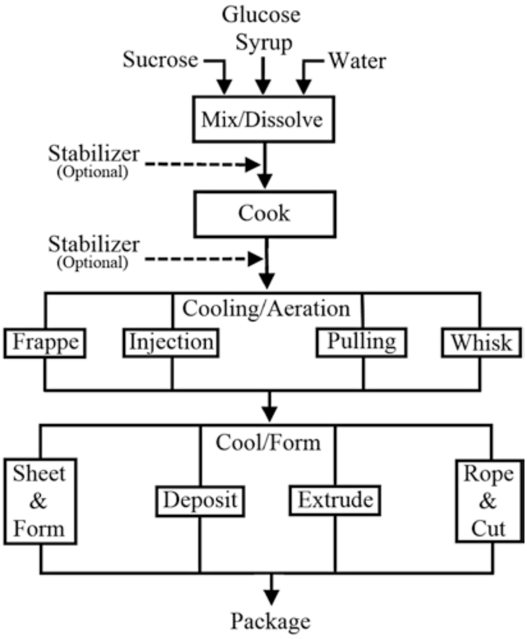

Figure 11.1 Schematic of typical process for manufacture of aerated confections

moisture content. Especially in nougat, chews and taffy, slight differences in moisture content may be sufficient to cause a product to exhibit cold flow (moisture too high) or be too hard (moisture too low). Thus, control of cooking temperature is critical to obtain uniformly consistent product with the desired textural and sensory properties.

Variance in texture can also occur when changes in cooking time are found. Increased cooking times in batch cooking systems can promote sugar inversion, which results in a softer texture and increase stickiness. Water quality should be monitored for pH and mineral content since this can also have an effect on sugar inversion. Changes in barometric pressure and relative humidity may also have an effect on the final product texture.

The simplest cookers are batch kettles, heated with either a steam jacket, electric heating element or open flame. These may require manual stirring or have internal stirrers, usually blades that sweep the surface. Large scale, continuous cookers (i.e., micro-film cookers, shell and tube heat exchangers, plate heat exchangers, scraped surface heat exchangers, etc.) may be used for higher throughputs and fully automated production lines.

11.3.2 Stabilizer Addition

Before a stabilizer can be used it must be properly hydrated so that all of the benefits of the proteins can be realized. Hydration is dependant upon the ratio of water to stabilizer (see Table 11.7 for minimum moisture and time required) and the time allowed for hydration. Typical hydration for gelatins and albumens is 2:1–4:1 water/stabilizer for 30 min. Exact hydration time is dependant on ratio and granulation size. It is also best practice to use cold water for proper dispersion and to prevent formation of ‘fish eyes’.

In marshmallows, hydrated gelatin may be added either before or after cooking. Although adding gelatin after the cooked syrup has cooled is preferred, it is not uncommon in batch cooking that the hydrated gelatin is added to the batch directly at the end of the cook, along with other heat sensitive ingredients (e.g., flavors). In larger continuous systems, gelatin and other proteins may be metered into the cooked syrup through an injection port ahead of an in-line static mixer.

When hydrated stabilizer is added after cooking, the initial cook temperature of the sweetener syrup must be set a little higher than what would be expected for the water content of the finished product to offset the amount of water added back. That is, the sugar syrup is cooked to slightly higher temperature to have reduced water content, which is then brought up to the desired moisture level by addition of the aqueous hydrocolloid.

To simplify the process, gelatin (and sometimes other proteins) may be added directly to the sugar syrup (slurry) and the entire mass cooked quickly to the desired temperature. Since protein degradation occurs at temperatures above about 68–70 °C (about 155–160 °F), cooking the protein with the sugar syrup means that some degradation will occur. This can have a negative effect on the aeration properties and the characteristics of the final product. However, if cooking time is short, the amount of degradation that occurs may be sufficiently small that the loss of aeration and structure is offset by the advantages of a single cooking step, without the need for secondary addition of hydrated stabilizer.

According to kinetic reaction laws, the rate of degradation increases exponentially as temperature increases and the extent of degradation is related to the length of time at elevated temperature. For example, it takes about 30 min at 95 °C (203 °F) for gelatin to lose about 10% of its bloom strength (pH 5), whereas at 80 °C, only 2–3% loss in bloom strength is observed in 30 min and at 60 °C, there is only about 1% change in bloom strength over that time. Lowering pH results in significantly faster degradation rates, with between 5% and 10% degradation in 30 min at 60 °C and pH 2. In modern rapid continuous cooking technologies, gelatin may experience temperatures over 120 °C (249 °F), but only for a short time (less than a minute). Although some gelatin degradation will occur at these conditions, which could potentially lead to less aeration capacity and weaker gel strength, the extent of degradation may be small enough that a manufacturer may choose to cook the gelatin directly in the sugar syrup. Egg proteins denature more quickly than gelatin and are most often added to the syrup after the cook.

Another negative consequence of cooking the protein with the sugar syrup is browning and discoloration. As one of the main reactants in the Maillard browning reaction (see Section 1.4.3.1), protein (egg, soy, whey and gelatin) reacts with reducing sugars to produce brown pigments and caramel flavors when heated. Continuous cooking technologies with short residence times at high temperature minimize color formation so that browning generally is not a problem.

11.3.3 Cooling

In general, the candy mass for aerated confections must be cooled somewhat before aeration, especially if the stabilizer is added after cooking. If not cooled sufficiently, the stabilizing agent may denature or degrade and no longer function properly as a whipping agent. On the other hand, if the candy mass is too cold before protein is added, it will be difficult to get a homogeneous dispersion into the sugar syrup. It is preferred to add gelatin and other protein sources once the syrup has cooled to 77 °C (170 °F) to reduce danger of severe degradation, although lower temperatures, around 65.5 °C (150 °F), are preferred to minimize negative effects. As noted above, however, the extent of degradation depends on both temperature and time, so in general, the higher the addition temperature, the shorter the time before extensive degradation.

For marshmallow, it is important that the candy mass be cooled to just above the setting point of the gelatin before whipping. It is, in part, gelation of the gelatin that keeps air bubbles separate during cooling and promotes aeration during whipping. If the candy mass is too warm during whipping, the air bubbles will coalesce and specific gravity will not be sufficiently low. Typically, the candy mass is cooled to 45–55 °C, just above gelatin's melting point, (113–131 °F) prior to aeration.

Cooling of the candy mass prior to stabilizer addition and subsequent aeration may be accomplished in several ways. In small-scale operations, the candy mass from a batch cooker is simply poured onto a cold table for cooling, with acids, flavors and other heat sensitive ingredients being added prior to folding. The cooling drum is another common method of cooling candy mass for nougat, chews and taffy. Cool water circulating inside the drum provides rapid cooling of a thin layer of sugar syrup. Drum rotation is sufficiently slow that the candy mass is cooled to the desired temperature after one-half to two-thirds of a rotation of the drum. The cooled candy mass is scraped off the drum and collected for further processing. In larger continuous operations, cooling of marshmallow and nougat candy mass may be accomplished in a scraped-surface heat exchanger (e.g., Votator). Other types of heat exchangers (plate, shell and tube, etc.) are typically not sufficient for cooling such thick candy masses.

11.3.4 Aeration

The extent and method of aeration depends on the type of candy being made. Numerous options are available although highly aerated products like marshmallow generally require different equipment than lightly aerated products like taffy. Aeration may either occur from simple open air whipping to more precise air injection during extrusion.

11.3.4.1 Marshmallow and Nougat

In marshmallow, aeration takes place at warm temperatures, when the candy mass is still liquid above the melting point of gelatin. One of the simplest methods for aeration of marshmallow is whipping in a kettle or bowl with a whisk-type mixer, often called a planetary mixer. The whisk action introduces air into the candy mass through a constant folding and refolding process. Larger air pockets are then broken down into smaller air bubbles by the continued shearing action of the whisk. The whisk itself wipes off the surface of the bowl to prevent build up on any one spot. The candy mass is whipped until it reaches the desired density, as measured by periodically weighing the candy in a cup of known volume. Densities as low as 0.3 or 0.4 can easily be achieved with a planetary mixer operated under the right conditions. However, besides being a batch process, there are several disadvantages to the planetary mixer method. For example, up to 2–3% water loss may occur during beating, which must be accommodated in the initial formulation. Also, since it is a batch process, control of aeration is less precise than with some other aeration methods, giving a wider variation in specific gravity of the finished product.

For better control, and more rapid aeration, a pressure mixer may be used. Enclosed kettles, or pressure whisks, are operated with (filtered) compressed air injected under pressures of up to 345 kPa (50 psig). Specific gravity is controlled by the amount of air injected into the mass, with densities as low as 0.3 being easily attained in marshmallow production. The whipping process is essentially identical to that described in the previous paragraph.

For large-scale production, aeration of marshmallows may be done in continuous pressure beaters, a process that also accomplishes several other steps (cooling and forming) at the same time. The cooked sugar syrup containing the hydrated gelatin is fed into the mixer, where a controlled flow of air is injected under pressure. A cooling jacket provides temperature control as the candy mass is whipped. The mixing head typically contains a rotor/stator arrangement to provide shearing action so that the relatively large air bubbles injected into the mixer get broken down into very small bubbles by the high shear forces (see Section 11.4.1.1.2). A back-pressure valve at the outlet of the mixer allows pressure to be maintained in the mixer. The tiny bubbles in the candy mass within the mixer expand slightly according to the ideal gas law as the candy passes through the outlet orifice. Continuous pressure beaters can also be used to aerate nougat. Because of the higher viscosity with these products, higher pressures are required to force aeration.

The size of air bubbles produced in marshmallow from a continuous pressure beater is determined by numerous factors, including (1) the applied shearing forces, which are a function of syrup viscosity (temperature and composition), the rotor/stator design (pins, head size), and rotational speed, (2) whipping temperature, (3) residence time within the mixing head, which is governed by the syrup pump rate and air injection rate, and (4) the pressure in the mixing head. Increased shearing force generally leads to smaller air bubbles; however, if too much heat is added to the marshmallow through mechanical energy input and frictional heat released, the decreased local viscosity can lead to coalescence and ultimately, larger air bubbles. Thus, temperature control is important in continuous aerators. A stiff marshmallow product with density of 0.5–0.7 g/mL exits through the outlet die where it is either cut in the appropriate sized pieces or collected on a take-away conveyor operating at the same speed as the product exits the extruder. Outlet temperature is critical since the gelatin should be starting to set up as it exits the aerator so that it does not collapse on the conveyor. Gelation aids, like sodium hexametaphosphate, can be added to the formulation to help solidify the marshmallow more quickly.

In some operations (nougat in particular), the frappé method is used to aerate the candy mass. In this case, frappé is made by separately whipping a portion of the sugar syrup at cool temperatures. Any of the aeration technologies noted above may be used to make the frappé, typically with a very low specific gravity (0.2–0.3). The bulk of the sugar syrup is cooked to the desired water content (accounting again for the water being added back in the frappé), cooled, and mixed with the frappé. The ratio of frappé added to the cooked sugar syrup and the specific gravity of the frappé govern the specific gravity of the finished candy.

11.3.4.2 Chews and Taffy

It is not unusual to see taffy being pulled by hand at fairs and resort areas. After cooking and cooling to the appropriate temperature, a plastic candy mass is placed on the hook and pulled downwards with half on either side of the hook. The two pulled ends of candy are brought together and looped back up over the hook. The two new ends are pulled down again and the process is repeated until the candy has been aerated to the appropriate level. Air is incorporated into the candy as it is stretched and folded over itself. Unlike other whipping methods, pulling creates nonspherical air pockets due to the stretching and refolding of the candy. A change in color is also observed as the candy is pulled, with color becoming lighter, almost pastel-like. Typically only light to moderate levels of aeration (density of 0.9 g/mL) can be accomplished with the hook. However, hand pulling is no longer used in commercial operations, having been replaced by more convenient and controlled pulling devices or automated whipping technologies.

Pulling machines, either horizontal or vertical, provide automated aeration of candy batches. They are used still for hard candy (see Section 8.3.2.2), chewy candies and taffy, among other applications. The plastic candy mass is mounted on the hooks and the machine pulls the mass until the desired aeration level has been reached. Moderate aeration levels (0.8–0.9 g/mL) can be achieved with pulling machines.

11.3.5 Final Ingredient Addition

After aeration and just before the final cooling and forming steps is often when other ingredients, such as fats and inclusions (and sometimes colors and flavors) are added, particularly for nougats. At this point, the candy mass has numerous small bubbles from the aeration step and these bubbles are stabilized to some extent by the stabilizer. However, the bubbles at this point are still prone to coalescence, where smaller bubbles combine to form larger bubbles with less surface area. Coalescence is promoted by the fluidity of the candy mass and by mixing, as this brings the bubbles together and promotes breaking of the interface between bubbles. Although mixing must be kept to a minimum at this point, sufficient mixing is needed to completely incorporate fats, colors and flavors into a homogenous candy mass at this point. Liquid fat can also destroy aeration so mixing in the fats should be as gentle as possible to retain the desired aeration.

11.3.6 Cooling and Forming

Once the final ingredients have been incorporated, the candy mass is cooled and formed into the desired shapes (or formed and cooled, depending on the technology). Numerous forming methods are available, with the choice depending on the nature of the candy being formed.

Marshmallows are typically formed either by depositing or by extrusion. Fluid marshmallow formulations are deposited into depressions in starch trays and solidified by allowing the trays to stay overnight in a warm, dry room to promote drying to the final moisture content (see Section 12.3.1.2.2.1 for more description of the starch mogul process). Products with well-defined shapes, like seasonal candies (Santas, turkeys, etc.) or promotional items that will be enrobed in chocolate, are often made this way. The fluid nature of the deposited marshmallow allows the candy to fill in details of the starch mold. Alternatively, marshmallow can be deposited directly onto a moving conveyor. In this case, the marshmallow must be formulated to the final moisture content and the gelatin must set quickly after depositing in order to retain the desired shape. Interesting candy designs (including chick shapes, with a beak) can be created by coordinating the motion of the depositing heads with the conveyor. Center-filled marshmallows (chocolate paste, fruit filling, etc.) can be formed by co-depositing a center around the marshmallow exterior. After depositing on a conveyor, the marshmallows are dusted with starch or sugar particles to prevent sticking.

Marshmallows can also be formed by extruding the candy mass through an orifice into the desired shape. Extruded marshmallows can be cylindrical in shape, with pieces cut in short lengths (e.g., jet-puffed marshmallows), or they can take almost any desired shape (stars, etc.) depending on the nature of the orifice through which the candy is forced. Co-extrusion technology can be used to create multi-colored marshmallow ropes or twists, or to put designs within the marshmallow rope. To prevent sticking of the final product, extruded marshmallows are typically coated with a dried starch powder, with the excess starch removed by tumbling the candies in a rotating screen drum.

Nougat, fruit chews and taffy, with higher density, are often formed using standard methods of either slabbing and cutting or forming into ropes in a batch roller (similar to that used in hard candy forming; see Section 8.3.1.5). Here, the plastic candy mass may be formed into ropes on the batch rollers and sized to the desired diameter prior to being cut and wrapped. Fruit chews and taffy are commonly formed in this way. Multi-colored and design (e.g., pumpkin face) taffy is made by blocking strips of different colors of taffy into a log for pulling on the batch rollers, in the same fashion as cut rock (see Section 8.3.2.1).

For a nougat that will form the base of a candy bar (e.g., enrobed in chocolate), there are many options from very manual to very automated. A typical automated line cools the cooked nougat to the desired temperature on a cooling wheel, which is then formed to the proper slab thickness by passing through sizing rollers. The slab is further cooled in a tunnel before being cut into strips with rotating slitter knives. The separated ropes of nougat are then guillotined to the proper length before being enrobed in chocolate.

11.4 Product Characteristics

The primary component that distinguishes aerated candies from other confections is air. The amount of air incorporated and nature of the bubble size distribution, along with the hydrocolloid used to stabilize the air, have considerable impact on product qualities such as texture, flavor release, and shelf life.

11.4.1 Microstructure

Arguably the most important structural aspects of aerated candies are the numerous small bubbles (or air cells) distributed throughout a continuous aqueous sugar phase. The stabilizer acts at the air/sugar interface to help stabilize the air bubbles (Figure 11.2). The continuous sugar phase may sometimes be amorphous (ungrained) and sometimes partially crystalline (grained). In grained confections, many small sugar crystals are distributed throughout the continuous aqueous sugar phase (Figure 11.3). The amount of air incorporated, their bubble size distribution, the viscosity of the continuous sugar phase, the elastic characteristics of the stabilizer, and the presence of sugar crystals are important parameters that affect the textural properties of aerated confections. In those candies that contain fat, the dispersion of fat globules, generally being partially crystalline, intermixed with the air bubble dispersion can also have considerable effect on the physical properties.

11.4.1.1 Aeration

The process of aeration generally involves two steps. First, air cells must be introduced in some process and second, those air cells must be stabilized to prevent them from coming back together. In many cases, intense shearing action within the aeration/mixing device helps reduce air bubble size.

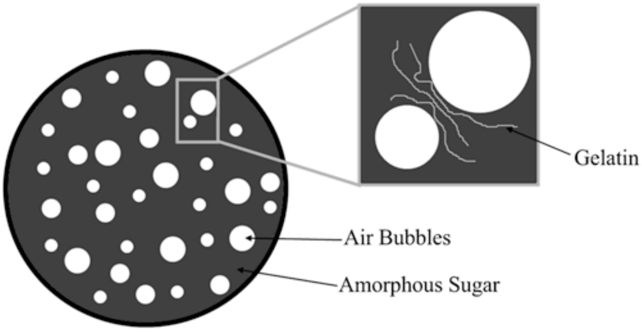

Figure 11.2 Schematic representation of ungrained marshmallow structure

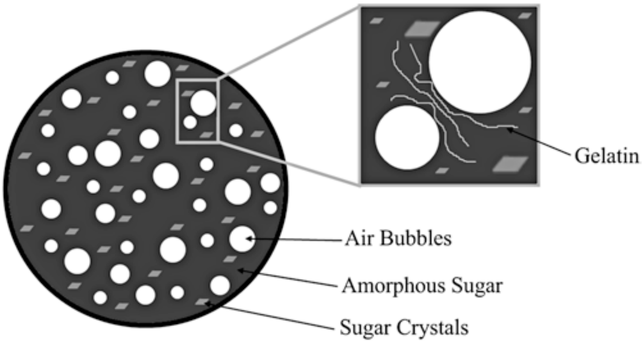

Figure 11.3 Schematic representation of grained marshmallow structure

11.4.1.1.1 Air Cells in Confections

Aeration can be accomplished by whipping a fluid candy mass open to the air, by direct injection of air into the liquid mass in an enclosed vessel, by pulling a plastic candy mass or by chemical aeration, with the nature of the air cells being quite different between the processes (see Section 8.3.2.2 for more details on aeration mechanisms). Whipping of a fluid mass, where the shear forces continually break down air bubbles into smaller and smaller sizes, typically results in formation of numerous small spherical bubbles. Pulling a plastic candy mass simply folds air pockets into the plastic candy mass, giving irregularly-shaped, smeared air cells. Chemical aeration produces air pockets dependent on the chemical reaction rate within the candy mass. Figure 11.4, a scanning electron micrograph of a jet puffed marshmallow aerated in a continuous air injection process (Zeigler and Decker 2002), shows the generally spherical nature of the air bubbles formed during whipping of a fluid mass. Compare the air cells found in a pulled taffy product (Figure 11.5), where irregularly-shaped air pockets are introduced by continually pulling, stretching and refolding the plastic candy mass. Finally, Figure 11.6 shows the smooth rounded bubbles formed from chemical aeration, in this case in an after dinner or grained mint.

The average bubble size in a typical marshmallow is between 20 and 25 μm, although bubble size may vary from as small as about 10 μm to well over 40 μm. Typically, in marshmallow, the largest number of smallest sized bubbles is desired to give the smoothest texture. In batch whipping, it is possible to take samples periodically for microscope analysis. With this method, the reduction in bubble size during whipping can be followed. The point at which bubble size begins to increase again is the point of overwhipping, where additional agitation simply serves to promote bubble coalescence rather than break down. Unfortunately, methods to study air cell formation in other aeration technologies are quite limited.

Air bubbles in finished products have been viewed in a variety of ways. Optical microscopy,

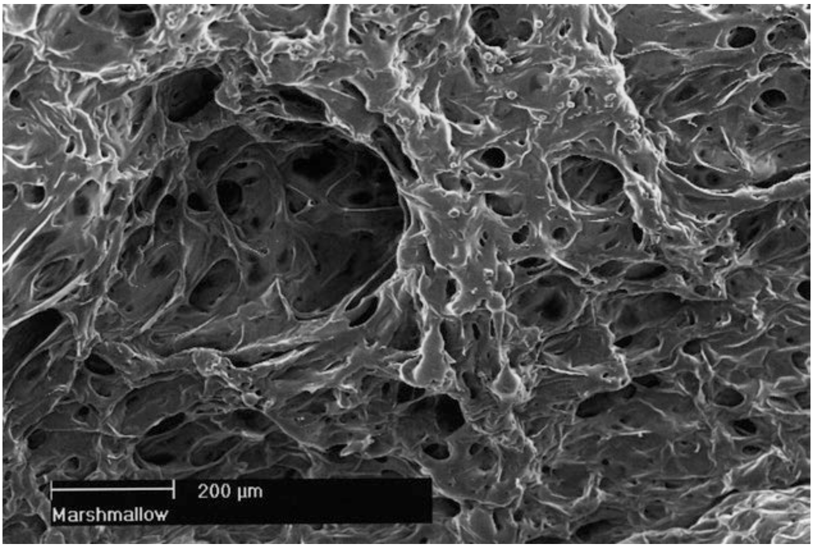

Figure 11.4 Scanning electron micrograph of jet-puffed marshmallow made by aeration in a continuous air injection process (From Ziegler and Decker (2002), with permission)

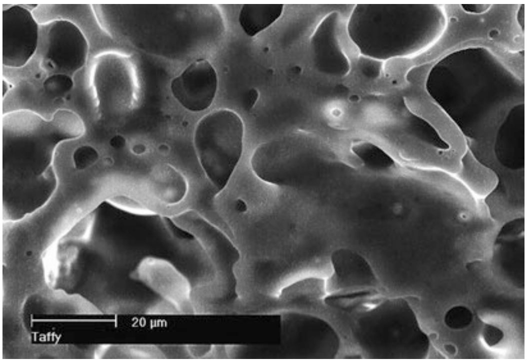

Figure 11.5 Scanning electron micrograph of taffy aerated by pulling (From Ziegler and Decker (2002), with permission)

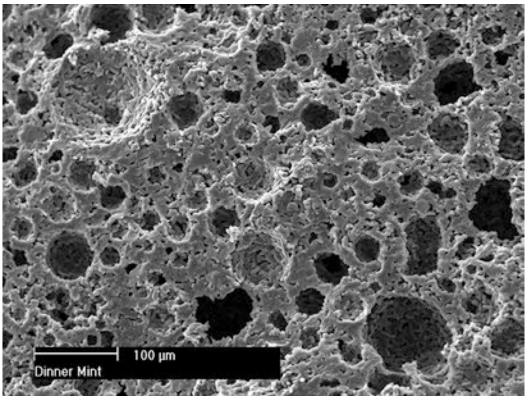

Figure 11.6 Scanning electron micrograph of grained after dinner mint aerated by chemical aeration (From Ziegler and Decker (2002), with permission)

particularly reflection stereomicroscopy, may be used in certain circumstances to visualize air bubbles. Groves (1995) suggests placing a sample of marshmallow between a slide and cover slip (without smearing) on an optical microscope to follow the development of air bubbles during batch whipping. The most commonly used method, however, for characterizing air cells in aerated products is scanning electron microscopy (SEM). Typically, sample preparation involves rapid cooling to solidify the candy matrix, followed by freeze fracturing and dehydration to produce a surface suitable for exposure to an electron beam for visualization. Decker and Ziegler (2002) discuss the difficulties associated with SEM sample preparation for aerated confections, but present a variety of informative images of aerated confections using this technique. Decker and Ziegler (2002) also discuss the possible use of X-ray computed tomography (CT) for imaging aerated confections but note that resolution is the main limitation of this new technique (see Lim and Barigou 2004, for more about X-ray CT). Reinke et al. (2016) used synchrotron

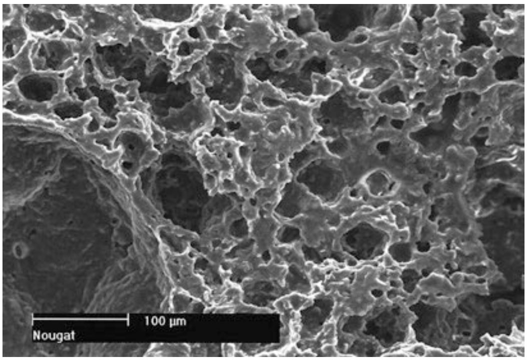

Figure 11.7 Scanning electron microscope image of grained nougat showing two distributions of air cells (From Ziegler and Decker (2002), with permission)

x-ray tomography to investigate the aerated structure of chocolate.

As noted earlier, the nature of the air cell distribution in an aerated confection depends on the process by which it was aerated. For example, Figure 11.7 shows the air bubble distribution in a grained nougat made by the frappé method. In this case, the numerous small air bubbles of about 20–40 μm were produced from addition of the frappé. A second population of larger (greater than 100 μm) air bubbles was also observed (see lower left corner of Figure 11.7). These larger bubbles were introduced when the cooked sugar syrup was added to the frappé to create the nougat.

11.4.1.1.2 Continuous Aeration: Technology and Mechanisms

Modern continuous aeration methods generally use rotor and stator technology to inject air and create small air bubbles. A photo of a continuous marshmallow aerator is shown in Figure 11.8. As the rotor spins, the sugar syrup and injected air bubbles are sheared between the stationary stator pins and pins on the rotor. High rotor RPMs and narrow clearances between rotor and stator cause high turbulent shear stresses on the candy mixture, resulting in substantial break-down of air bubbles. The shear forces are dependent not only on rotor RPM, but also on the number of pins and the surface area of the rotor pins.

In principle, the reduction in air bubble size in a rotor-stator device can be explained through the Weber number, We, given as (Hanselmann and Windhab 1999)

$$We = \tau d \,/\, 4\sigma \qquad (11.1)$$

Here, τ is the shear stress applied between rotor and stator, d is bubble size, and σ is the interfacial tension between the air bubble and the sugar syrup. Typically, for turbulent flow, a critical Weber number, We_c, is defined, which correlates the shear forces with the air bubble size. The maximum bubble size, d_{max}, then can be written as

$$d_{\max} = 4\sigma We_c \,/\, \tau \qquad (11.2)$$

From Eq. 11.2, several effects can be seen. First, air bubble size is inversely proportional to shear stresses applied in the mixing head. Higher shear stresses, as noted above, result in proportionately smaller bubble size. Second, the interfacial tension has a direct effect on maximum bubble size. Lower interfacial tension results in smaller air bubbles.

Once an air bubble has been reduced in size by shearing, however, it must be stabilized in some way to prevent coalescence and phase separation. Stabilization occurs by preventing the bubbles from coming back together, either through high viscosity of the continuous phase and/or through addition of a stabilizing agent that adheres to the bubble surface and thereby prevents coalescence. Both mechanisms are important in aerated confections, with viscosity playing a major role in chewy and taffy candies, and protein surface stabilization being more important in marshmallow products. Ultimately, the stabilization of air bubbles in all aerated confections occurs by a combination of the two mechanisms, viscosity and surface coating. In some cases, solid particles like sugar or fat crystals may also influence air bubble stability. Furthermore, the presence of liquid fat at an air bubble interface leads to rapid coalescence.

If not stabilized appropriately, the finely divided air bubbles in aerated confections can come back together and lose their individual character, increasing the average size. Mechanisms of bubble re-formation are coalescence, drainage and disproportionation. Coalescence is the action

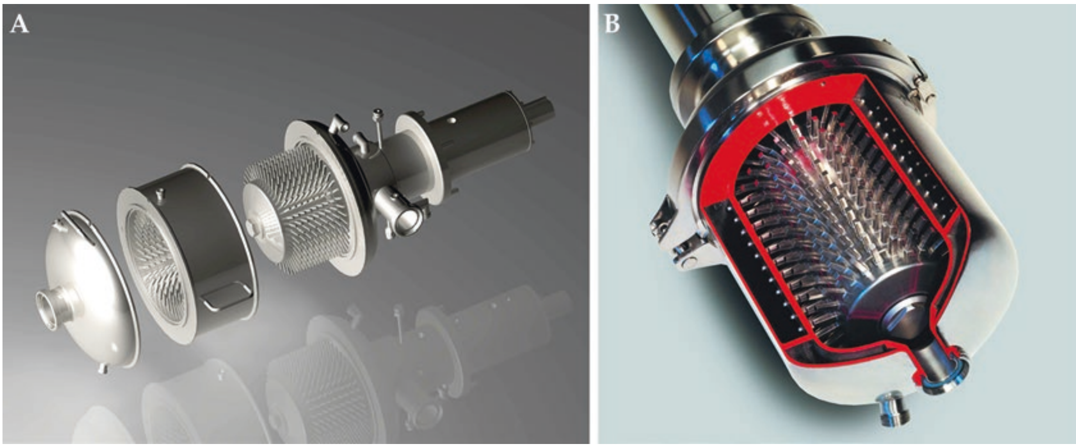

Figure 11.8 Continuous marshmallow aerator of rotor-stator design: (**a**) Entire assembly; (**b**) rotor-stator head (Courtesy of Haas-Mondomix)

of two distinct bubbles joining together to form a single larger bubble. The two bubbles must be in close proximity and not have any components preventing them from coming together. Surface-active agents, like fats and emulsifiers, can reduce the interfacial tension at the bubble surface and promote coalescence. Drainage refers to the flow of the liquid phase around the bubbles, which causes bubbles to come into closer proximity and leads to coalescence. Higher viscosity and lower temperature inhibit drainage and help to stabilize air bubbles against coalescence. In some cases, disproportionation can occur, where small bubbles shrink and large bubbles grow due to the thermodynamic difference in stability of bubbles of different sizes. In most confectionery applications, disproportionation is generally not a problem. However, in many aerated confections, there is some degree of air cell coalescence (or partial coalescence) during storage with an interconnected air cell network formed (to varying degrees) over long-term storage.

11.4.1.1.3 Graining

As shown schematically in Figure 11.3, grained marshmallow, grained nougat and most chewy candies contain small sugar crystals dispersed throughout the continuous aqueous sugar phase. In some respects, this dispersion of crystals is quite similar to that found in fondants and creams, except there is much higher crystal content in fondant. Whereas fondant typically has 50–60% crystalline content, grained marshmallow and nougat have only about 20–30% and fruit chews have less than 10%. A polarized light microscope image of the crystalline structure of grained nougat (from a commercial candy bar) is shown in Figure 11.9. Individual crystals smaller than approximately 20–30 μm are seen. These are dispersed throughout the continuous phase and induce a short texture to the nougat. Figures 11.10 and 11.11 show electron micrographs of grained nougat and marshmallow, respectively. Although it is sometimes difficult to identify individual sugar crystals with this technique, the entire structure of the grained candies is clearly different from that of ungrained candies (compare Figures 11.4 and 11.5 for marshmallow and nougat, respectively). Even though it may not be perfectly clear from these images, sugar crystals also have an impact on air cell formation and stabilization, through a combination of their surface-active behavior and their effect on the viscosity of the continuous sugar phase.

The extent of crystalline content present in aerated candies is primarily a function of (1) the relative amount of crystallizing species (sucrose) to inhibitors (glucose syrup) present in the formulation and (2) the water content. Although sucrose is usually the main crystallizing component in aerated confections, sugar-free versions would contain sugar alcohol (sorbitol, isomalt, maltitol, lactitol, etc.) crystals and some doctoring component (e.g., maltitol syrup, etc.) to

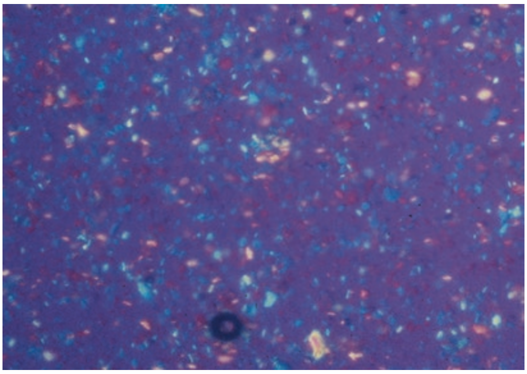

Figure 11.9 Polarized light microscope image of sugar crystals in the grained nougat of a candy bar (magnification 40×)

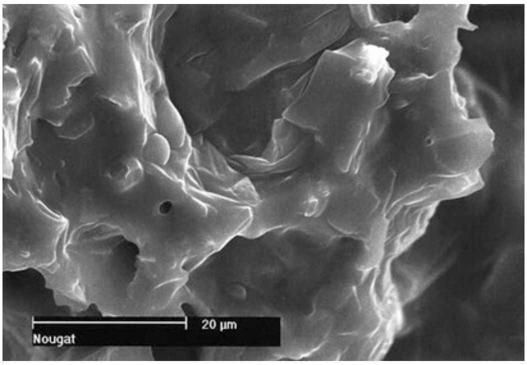

Figure 11.10 High magnification scanning electron microscope image of grained nougat (From Ziegler and Decker (2002), with permission)

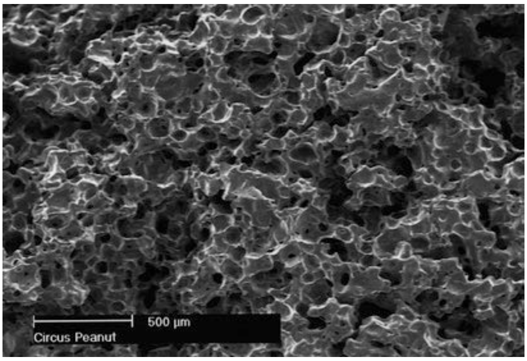

Figure 11.11 Scanning electron microscope images of grained marshmallow – circus peanuts (From Ziegler and Decker (2002), with permission)

moderate the extent of graining. The state diagram approach discussed in general in Section 2.10, and specifically for fondant in Section 9.4.1, could be applied to aerated confections to determine the crystalline content of the sugar phase. Ergun and Hartel (2009) used the phase/state diagram approach to compare grained and ungrained nougats. Based on estimates of sucrose solubility in the presence of glucose syrup in the two formulations, it was found that the liquid phases of both grained and ungrained nougats were supersaturated. The grained nougat, however, was seeded with powdered sugar to set the grain, whereas the ungrained nougat had sufficient glucose syrup present to inhibit graining even over long periods of time.

Empirically, candy makers know that if there is more sucrose than other sugars (glucose syrup, invert sugar, etc.) in a formulation, the likelihood of graining is high. The higher the ratio of sucrose to other sugars, the greater the likelihood of crystallization, the faster it will take place and the more crystalline material will form. Therefore, aerated candies that are designed to grain should be formulated with higher ratios of sucrose to glucose syrup. Ungrained aerated confections should have less sucrose, with either glucose syrup, invert sugar or some other sugar added in its place to prevent crystallization. Replacing sucrose with other sugars is effective in preventing crystallization in two ways. First, there is less sucrose present so the residual supersaturation will be significantly less than for grained confections and second, the other sugars act as inhibitors that reduce the rate of crystallization. If there are sufficient quantities of other sugars present, sucrose graining does not occur over the life time of the product despite the residual supersaturation.

An empirical approach to understanding and controlling crystallization in nougat relates the ratio of crystallization accelerator sugars to that of crystallization inhibitors (Ergun and Hartel 2009). In this approach, the Graining Factor (GF) is defined as:

$$\mathrm{GF}(\%) = \frac{[\text{accelerator sugars}]}{[\text{accelerator sugars} + \text{inhibitor sugars}]} * (100) \qquad (11.3)$$

For example, in a nougat containing only sucrose and glucose syrup (and discounting stabilizer and fat as inhibitors), GF would be calculated as the ratio of the total sucrose content to the sum of total sucrose plus glucose syrup contents (on a dry basis). If there were equal parts of sucrose and glucose syrup on a dry solids basis, GF would be 50%. Based on empirical evidence (Y. Noda, personal communication), a formulation with GF less than about 45% would be unlikely to support sucrose crystals, whereas formulations with higher GF could potentially be grained. Formulations with increased GF would be expected to have increased crystal content.

Comparing the empirical GF approach to the fundamental phase diagram approach (Section 9.4.1), one can see that GF represents only one aspect of the phase diagram. The critical GF (above which crystalline sugar might be expected) correlates to the equilibrium condition; however, the ratio of sucrose to other sugars by itself is not sufficient to identify that equilibrium exactly. Water content, temperature and agitation also factor into determining whether or not crystals form in a specific formulation.

Crystal formation in grained chewy candies can occur either by allowing the candy to crystallize on its own, with sufficient agitation during processing, similar to what is done in fondant, or by seeding the candy mass through addition of fondant or icing sugar, similar to what is done with fudge. The sucrose to glucose syrup ratio is critical to give the desired effect. If graining is to be done in the process, the sucrose to glucose syrup ratio should be sufficiently high to provide a supersaturation sufficient for crystallization. The nucleating ability of intense agitation is also often needed to initiate graining in the batch. If fondant or powdered sugar is to be added to set the grain, the sucrose to glucose syrup ratio can be lower, ideally such that the continuous phase is just saturated with sucrose when the fondant is added. In principle, all of the sugar crystals from the fondant then should remain intact (neither dissolve or grow), although in practice some crystal growth is generally the case.

11.4.1.1.4 Lipid Emulsion

In nougat and chewy candies, about 5–8% fat is added to reduce stickiness and enhance lubricity. Melted fat is typically blended into the warm candy mass under agitation to emulsify the fat through the sugar matrix. If emulsifiers were used in the formulation, they would migrate to the oil/water interface to coat the fat globules and help isolate the fat from the aqueous phase. The size of the fat globules and their dispersion throughout the candy depend on the extent of agitation. However, typically fat globules migrate to the air/water interface, a phenomenon well-known in ice cream and whipped cream. Fat globule migration to the air interface may not occur so readily in nougats due to the high viscosity of the continuous phase.

Figure 11.12 shows two views of fat globules in a sample of commercial nougat. At lower magnification, fat globules can be seen distributed throughout the continuous phase (aqueous sugar solution), although some preference for fat globules at the air/water interface can be seen. At higher magnification, fat globules can clearly be seen as the very small droplets dispersed throughout the continuous phase. The larger globular shapes are air cells. The circular arrangement of fat globules evident in Figure 11.12b was thought to be due to fat globules that coated the interface of an air bubble interface that no longer existed.

11.4.2 Physical Properties

The physical properties of aerated confections are governed by numerous factors, including (1) water content, (2) air content, (3) stabilizer type and content, (4) sugar phase (grained, ungrained, viscosity, etc.), (5) lipid content and arrangement, and (6) presence of inclusions. As with most confections, water content has a direct impact on hardness of aerated confections, with lower water content giving harder candy by raising the glass transition temperature (T_g) (see Section 2.9). Based on the relatively pliant texture of aerated candies, T_g must be substantially below 0 °C (32 °F), although the exact value depends on both water content and the composi-

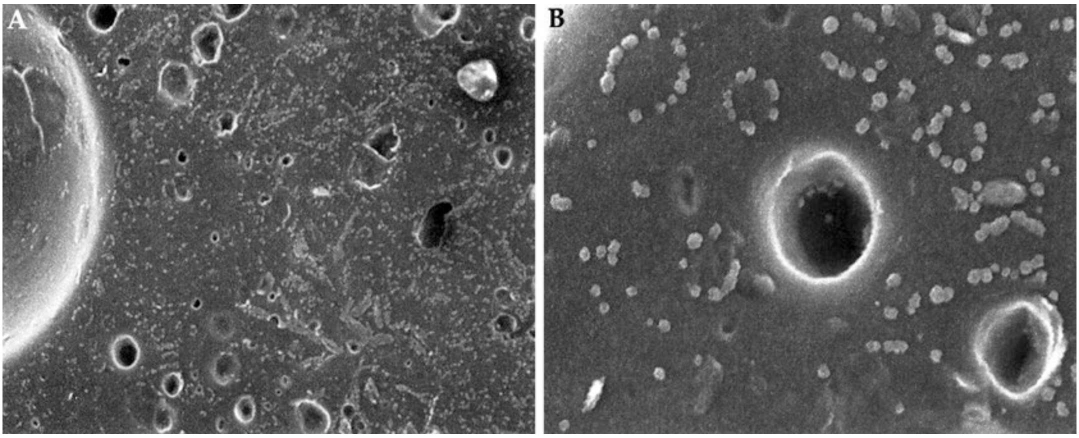

Figure 11.12 Scanning electron microscope images of fat globules in nougat: (**a**) low magnification; (**b**) high magnification (From Ziegler and Decker (2002), with permission)

tion of the continuous sugar phase. T_g of a commercial chewy nougat product (unspecified water content) was measured to be about −14.4 °C (Ziegler and Decker 2002). For marshmallow, T_g was measured as function of water content by Lim et al. (2006). When water content was 19.5%, T_g was about −45 °C, but that increased to 2 °C when water content was as low as 8% (Figure 11.13). It is this increase in T_g that, in part, causes dried marshmallows to have a harder texture.

Likewise, the presence of sugar crystals, emulsion droplets, and other particulate inclusions can break up the continuous phase and give a shorter texture to aerated confections. These components also increase stand-up quality and reduce cold flow.

Unique to aerated confections, though, are the effects of air and stabilizer on the textural properties. Of particular importance is how air and stabilizers influence the elastic properties of the confection. Both the amount of air incorporated and the nature of the air dispersion, specifically whether the bubbles are distinct, separate entities (closed cell) or whether they interact to form a network structure (open cell), have an important impact on physical properties. Furthermore, the nature of the stabilizer at the air interface and its inherent elastic properties also contribute to the viscoelastic response of aerated confections. However, very few scientific studies have investigated the effects of these factors on product attributes. Two of those studies will be briefly reviewed here.

The elastic properties of two commercial marshmallow products were investigated by Kaletunc et al. (1992). The marshmallow products were subjected to repeated compression and relaxation (decompression) cycles to investigate their elastic response. Not surprisingly, marshmallow exhibits viscoelastic properties in response to applied forces. When compressed, marshmallow may spring back to nearly its original shape, demonstrating elastic behavior. However, when subjected to repeated compressions, with or without a relaxation time (for recovery), the gelatin loses its elastic properties, resulting in a marshmallow that becomes increasingly shorter and more compact, with an increase in its apparent stiffness (modulus). Slight differences were observed between the two commercial marshmallow products studied, but no connection to the actual marshmallow microstructure was made.

Aerated confections also respond to tensile forces (stretching the candy apart) as anyone who has pulled a marshmallow apart in their hands can attest. The effects of specific gravity (from 0.66 to 1.1) on tensile properties of nougat were studied by Decker and Ziegler (2003). To produce nougat with different specific gravity, different levels of frappé were added to the cooked

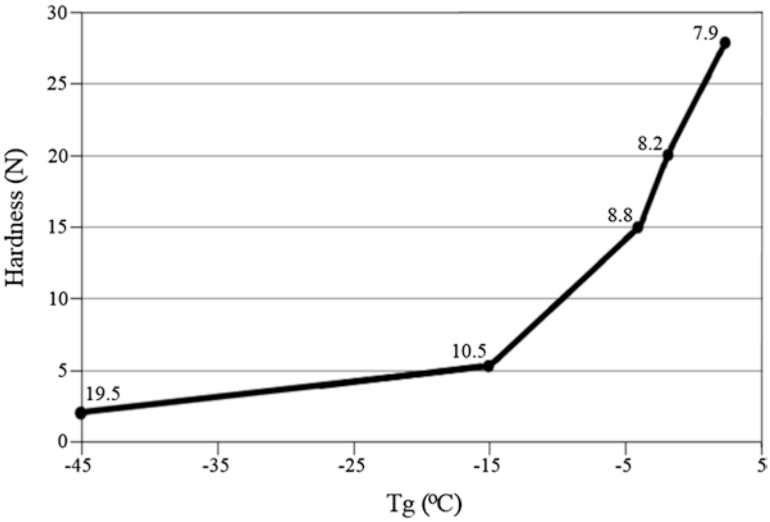

Figure 11.13 Hardness of marshmallow based on glass transition temperature (T_g) (Redrawn from data of Lim et al. (2006)) (Reprinted from Ergun et al. (2010) with permission). *Numbers* with each point indicate water content

sugar syrup, meaning that the amount of egg albumen (used for the frappé) also varied with specific gravity. Thus, differences in tensile forces documented were due to the combined effects of air incorporation and stabilizer level in the nougats. As specific gravity increased (less frappé added, so less aeration), the tensile modulus increased exponentially; in addition, penetration modulus and cutting force also increased exponentially over the same conditions. These results document the increasing effect of the dispersed air phase on physical properties of nougat. More air results in a product that is easier to chew and cut (than a similar sugar matrix with no aeration).

11.4.3 Shelf Life

Probably the main issue with reduced shelf life in nearly all classes of aerated candies is moisture loss during storage. A reduction in water content leads to hardening or toughening of the product. The ERH of aerated confections varies from as low as 0.4 for dried marshmallows to as high as 0.75 for the softest products with highest water content (Ergun et al. 2010). Under ambient conditions where relative humidity is less than 50%, there is a driving force for moisture to move from the candy to the air. Packaging layers help to retard water migration, but over time these candies will eventually lose moisture and become harder.

The loss of moisture from marshmallow to air was measured by Lim et al. (2006), who also correlated the changes in hardness and glass transition temperature, T_g (see Section 2.9). As seen in Figure 11.14, the marshmallow decreased in moisture content from an initial value of 19.5% to as low as 7.9% after 20 weeks of storage exposed to air at 21% relative humidity and room temperature. A significant increase in hardness also occurred over that time. The increase in hardness correlated to the increase in T_g, as shown previously in Figure 11.13.

Other changes that can occur in aerated confections relate to changes in either pressure and/or temperature during storage. The air within the candy obeys the ideal gas law so that any changes in ambient pressure cause changes in volume of air cells. For example, a decrease in pressure causes a subsequent increase in volume of the air cells (assuming temperature remains the same). The expansion caused by reduced pressure may cause problems, especially when the candy is not tightly constrained. For example, the change in air volume caused by shipping chocolate-coated nougat or marshmallow by truck across the mountains may cause cracking of the chocolate coating and result in unacceptable product.

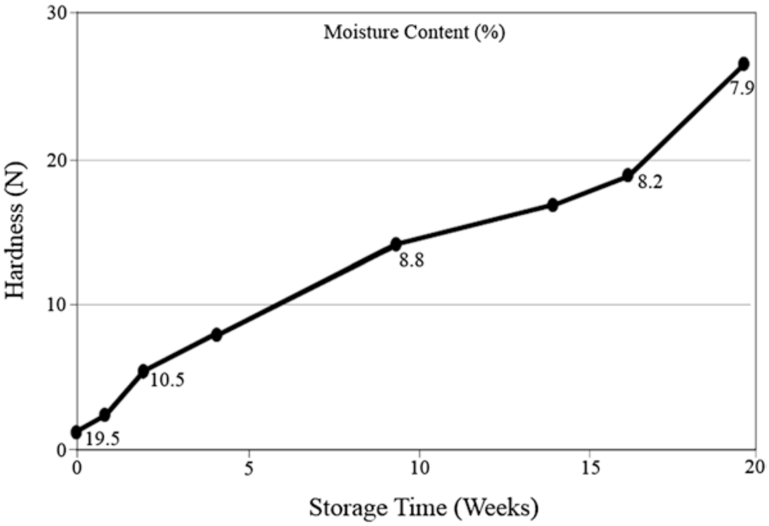

Figure 11.14 Changes in hardness, as correlated to moisture content, in marshmallow stored at room temperature and 21% relative humidity (Redrawn from Lim et al. (2006))

Furthermore, since proteins are not perfectly elastic, when marshmallows are shipped over mountains and then return to sea level, the gelatin does not return to its initial elastic state (as documented by the Kaletunc et al. 1992 study). Even though the decreased pressure causes an initial expansion of the marshmallow, the return of the marshmallow to sea level causes the marshmallow to collapse. Thus, maintaining careful control of ambient pressure is important to extending product shelf life for aerated confections.

Another issue during storage relates to the thermoreversible nature of the gelatin gel network. Typically, the melting point of gelatin in marshmallow candies is about 40 °C (104 °F). Storage above the melting point leads to the loss of gel strength and increase in fluidity. This can result in collapse of the air cell structure and loss of volume in the marshmallow. Thus, marshmallow products should be stored at cool conditions, well below the melt point of gelatin.

11.5 Troubleshooting

Some of the problems associated with each type of aerated confection cross the different categories, but some problems are specific to the type of candy and manufacturing process.

11.5.1 Improper Density

If specific gravity is different from that expected, the causes may either be related to the formulation or the process. Control of specific gravity of confections requires careful control of the aeration process, although each method of aeration generally has different control points. Batch pulling of chews or taffy is highly variable, depending on the operator for a decision point as to when the candy is sufficiently aerated. The frappé method of nougat manufacture relies on proper density of the whipped frappé plus proper ratio of frappé and cooked sugar syrup. Continuous aerators have high reproducibility because the exact ratio of air and sugar syrup can be metered into the enclosed chamber.

One potential reason that density of aerated confection might be higher than expected is that the stabilizer has been improperly hydrated, denatured or degraded. To be fully effective, any dried stabilizers need to be completely hydrated prior to use. If not, they will not support as much air incorporation. Also, heating proteins to excessively high temperature may cause denaturation (egg albumen, whey proteins) or degradation (gelatin) and lead to a decrease in their aeration capacity. Another potential cause for high density (low aeration) is that fat was added too early or overmixed, which caused collapse of air bubbles.

11.5.2 Product Too Hard or Rubbery

The primary reason for hard aerated confections is most likely related to moisture content. Depending on the candy, this might be seen as candy that is too stiff (nougat, grained marshmallow, chews and taffy), or tough and rubbery (ungrained marshmallow). Taffy that is too hard to eat is one of the main consumer complaints.

There are a number of potential causes for the water content of an aerated confection being too low. Cook temperatures that are too high is a possibility, either caused by inattention to the process conditions or from having thermometers out of calibration. However, water loss can also be caused during certain aeration processes (e.g., atmospheric planetary mixer), particularly if the environment is dry or if whipping is carried out for too long. Also, starch-deposited marshmallows can dry too far and become hard and rubbery if left in the starch for too long.

Other reasons for having hard or rubbery texture include (1) improper sugar formulation and (2) improper stabilizer selection. Using a higher DE glucose syrup or adding a humectant can help offset a hard texture. In marshmallow, a tough and rubbery texture might be related to the choice and amount of gelatin used. Reducing gelatin content leads to a softer, less rubbery, texture.

11.5.3 Product Too Sticky

Simply by their nature, aerated candies tend to be stickier than most candies. A coating of corn starch or sanding sugar is typically applied to marshmallow to prevent stickiness. Often, a sticky product is due to high moisture content, although it may also be related to sugar composition and fat content (nougats, etc.).

Candy with undesirably high moisture content is most likely due to improper cook temperature. For example, removing the candy mass from the cooker prematurely will leave excess water in the candy mass and lead to stickiness. As noted before, thermometers must be calibrated to ensure proper cook temperature. High moisture content can also occur when hydrated stabilizer is added back to the cooked sugar syrup; for example, improper water content of the stabilizer blend would lead to candy with high moisture.

Stickiness can also be caused by improper sugar composition, one with too many low-molecular weight sugars. One possible cause of this is excessive inversion of the sugar syrup during cooking. Using a lower DE glucose syrup or removing excess humectant can offset a sticky texture. Fat in nougats, chews and taffy is added to help prevent stickiness to processing equipment, packaging wrappers and teeth during consumption. Sufficient fat must be used in the formulation to provide the appropriate texture and further, the fat must be distributed homogeneously, in the form of small fat globules, throughout the candy mass to prevent stickiness. Finally, products can become too sticky (or hard) if improper barrier packaging materials are used or not sealed correctly. Candy that is not properly packaged can have moisture changes due to the environmental relative humidity.

11.5.4 Graining During Storage

Excess crystal formation in aerated confections can lead to undesirable changes in texture and appearance. Generally, graining occurs when the sugar matrix is too highly supersaturated. When the ratio of sucrose to other sugars (glucose syrup, invert sugar, etc.) is too high, or graining factor is too high, crystallization is promoted. Higher graining factors indicate higher crystal content and perhaps excessive shortening of the texture. Proper reformulation may be necessary to inhibit excess graining. A low water content can also lead to excessive graining as the sugar phase would be more highly supersaturated, although very low water content generally tends to inhibit graining due to the limited molecular mobility.

Graining may also occur if the crystalline sugars are not fully dissolved prior to boiling. There should be sufficient moisture in the premix (16–20%) to allow sugars to be dissolved before boiling occurs. Further, the sides of a batch cooker should be washed down after a full boil has started to prevent the splashing syrup from drying and graining, and then dropping seed crystals into the boiling batch. If the boiling mass is not above the scrapers, graining may also be induced.

11.5.5 Mold Growth

Although highly unlikely, mold growth may become a problem in ungrained marshmallows, particularly if the water content is too high and there are insufficient low molecular weight sugars to reduce water activity. Osmophilic molds are known to grow in systems with water activity as low as about 0.65. If a marshmallow product is formulated with a higher water activity, it is prone to mold growth. Reformulation to reduce water activity may be necessary. Addition of humectants (glycerol, sorbitol, invert syrup, etc.) may be required to retain a softer texture in candy with low water activity. Good sanitation practices for processing equipment, including drying starch if used, will also help prevent contamination before packaging.

11.5.6 Weeping

Marshmallow exposed to temperatures above the melting point of gelatin may weep, or exude sugar syrup, since the melted gelatin molecules are no longer capable of providing a network to hold the viscous sugar matrix. The melting point of gelatin depends on the gelatin source (fish being lower) and bloom strength (higher bloom results in higher melt point).

At high temperatures, the sugar syrup phase also decreases in viscosity, further promoting flow and weeping. Maintaining low temperatures during storage and distribution will prevent this problem. Use of a higher melting point gelatin might be an alternative, although the textural differences may be unacceptable. Higher levels of gelatin might also improve the problem. Sodium hexametaphosphate is thought to improve heat stability as well.

11.5.7 Shrinkage

Shrinkage and deformation of marshmallow is most often related to changes in the gelatin, but may also be caused by transportation under reduced pressures (e.g., over mountains) or storage at elevated temperatures (above 35–40 °C; 95–104 °F). Gelatin that has been excessively degraded during processing will not be as good at maintaining distinct air bubbles and can lead to shrinkage. High water content may also lead to shrinkage as can addition of fat-based ingredients.

11.5.8 Problems in Starch Deposited Marshmallows

When marshmallows are deposited into dried starch powder, moisture is lost from the product to the starch. This moisture loss is factored into the process design so that the candy after it is removed from the starch has the proper moisture content. For efficient drying, it is important that the molding starch has the right moisture content and be at the right temperature. If temperature, time and moisture content are not controlled, problems can occur that affect product quality. Typically, molding starch for depositing marshmallow should be at about 38–43 °C (100–110 °F) and moisture content of about 5–7%, depending on whether it is grained or not.

When the starch is too cold, the marshmallow in contact with the cold starch forms a sort of crust that inhibits further moisture loss from the interior and retards the drying process. The result is candy that is too soft in the middle with a harder crust layer. When the starch is too warm, a different problem occurs. The warm starch temperature causes loss of aeration and results in more of a jelly-like texture rather than an aerated marshmallow. If the starch is too dry, excess moisture loss can occur at the surface of the piece, potentially leading to a skin or crust formation while the interior of the marshmallow may be too soft (too much water). The texture and appearance of such a product are undesirable. Also, starch powder that is too dry is a risk for a powder explosion, which may be induced by a spark or heat source. If the moisture content of the starch is too high, the rate of drying is impeded and visible, discolored crust forms on the surface.

Surface crust formation may also occur if the water content of the marshmallow when deposited is too high. This can lead to rapid moisture loss from the surface and formation of a hardened layer. Depositing at solids content greater than 74% is necessary to prevent this type of crust formation. Finally the time the deposited candies are left in the starch must be consistent to provide proper moisture content and product texture.

11.5.9 Cold Flow

An amorphous sugar mass is prone to exhibit cold flow, where the candy spreads out either to fill a container or, if unbounded, to produce a puddle of candy. The microstructural elements (fat globules, air cells, protein networks, sugar crystals, etc.) are what provide stand-up properties to an amorphous sugar matrix. Thus, if any of these microstructural elements does not set up properly, even highly aerated confections can flow. This is particularly a problem with higher specific gravity confections like nougat, chews and taffy – without numerous stabilized air cells to prevent cold flow. Cold flow of salt water taffy, particularly in warmer temperatures, is a major concern. For this reason temperature control of product storage and transportation is critical.

Solutions to preventing cold flow are many, although not all solutions will work in a given situation. Probably one of the first approaches to resolve cold flow is to decrease the water content (cook to higher temperature). Less water means the amorphous sugar phase is more viscous and more resistant to flow. Unfortunately, lower water content also means a harder or tougher candy texture, something that may be undesirable in the finished goods.

Other approaches to inhibit cold flow involve manipulation of the microstructural elements. For a given specific gravity, more numerous and smaller air bubbles are better for stand-up properties than fewer and smaller bubbles. Thus, making sure that air bubbles are as numerous and as small as possible may help prevent cold flow. The same principle applies for fat globules – numerous small fat globules homogeneously distributed throughout the candy matrix provide the best stand-up properties. Using a fat with slightly higher melting point or solid fat content can also inhibit cold flow, although if the melt point is too high, there will be a waxy mouthfeel and loss of flavor notes. Some taffy manufacturers add intact corn starch granules after cooking, so that the particulate nature of the starch inhibits cold flow. Too many starch granules, however, also cause an undesirable short texture to the taffy. Inducing a fine grain in taffies and chews will prevent cold flow and provide a softer eating texture. Tight twist wrap packaging will by physical restraint help reduce cold flow.

Acknowledgment Thanks to Barbara Klubertanz (Melster Candies) and Kristi Sufferling (Nitta Gelatin) for their assistance and input with this chapter. Thanks also to Dr. Greg Ziegler, Pennsylvania State University, for permission to use micrographs of aerated confections showing microstructure.

References

Decker NR, Ziegler GR. The structure of aerated confectionery. Manuf Confectioner. 2002;82(9):101–8.

Decker NR, Ziegler GR. Mechanical properties of aerated confectionery. J Texture Stud. 2003;34:437–48.

Ergun R, Hartel RW. Phase transitions in confections: the graining factor approach. Manuf Confectioner. 2009;89(10):51–5.

Ergun R, Lietha R, Hartel RW. Moisture and shelf life in confections. Crit Rev Food Sci Nutr. 2010;50(2):162–92.

Groves R. Marshmallow production: technology and techniques. Manuf Confectioner. 1995;82(5):99–103.

Hanselmann W, Windhab E. Flow characteristics and modeling of foam generation in a continuous rotor/stator mixer. J Food Eng. 1999;38:393–405.

Kaletunc G, Normand MD, Johnson EA, Peleg M. Instrumental analysis of elasticity of marshmallow. J Texture Stud. 1992;23:47–56.

Lim KS, Barigou M. X-ray micro-computed tomography of cellular food products. Food Res Int. 2004;37:1001–12.

Lim MH, Yin J, Heenan S. The mystery of marshmallow hardening. In: Beura P, Welti-Chanes J, Lillford PJ, Corti HR, editors. Food preservation technology series – water properties of food, pharmaceutical and biological materials. New York: CRC Press; 2006. p. 325–42.

Reinke SK, Wilde F, Kozhar S, Beckmann F, Vieira J, Heinrich S, Palzer S. Synchrotron x-ray microtomography reveals interior microstructure of multicomponent food materials such as chocolate. J Food Eng. 2016;174:37–46.

Ziegler G, Decker N. The forgotten ingredient: air in confectionery. In: Ziegler GR, editor. Proceedings of 4th International PSU/PMCA Symposium. Penn State University; 2002. p. 128–156.