Kirk-Othmer Encyclopedia of Chemical Technology.

FILM AND SHEETING MATERIALS

Film and sheet are defined as flat unsupported sections of a plastic resin whose thickness is very thin in relation to its width and length. Films are generally regarded as being 0.25 mm or less, whereas sheet may range from this thickness to several centimeters thick. Film and sheet may be used alone in their unsupported state or may be combined through lamination, coextrusion, or coating. They may also be used in combination with other materials such as paper, foil, or fabrics.

Film or sheet generally function as supports for other materials, as barriers or covers such as packaging, as insulation, or as materials of construction. The uses depend on the unique combination of properties of the specific resins or plastic materials chosen. When multilayer films or sheets are made, the product properties can be varied to meet almost any need. Further modification of properties can be achieved by use of such additives or modifiers as plasticizers (qv), antistatic agents (qv), fire retardants, slip agents, uv and thermal stabilizers, dyes (qv) or pigments (qv), and biodegradable activators.

The first film or sheet materials were manufactured in the early twentieth century from cellulose nitrate, and later from cellulose acetate. These products were essential to the development of the photographic film industry. Colored films were also used from the earliest days as color filters for lighting. These products were followed in 1929 by the universally recognized clear packaging film, cellophane. Following World War II, polyethylene film became the largest volume film product, and later polypropylene, polystyrene, polyester, poly(vinyl chloride), and others joined the list of commercial film products. Sheet markets grew with poly(acrylate), polystyrene, polycarbonate, and polyolefin resins as the predominate materials. By 1990, many other polymers were used in films or sheet applications, such as the specialty resins, polysulfone, poly(acrylate), polyamide, polyimide, and poly(arylketone), each used primarily for high performance market needs.

1. Properties and Test Methods

Film and sheet materials have an amazing range of properties so that a product may generally be formed or produced to meet the needs of a specific end use. Films as thin as 1.5 μm are produced for capacitor insulation, whereas cast sheet products ranging up to 5.7 cm are used for the construction industry. Films are generally wound on spools or in rolls in widths from 3 mm to several meters. Sheeting materials may be wound in rolls, but more likely are cut and shipped as flat sheet 1–3 meters in width and length. The products may be very stiff and have high tensile strengths, or may be rubbery or flimsy. They may be impermeable to water or gases, or may dissolve or be porous. Some may be crystal clear or opaque, colorless to brilliantly hued. Films may degrade quickly or last indefinitely as the base material for information storage. They may be excellent insulators for use as protective materials, or may be compounded to conduct small currents. Films may be inert to chemical attack or be made easily printable, even degradable. Sheets may be intractable or readily thermoformed into complex shapes. Some films may dissolve in water, whereas others may act as barriers to moisture permeation almost as effectively as metal.

Table 1. Film and Sheet Test Methods

Property	Units	ASTM method
general		
thickness and yield	mm	D2103
mechanical		
tensile strength	MPa	D882
elongation	%	D882
stiffness, tensile modulus	MPa	D638
tear strength, propagation (Elmendorf)	g/mm	D1922
tear resistance (initiation)		D1004
burst strength (Mullen)	points	D774
impact (dart drop)	g/mm	D1709
tensile impact	(N·m)/m	D1822
Izod impact	(N·m)/m	D256
folding endurance		D643
coefficient of friction (slip)		D1894
abrasion resistance		
surface (Tabor)		D1044
falling sand		D968, 1003
optical		
refractive index	n_D	D542
haze	%	D1003
luminance transparency	%	D1746
gloss		D523
chemical		
water absorption	%	D570
water-vapor transmission	[a]	E96
gas permeability	[a]	D1434
electrical		
dielectric constant		D150
dissipation (power) factor		D150
dielectric strength	kV/mm	D149
volume resistivity	Ω·cm	D257
permanence		
thermal shrinkage	%	D1204 D2411
outdoor weatherability		D1435
coefficient of humidity exposure		E104

[a] See Barrier polymers for a discussion of units of gas permeability and WVTR.

Film and sheeting materials test methods have been standardized by ASTM, DIN, and others. As with all materials, the test specimens must be carefully prepared and conditioned. Thin-film specimens are vulnerable to nicks and tears which mar the results. Moisture and temperature can affect some materials. Common test methods are listed in Table 1.

Tensile properties of importance include the modulus, yields, F^5 (strength at 5% elongation), and ultimate break strength. Since in many uses the essential function of the film may be destroyed if it stretches under use, the yield and F^5 values are more critical than the ultimate strength. This is true, for example, where film is used as the base for magnetic tape or microfilm information storage. In some cases, the tensile properties at temperatures other than standard are critical. Thus if films are to be coated and dried in hot air ovens, the yield at 150°C or higher may be critical.

Tear strength is critical for packaging and other film end uses. Both tear initiation and tear propagation are important. Very high tear initiation may require the use of notching, perforation, or tear strips to facilitate opening a packaging. Low tear strength can be a significant problem in processing ultrathin films such as are used in capacitors.

Impact tests for film and sheet vary. Tensile impact and dart drop are used to measure the force required to rupture films. Izod impact is generally used on sheet materials. Correlation of test results with end use performance may not be good. Temperature is critical to impact results. Some users of film perform actual package tests to measure performance, where packages of the product are produced and then dropped or thrown under controlled conditions to see if the package will withstand shipping and handling. Actual shipping tests may also be used.

Stiffness of the films and sheeting can be measured as the tensile modulus of elasticity. Droop or drape tests may be used, particularly for multilayer products. The stiffness is strongly influenced by thickness (to the third power) and temperature, and is important to the processing of film in printing, coating, or end use applications where it affects the “hand” of the product.

The slip characteristics of film and sheeting are also critical to processing and use. It may influence the hand, but is particularly critical to the free passage of film over rolls and through equipment. Slip is measured as the static or kinetic coefficient of friction and may be measured as film-to-film, or as film to another surface. Hot slip, or slip over heated platens or rolls, can be an important characteristic of packaging film. Closely related to slip is abrasion resistance, a property difficult to measure. Tabor abrasion is often used but is difficult to compare from one material to another, and correlation with end use performance is only fair. Falling sand abrasion is sometimes used, and this simulates a different abrasion mechanism from the rubbing action of the Tabor. Steel wool abrasion testing has also been used. The effect of abrasion is generally determined by change in haze or gloss, although weight loss can also be used. This property is critical where constant abrasion in use may occur, as with magnetic tape or in glazing, where long-term optical clarity is critical, eg, in solar collectors or vehicle glazing.

Transparency, color, haze, and gloss are all important elements of film and sheet used for optical end uses. These include packaging, reprographic and photographic uses, glazing, solar, etc. Spectral transmission, index of refraction, as well as standard haze and gloss tests are used. Lack of color (yellowness) of film and sheet can be important. Matching specific color or transparency characteristics for end uses as light filters or for a decorative purpose is necessary in some uses. The permanence of these properties after long-term exposure to heat, rain, and sun and uv light lead to the need for such tests as the Weather-O-Meter, Q-UV, and outdoor exposure tests. Some applications call for 10–20-year lifetimes under intense exposure conditions. Predicting performance for such uses accurately is difficult. Although resistance of the film or sheet base material to light or moisture may be key, the selective passage or blockage of light through the material may be an essential requirement. Thus some films or sheets have been developed to prevent uv or ir light transmission for use in glazing applications.

Moisture and gas barrier properties are of prime interest in packaging applications (1). These are measured in standard tests which in recent years have been improved to give more meaningful predictive information (see Barrier polymers). Sensitive techniques have been developed to measure lower concentrations of permeants and thus get information more quickly. Some films are good barriers to both moisture and gases, whereas others may be barriers to moisture but allow gases to pass (and the product to breathe). High fat food products need to be protected from oxygen or they rapidly become rancid, particularly if uv light also penetrates the packaging. Bland products may be susceptible to pickup of off-taste or flavor if volatile oils or spices permeate the package material, or the reverse can be true if highly seasoned contents are packaged. To achieve the right combination of barriers, combinations of films are often needed. Coating, coextrusion, or lamination with another film, foil, or paper are commonly used.

Other important properties that can be measured in the laboratory include sealability, printability, or coating adhesion. Many of these tests have been developed by the film manufacturer in cooperation with customers and are specifically designed to measure product performance in the end use. Some tests, like sealability, can be standardized to time, pressure, and temperature of sealing with instrument-measured peel values, but other tests are subjective, such as evaluations of printing loss to pulloff by adhesive tape.

Dimensional stability of films or sheet when exposed to temperature or humidity are important. Inherent dimensional change with temperature or humidity (coefficient of thermal or humidity expansion over a selected temperature range) may be measured, but for film in particular this may be less important than shrinkage due to relaxation of stress imparted to the film during manufacture. Often films shrink in one direction and grow in the other direction depending on orientation, heat-setting, and other parameters in their manufacture. These changes may be irreversible in the base film and destroy its usefulness. In other cases, eg, shrink films, the film is designed to shrink with controlled force and amount in order to shrink-wrap a container or packaging without distortion. Creep, or elongation under long-term low or no load, can be measured and controlled for those applications where it is important, such as strapping tape.

Thermoformability is a property required by the many sheet materials used in the thermoforming industry. These properties are unique for the specific forming methods used, and are best determined by actual thermoforming tests on small-scale equipment. The softening or drape temperature of the material, residual stress in the sheet from its manufacture, and its melt strength and viscosity are important parameters relating to this use.

An important property of all film and sheet products is the gauge (or thickness) uniformity. Machine direction uniformity is vital to consistent processibility in web-handling equipment and to controlled economic production. More important, perhaps, is uniformity of transverse gauge. Irregularities in TD gauge, particularly consistent ones, lead to gauge bands, soft spots, honeycomb or chain-like defects, which in turn lead to poor handleability, bad coating or printing, improper tracking, and totally unusable product. Measurements of thickness variation are usually done in-line in order to provide feedback control. Laboratory measurement is also used to calibrate and more precisely determine the film's suitability for use. The average thickness, gauge variation (high and low), and rate of gauge change (ie, slope) across the web are among the characteristics measured.

Performance measures such as slittability (ease of slitting the film web into smaller widths), or cuttability (ease of trimming, stamping, or cutting the sheet by shearing) can be determined usually by actual performance testing on processing machines. Good materials can be so processed with a reasonable force and without generating debris, stringy edges, or chips or tears in the product.

Because of the nature of film and sheet products, ie, large area-to-volume ratio, optical defects in the polymer may be readily evident and unacceptable. Thus the presence of degraded polymer, gels, fish-eyes, contamination, or improperly dispersed additives, pigments, or colorants may result in a product that is aesthetically displeasing or functionally unacceptable. In addition, such contaminants may cause mechanical or electrical failures under stress. Visual inspection, for optical defects on the moving web, or microscopic inspection are used to measure and define these problems. Fortunately, new technology is now available that can determine the presence of relatively small particles within a web moving at speeds of several hundred meters per minute. These devices can alert the production operator to take the necessary action to correct the problem.

Tables 2, 3, 4, 5 list some typical properties or ranges of properties for the more common film and sheet products. Although these values are good for comparative purposes, actual performance tests are best to determine suitability for use. Properties of multiple-layer films or sheets in laminar structures cannot always be predicted from values for the individual polymer layers. Use conditions of stress, temperature, humidity, and light exposure all strongly influence performance. Film and sheet manufacturers can recommend product combinations or variations that may provide significant performance advantages to the user.

Table 2. General and Thermal Properties of Film and Sheet[a, b]

Material[b]	Abbreviation	CAS Registry Number	Manufacturing method[c]	Thickness range, mm	Max width, m	Max use temperature, °C	Min use temperature, °C	Heat seal range, °C	Dimensional strength at 100°C, % change
acrylonitrile–butadiene–styrene[d]	ABS	[9003-56-9]	EX, CL	0.25–0.75	2.67	97			
cellophane[e]		[9005-81-6]	REG	0.02–0.04	1.19	177	−17	82–177	−0.7 to 3.0
cellulose acetate	CA	[9004-35-7]	CAST, EX	0.02–6.35	1.52	79	−26	177–232	+0.2 to 3.0
cellulose triacetate	CTA	[9012-09-3]	CAST	0.05–0.51	1.19	175			0 to 0.7
fluoroplastics									
ethylene–tetrafluoroethylene copolymer	ETFE	[26770-96-4]	EX	0.01–2.1	1.22			274	
fluorinated ethylene propylene copolymer	FEP	[25067-11-2]	EX	0.01–2.41	1.22	249	−254	282–371	<1
polychlorotrifluoroethylene copolymer	PCTFE	[9002-83-9]	CAST, EX	0.01–0.76	1.37	135	−196	232–260	+2 to −2
polytetrafluoroethylene	PTFE	[9002-84-0]	CAST, EX	0.01–3.18	1.22	260	−253		
poly(vinyl fluoride)	PVF	[24981-14-4]	EX	0.01–0.10	3.51	113	−73	204–218	1
ionomer		[25608-26-8]	EX	0.03–0.25	1.52	66	−73	93–260	
nylon-6		[25038-54-4]	EX, BO	0.01–0.76	2.13	150	−73	193–232	
polycarbonate	PC	[24963-68-3]	EX	0.006–12.7	1.37	132	−101	204–221	
poly(ethylene terephthalate)[f]	PET	[25038-59-9]	EX, BO	0.003–0.36	3.05	149	−79	218–232	<0.5
polyimide[e]	PI	[25036-53-7]		0.008–0.13	0.90	400	−270		0.3
polyethylene[f]	PE								
low density	LDPE	[9002-88-1]	EX	0.0008 up	12.19	88	−57	121–204	−2
linear low density[e]	LLDPE		EX						
medium density	MDPE		EX	0.008 up	6.10	104	−57	121–204	0 to 0.7
high density	HDPE		EX	0.01 up	1.52	121	−45	135–204	−0.7 to 3.0
ultrahigh molecular weight	UHMWPE		EX	0.05 up	1.52	121	−45	135–204	
poly(methyl methacrylate)	PMMA	[9001-14-7]	EX, BO	0.13–0.25	1.09	77			
polypropylene[f]	PP	[25085-53-4]	EX	0.02–0.25	1.52	140	−18	140–200	2
			BO[e]	0.01–0.03	2.03	143	−51	88–150	
polystyrene[f]	PS	[9003-53-6]	BO	0.006–0.51	1.93	88	−63	121–177	
poly(vinyl chloride)	PVC	[9002-86-2]							
rigid			CAL, EX	0.015–1.91	2.13	79		177–216	−7 to 4
plasticized[f]			CAL, EX	0.013–2.54	2.03	79	−46	157–182	−7 to 15

[a] Much of this data was obtained from Refs. 2 and 3.

[b] Available as both film and sheet unless otherwise noted. All materials are available in FDA grades except for CTA, PVF, and PI.

[c] EX = extrusion; CL = calendering; REG = regeneration; CAST = casting; BO = biaxial orientation.

[d] Sheet only.

[e] Film only.

[f] Heat shrinkable grades available.

Table 3. Physical and Mechanical Properties[a]

Material	Tensile strength, MPa^b	Elongation, %	Impact strength, (kN·m)/m^c	Tear strength N/mm^d	Burst strength (Mullen)
ABS	50	25			
cellophane	80	30	31–58	0.8–8	30–50
CA	75	15–55	10.8	1.6–3.9	30–60
CTA	86	10–50		1.6–11.8	50–70
fluorocarbons					
ETFE	52	300		235–350	
FEP	20	300		49	10
PCTFE	52	50–150		1–15.7	23–30
PTFE	20	100–400		3.9–39	
PVF	86	115–250		3.9–39	19–70
ionomer	34	250–400		11.8–49	
nylon-6	225	85–120		6.3–11	
PC	67	40–100		8–10	
PET	210	60–165		20–118	55–80
PI	172	70		3	75
PE					
LDPE	15	200–600	27–42	20–118	10–12
LLDPE	38	400–800	31–50		
MDPE	24	200–500	15–23	20–118	
HDPE	38	10–50	4–12	20–118	
UHMWPE	29	300			
PMMA	59	4–12			
PP^e	50–275	35–500	19–58	1.2–3.9	
PS^f	70	3–60		0.8–5.9	16–35
PVC					
rigid	58	25–50		3.9–275	30–40
plasticized	52	3–100		2–275	20

[a] See Table 1 for ASTM test methods.
[b] To convert MPa to psi, multiply by 145.
[c] To convert (kN·m)/m to (kgf·cm)/mil, divide by 3.861.
[d] To convert N/mm to gf/25 μm, multiply by 2.549; to convert to ppi, divide by 0.175.
[e] Biaxial orientation.
[f] Oriented.

2. Materials

2.1. Acrylonitrile–Butadiene–Styrene

Available only as sheet, ABS has good toughness and high impact resistance. It is readily thermoformable over a wide range of temperatures and can be deeply drawn. ABS has poor solvent resistance and low continuous-use temperature. It is often used in housings for office equipment (see Acrylonitrile polymers).

2.2. Acrylic Polymers

A small amount of film is produced, but most acrylic resin is used in sheet and is produced from poly(methyl methacrylate) (PMMA). This material has optical clarity approaching glass and is resistant to uv exposure (see Methacrylic polymers). It has good rigidity, impact resistance, and scratch resistance so it finds a large market for signs and safety glazing. It can be stretched to increase its toughness and coated to improve its abrasion

Table 4. Optical and Electrical Properties

Material	Refractive index	Transparency, %	Haze, %	Dielectric constant, kHz	Dissipation factor, kHz	Dielectric strength, kV/mm	Volume resistivity, Ωm·cm
ABS	1.53	33	100	2.75		14.3	10^{16}
cellophane			3.5	3.2	0.015	79.99	10^{11}
CA	1.50	88	<1	3.6	0.013	126–197	10^{10--15}
CTA				4.0	0.016	146	10^{13}
fluorocarbons							
ETFE				2.6	0.0008	138	10^{10}
FEP	1.34	<90	4	2.25	<0.002	276	10^{19}
PCTFE	1.43			2.6	0.023	39–146	10^{12}
PTFE	1.35			4.1	0.0002	17	10^{13}
PVF				8.5	1.6	138	3×10^{13}
ionomer				2.4	0.002	39	10^{16}
nylon-6				3.7	0.03	50	
PC	1.59	83–90	0.5–2.0	2.9	0.0015	59	10^{16}
PET		88	1.0–3.0	2.8	0.005	296	10^{18}
PI				3.5	0.003	276	10^{18}
PE							
LDPE	1.51	0–75	4–50	2.2	0.0003	19	10^{16}
LLDPE			5–7				
MDPE	1.52	10–80	4–50	2.2	0.0003	20	10^{16}
HDPE	1.54	0.40	10–50	2.2	0.0005	20	10^{15}
UHMWPE	1.54				2.3×10^{-4}	51	10^{18}
PMMA	1.5	92	1	3.75	0.04	16	10^{15}
PP[a]			1.5–25	2.2	0.0002	276–400	3×10^{16}
PS[b]	1.6	87–92	0.1–30	2.5	0.0005	197	10^{16}
PVC							
rigid	1.53	76–82	8–18	3.0–3.3	0.013	17–50	10^{16}
plasticized				4.0–8.0	0.11	10–40	10^{11--14}

[a] Biaxially oriented.
[b] Oriented.

resistance. This product is used for airplane canopies and windows. It is, however, susceptible to stress crazing, has poor solvent resistance, and is flammable.

2.3. Cellophane

Once the leading clear packaging film, cellophane has a small fraction of the film market in the 1990s. It has largely been replaced by cheaper biaxially oriented polypropylene films and superior polyester films. Cellophane has set the standard for processibility on printing and packaging equipment. Cigarette packaging equipment was specially designed to process it at high speeds. Cellophane is produced from regenerated cellulose and is quite moisture-sensitive. It is necessary to coat it to provide moisture control and sealability. Cellulose nitrate was first used as a coating but this gave way to poly(vinylidene chloride) and to polyethylene. Cellophane has excellent stiffness and strength and its optical properties are outstanding; however, it does tend to yellow with age. Manufacturing cost is high, due in part to the large quantities of hazardous solvents required. It is still used for high quality transparent packaging.

Table 5. Barrier and Chemical Properties

		Gas permeability, nmol[b]/m·s·GPa			Resistance[c] to:					
Water absorption, %	WVTR, nmol[a]/m·s	O_2	CO_2	N_2	Acid	Alkali	Grease	Organic solvent	Water	Sunlight
0.6–1.0		100	300	14–19	G–F	G	G	F–P	G	F
45–115	0.1–32	1	1–100	0.2	P	P	G	P	F	G
3–8.5	2.6–10	180–240	1700–2000	65–95	P	P	G	P	G	G
2–4.5	7.7–10	240	1800	65	F	P	G	F–P	G	G
<0.02	0.4	160	500	65	G	G	G	G	G	G
<0.01	0.1	1200	3500	680	G	G	G	G	G	
nil	0.006	12–24	30–120	5.3	G	G	G	G	G	G
nil	0.013				G	G	G	G	G	G
<0.5	2	4–8	20	0.5	G	G	G	G	E	E
0.4	0.45	2400			G	G	G	G	G	G
9.5	2.7	4–6	20–24	1.9–2.5	P	F	E	G	G–P	F
<0.8	2.8	480	1600	100	G	P	G	G–P	G	F
0.25	0.3	6–8	30–50	1.4–1.9	G	P	G	G	G	F
2.9		40–60	80	10	G	P	G	G	G	G
<0.01	0.35	500–700	2000–4000	200–400	G	G	P	F	G	F
<0.01	0.2	250–600	1000–3000	150–600	G	G	F	F	G	F
nil	0.09	200–400	1200–1400	80–120	G	G	G	G		
nil					G	G	G	G	G	F
0.3–0.4	0.32				G	G	P		G	G
<0.005	3.2	300–500	1000–1600	60–100	G	G		G	G	F
0.04–0.1	1.8	500–800	1400–3000		G	G		G–P	G	F
nil	0.2–1.3	8–30	40–100		G	G		G–P	G	G
nil	1.3–7.7	50–3000	160–5000		G	G		G–F	E	F

[a] To convert nmol/(m·s) to (g·mm)/(m^2·d), multiply by 1.55.
[b] To convert nmol/(m·s·GPa) to (cm^2·mil)/m^2·d·atm), multiply by 0.13.
[c] G = gppd; F = fair; P = poor.

2.4. Cellulosics

The four previously common cellulosic films and sheets are less important factors in the markets of the 1990s. These include cellulose acetate, cellulose acetate propionate, cellulose acetate butyrate, and cellulose triacetate. These materials have excellent optical properties, and good scuff and grease resistance. Their barrier properties are midrange. With the exception of cellulose triacetate, they can be readily thermoformed and make fine clear boxes, and blister and skin packages. The butyrate and propionate copolymers are tougher than cellulose acetate, providing better protection. They also weather well and have been used to make outdoor signs. The cellulose triacetate is still widely used as the base for amateur photographic film. Environmental concerns and the relatively high manufacturing costs have driven most U.S. producers to limit their production (see Cellulose esters).

2.5. Fluoropolymers

Fluoroplastic film and sheets as a class possess the most chemically inert behavior of the materials generally used. In addition to their good strength, their resistance to thermal and electrical stress give them a unique niche in the market. The resistance to flame is important for use as liners in aircraft interiors. They are very resistant to moisture and provide a good barrier. When combined with fabrics or other materials, they provide a weatherable surface that is easy to clean. On the other hand, the resins tend to be intractable, difficult to handle, and require special bonding techniques. Because of their good slip and inertness, they are often used as gasketing material. Their relatively high cost limits their market penetration (see Fluorine compounds, organic–polytetrafluoroethylene).

2.6. Ionomer

Ionomer resins are a specialized class of polymers in which ionic bonding units provide cross-linking in the intermolecular structure. They make good film resins because of their strength, flexibility, adhesion, and optical properties. Ionomers (qv) have a relatively low sealability temperature and thus are used in coextrusion to provide a bonding layer between otherwise incompatible layers.

2.7. Polyamide

Polyamide or nylon film is primarily made from nylon-6 or nylon-6,6. About one-quarter of the film produced is biaxially oriented. Similar in most properties to polyester, it has somewhat superior resistance to flex-cracking, has good resistance to oils and grease, and is an excellent gas barrier. Nylon films, however, are sensitive to moisture so they are often laminated or extrusion-coated with PVDC, polyethylene, or ionomer. Typical use is for meat and cheese packaging and brown-and-serve cooking bags. It is used industrially for sheet-molding compound carrier and vacuum-bag molding. Nylon is the material used in metallized balloons. Some nylon is extruded into stock sheets used for machining into precision parts (see Polyamides).

2.8. Polycarbonate

Polycarbonate sheet is an important material for use in window glazing, aircraft windshields, and outdoor signs because of its excellent impact resistance stability, transparency, and heat resistance. Glazing and sheet uses account for the largest segment of polycarbonate resin. Impetus for its growth has come from the increasing demand for safety and security glazing in banks, government facilities, schools, hospitals, storm doors, and ice rinks. Its resistance to vandalism warrants it premium over glass and acrylics. Polycarbonate's one-third share of the plastic glazing market will grow as new products with abrasion-resistant coatings overcome one of its deficiencies. New, improved uv stabilizers will provide longer useful life in outdoor applications, and new technologies are being introduced to improve smoke and flame properties (see Polycarbonates).

2.9. Polyester

Poly(ethylene terephthalate) is used in both film and sheet form. Biaxially oriented film is the premier high volume film in terms of performance characteristics, combining such properties as high tensile properties, excellent dimensional stability, good barrier properties, high usage temperature, and excellent optical properties into a range of products for magnetic tape base, reprographic and photographic film base, electrical insulation, capacitors, decorative labeling and laminates, packaging, and many other uses. New films combining in-line coatings and coextrusion to produce multilayers are growing in sales volume based on enhanced printability, sealability, adhesion, or release characteristics.

Polyester sheet products may be produced from amorphous poly(ethylene terephalate) (PET) or partially crystallized PET. Acid-modified (PETA) and glycol modified (PETG) resins are used to make ultraclear sheet for packaging. Poly(butylene terephthalate) (PBT) has also been used in sheet form. Liquid-crystal polyester resins are recent entries into the market for specialty sheet. They exhibit great strength, dimensional stability, and inertness at temperatures above 250°C (see Polyesters, thermoplastic).

2.10. Polyimide

Polyimide is a biaxially oriented high performance film that is tough, flexible, and temperature- and combustion-resistant. Its room temperature properties compare to poly(ethylene terephthalate), but it retains these good characteristics at temperatures above 400°C. Its electrical resistance is good and it is dimensionally stable. The principal detriment is fairly high moisture absorbance. The main uses are for electrical insulation, particularly where high temperatures are prevalent or ionizing radiation is a problem. The films may be coated to reduce water absorption and enhance sealing (see Polyimides).

2.11. Polyethylene

Polyethylene remains the largest volume film and sheet raw material. It is available in a wide range of types, with variations in copolymers, homopolymers, molecular weight, and other factors contributing to a long list of resins. Resins are designed specifically for end use, and in addition blends of the various types may be used by processors to optimize properties, processibility, and economics. Almost two-thirds of the volume of all polyethylene resins are used in film or sheet applications (see Olefin polymers).

Low density polyethylene (LDPE), or as it is more precisely known, high pressure, low density polyethylene (HP-LDPE), the oldest form of polyethylene, still commands a large market share based on its transparency, tear resistance, impact resistance, and moisture resistance. It does have poor resistance to oils and grease, marginal weatherability, relative low resistance to high temperature, and is permeable to odors and gases. It is primarily used in clear packaging of such items as bread, produce, meat, poultry, seafood, and frozen foods, as well as in garment bags. It is also used in industrial applications such as liners, stretch wrap, heavy-duty bags, shrink wrap, and overwrap.

In the late 1980s, linear low density polyethylene (LLDPE) became a significant factor in the polyethylene film business. These resins have somewhat better strength than HP-LDPE and are cheaper to produce. LLDPE has been most successful in nonclear packaging, industrial or trash-bag use where its milky character is not critical and its properties allow downgauging with substantial cost savings. LLDPE is often used in grocery sacks, stretch wrap, liners, and mulch film. There is a growing market for its use in diapers, both infant and adult.

High molecular weight, high density polyethylene (HMW-HDPE) also has a large market share in film and sheet. As molecular weight and density of the polyethylene increase the tensile properties, chemical resistance and barrier properties of the film products increase. Excellent abrasion resistance is also achieved. As film, HMW-HDPE has a large share of the grocery sack business. It is also used for cereal and snack food packaging, where its resistance to moisture penetration is a prime factor.

In the sheeting market, the low density polyethylenes are less important than the high density resins. The high density resins have excellent chemical resistance, stress-crack resistance, durability, and low temperature properties which make them ideal for pond liners, waste treatment facilities, and landfills. In thicker section, HMW-HDPE sheet makes good containers, trays, truck-bed liners, disposable items, and concrete molds. The good durability, abrasion resistance, and light weight are critical elements for its selection.

2.12. Polypropylene

Polypropylene (PP) film, the bulk of which is biaxially oriented (BOPP), is characterized by its excellent clarity, strength, and low moisture transmission. It has captured a large share of the packaging market originally held by cellophane and competes with poly(ethylene terephthalate) film, glassine, paper, and other plastics in some markets. The packaging markets of importance are snack foods, baking items, cigarettes, candy, overwrap for boxes or trays, bottle labels, and more. It is used for pressure-sensitive tapes, sheet protectors, and stationery products, overwrap for toys and games, and as label stock. Its excellent electrical characteristics provide for its use as metallized thin-film capacitor dielectric.

Some cast (unoriented) polypropylene film is produced. Its clarity and heat sealability make it ideal for textile packaging and overwrap. The use of copolymers with ethylene improves low temperature impact, which is the primary problem with unoriented PP film. Orientation improves the clarity and stiffness of polypropylene film, and dramatically increases low temperature impact strength. BOPP film, however, is not readily heat-sealed and so is coextruded or coated with resins with lower melting points than the polypropylene shrinkage temperature. These layers may also provide improved barrier properties.

Because of poor thermoformability, there are relatively few applications for polypropylene sheet. New solid-phase pressure forming (SPPF) techniques are under development for forming PP sheet. Polypropylene is used in coextruded sheet to some extent for food packaging containers. Glass-filled, wood-filled, or other modified polypropylene sheet materials are used in limited automotive applications.

2.13. Polystyrene

Polystyrene (PS) film and sheet has the third largest production volume, behind only the polyethylenes and poly(vinyl chloride). As biaxially oriented film, it has excellent clarity and a crisp metallic feel, with high gas permeability and moderate moisture vapor permeability. It is used mostly for fresh produce wrapping. Sheet markets for thermoforming predominate, both as crystal clear impact grades and foamed sheet. The high melt strength of clear polystyrene makes it easy to thermoform by pressure or vacuum forming, and it stamps and cuts easily. Natural polystyrene is very clear but brittle, so impact grades are produced using butadiene as a comonomer, or by the addition of impact modifiers. Products produced from sheet range from cups and containers for foods and beverages, trays, furniture components, and lighting fixtures to architectural components.

Foamed polystyrene sheet has excellent strength, thermal resistance, formability, and shock resistance, as well as low density. It is widely known for its use in beverage cups, food containers, building insulation panels, and shock absorbent packaging. Polystyrene products can be recycled if suitable collection methods are established. Foamed polystyrene sheet can also be easily thermoformed (see Styrene plastics).

2.14. Vinyl Films

Vinyl films include a number of polymers, both homo- and copolymers, with a range of properties. They include poly(vinyl chloride) (PVC), vinyl chloride–vinyl acetate copolymers, poly(vinylidene chloride) (PVDC), and poly(vinyl alcohol) (PVOH) (see Vinyl polymers). The chemical and physical properties can vary over a wide spectrum. Blending, plasticizers, modifiers, and other additives are used to match properties to end use requirements. The properties are also influenced by the method of manufacture. They are generally made by extrusion, casting or calendering, and in some instances have been biaxially oriented. The products may range from hard, brilliant sheet to soft, pliable films. Poor thermal stability, plasticizer migration, poor solvent resistance, and low yield have acted to restrict applications. Shrinkable films can be made by biaxial orientation, and find use in food and other packaging. Vinyl resins may be blown into film of lesser quality than cast film.

Rigid sheet extrusion products are self-extinguishing and their excellent weatherability have led to expanding use in siding for housing.

Calendering is used to produce flexible vinyl sheet and film above 0.8 mm (see Polymer processing). These products can be readily thermoformed and have good sealability and are useful in packaging. The calendering of rigid vinyl sheet reached a low point in the mid-1970s, but has regained favor in the 1990s. Crystal clear sheet is used for box formation. Calendered rigid vinyl sheet is used in labels, print stock, credit card stock, and floppy disk jackets. It is easily stamped, cut, embossed, printed, thermoformed, and sealed.

Poly(vinylidene chloride) (PVDC) film has excellent barrier properties, among the best of the common films (see Barrier polymers). It is formulated and processed into a flexible film with cling and tacky properties that make it a useful wrap for leftovers and other household uses. As a component in coatings or laminates it provides barrier properties to other film structures. The vinylidene chloride is copolymerized with vinyl chloride, alkyl acrylates, and acrylonitrile to get the optimum processibility and end use properties (see Vinylidene chloride monomer and polymers).

2.15. Polyurethane

Small quantities of polyurethane film are produced as a tough rubber-like film. Polyurethane is more commonly used to produce foamed sheet, both flexible and rigid. The flexible foam is used as cushioning in furniture and bedding; the rigid foam is widely used for architectural insulation because of its outstanding thermal insulation efficiency (see Urethane polymers).

2.16. Specialty Films

Small quantities of film or sheet are manufactured from high performance resins for a variety of specialty applications. Most of these are for electrical insulation or support structures exposed to temperature, radiation, or environmental extremes. Some are designed to resist burning or flame. Excellent retention of dimensions under environmental changes may also be a prerequisite (see Engineering plastics). Among the polymers of commercial use are polysulfones (PSO), poly(phenyl sulfide) (PPS) (see Polymers containing sulfur), liquid crystal polyesters (LCP), poly(arylates), polyetherketones, and acetal resins(qv). Another specialty film product is poly(vinyl butyral) film (4). This film is the safety inner layer of automotive safety glass used in windshields and other safety glazing. It is produced under clean room conditions, wound in rolls supported on a carrier web, and laminated to glass. Its excellent flexibility and ability to absorb shock combined with its tenacious bond to glass to prevent dispersal of fragments of broken glass are its special attributes. The use of this film in architectural glass is expected to grow as the emphasis on safety and security continues.

2.17. Water-Soluble Films

Water-soluble films can be produced from such polymers as poly(vinyl alcohol) (PVOH), methylcellulose, poly(ethylene oxide), or starch (qv) (see Cellulose ethers; Polyethers; Vinyl polymers). Water-soluble films are used for packaging and dispensing portions of detergents, bleaches, and dyes. A principal market is disposable laundry bags for hospital use. Disposal packaging for herbicides and insecticides is an emerging use.

3. Manufacture

The processes used commercially for the manufacture of film and sheeting materials are generally similar in basic concept, but variations in equipment or process conditions are used to optimize output for each type of film or sheeting material. The nature of the polymer to be used, its formulation with plasticizers (qv), fillers

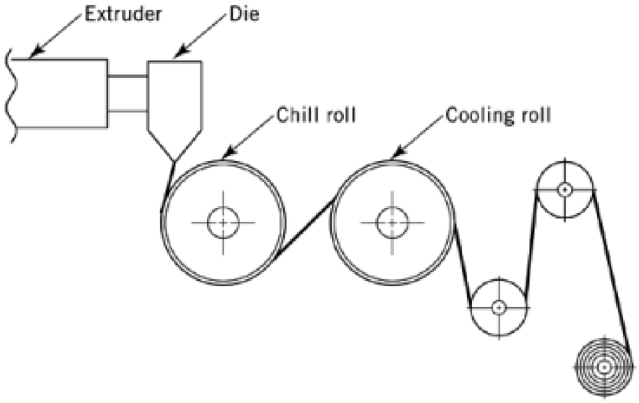

Fig. 1. Slot-die melt extrusion.

(qv), flow modifiers, stabilizers, and other modifiers, as well as its molecular weight and distribution are all critical to the processibility and final properties of the product. Most polymers are amenable to one or another of the common manufacturing processes, but some are so intractable they can only be made into film by skiving from large casting of the resin.

The basic methods for forming film or sheeting materials may be classified as follows: melt extrusion, calendering, solution casting, and chemical regeneration. Of special note is the use of biaxial orientation as part of the critical manufacturing steps for many film and sheet products.

3.1. Melt Extrusion

By far the most important method for producing film and sheeting materials relies on one or another of the various melt extrusion techniques (5). The main variations of melt extrusion are the slot (or flat) die-cast film process, the blown films process, and the flat die sheeting-stack process. These may be combined with one or more steps such as coextrusion wherein multilayer film or sheet is formed, biaxial orientation, and in-line coating (6).

The simplest form of melt extrusion is the use of a slot die to form the molten polymer into a thin flat profile which is then quenched immediately to a solid state (Fig. 1). This is usually done by contacting the hot web very quickly on a chilled roll or drum. A liquid quenching bath may be used in place of or contiguous to the chill roll. Depending on the polymer type or formulation, the quenched web is generally substantially amorphous. In some cases, the web may be drawn down in thickness by overdriving the quenching roll relative to the extrusion velocity.

With liquid bath quenching it is difficult to achieve an optically smooth surface unless all surface ripples are eliminated. In chill roll quenching, it is frequently necessary to pin the hot web to the drum to eliminate air pockets, surface ripples, and other defects. As line speeds increase this can become a controlling factor in quality film production. The most common methods used to pin a web are to use an air knife in close proximity to the emerging melt, or electrostatic pinning, where a high voltage field is established to force the web to the drum. Vacuum assist under the web or hooded quench rolls may be used to control the atmosphere near the die and quench roll(s). Thicker webs or higher line speeds may demand the use of multiple cooling rolls. The quenched film may be further processed (uni- or biaxially drawn, coated, or corona-discharge-treated to enhance adhesion). Generally the film is fed directly in-line to these other processes. If the film is suitable for use, it has the uneven edges trimmed off and is then wound into master rolls for subsequent slitting into narrower rolls, or is wound directly for shipment to customers.

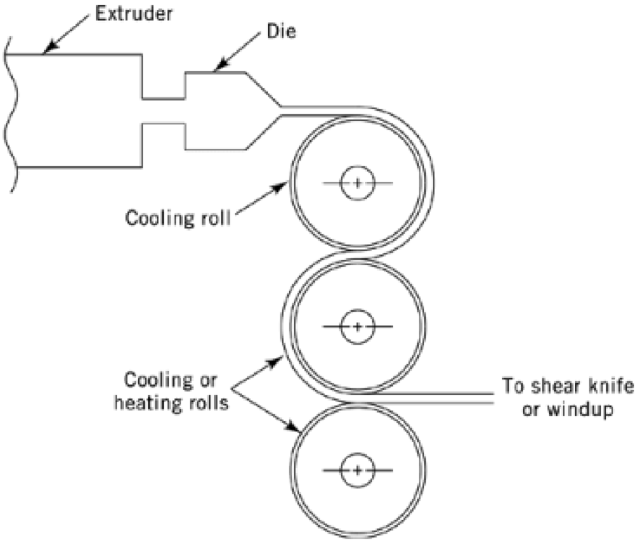

Fig. 2. Sheet extrusion casting.

The most critical factor in the slot-film process is the design of the die. The control of transverse gauge is extremely important and requires some form of cross-web gauge adjustment. Mechanical alternation of the die gap across the web may be done by using precisely controlled bolt action on the die lips, or by controlled application of heat in small increments across the die. Interior die geometry must be carefully designed to accommodate the flow and shear characteristics of the particular polymer being used. Care must be taken to prevent melt fracture by adjusting die characteristics to extrusion rate, drawdown, viscosity, and temperature.

When drawdown is high, the film may be uniaxially oriented and the properties of the final film isotropic. In the manufacture of strapping tape this effect is accentuated. If the cast or quenched film is to be used to feed an orientation line, additional attention must be given to the amorphous–crystalline nature of the film in the draw processes so that maximum strength can be achieved and uniform gauge and optical quality maintained. Slot casting is used for the orientation of these resins, polyesters, polyamides, and a variety of others.

Sheet can be produced by melt extrusion, but in this case a three-roll stack of quenching rolls is generally used (Fig. 2). More than three rolls may be used where necessary. The rolls may be mounted vertically or horizontally. The web is extruded through a slot die in a thickness close to the desired final thickness. The die is in very close proximity to the first chill roll or chill-roll nip. The web may be cast horizontally directly onto the upper chill roll of the stack as shown (Fig. 2), or it may be extruded into the first nip directly. The rolls quench the sheet and provide the surface polish desired. In some applications, matte or embossed rolls may be used to impart special surface characteristics for certain functions. Where the utmost in optical (glazing) quality is desired the trend has been to mount the roll stack horizontally. The hot melt is then extruded vertically down into the first nip. This avoids problems associated with sag of a horizontal hot melt no matter how short the distance between die and quench.

Quenched sheet is pulled horizontally from the stack and is then either wound on rolls or sheared into sheets of the required dimension. Among the polymers made into sheet this way are the polyolefins, poly(vinyl chloride), amorphous polyester, polycarbonate, and polyarylate.

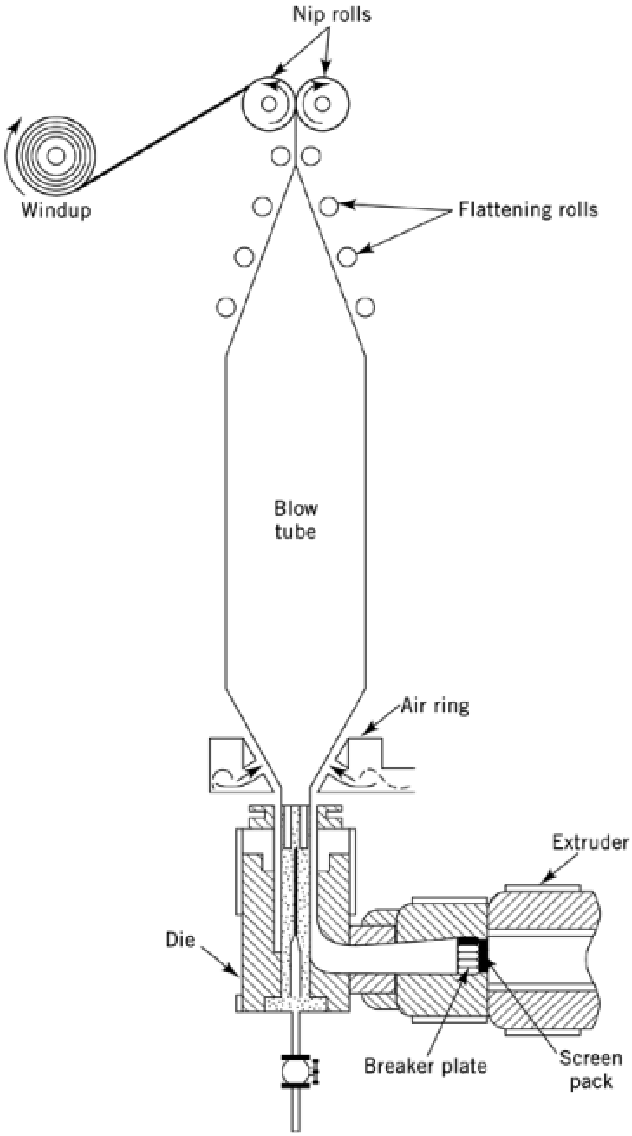

Fig. 3. Blown film extrusion.

3.1.1. Blown Film

The blown or tubular film process provides a low cost method for production of thin films (Fig. 3). In this process, the hot melt is extruded through an annular circular die either upward or downward and, less frequently, horizontally. The tube is inflated with air to a diameter determined by the desired film properties and by practical handling considerations. This may vary from as small as a centimeter to over a meter in diameter.

As the hot melt emerges from the die, the tube is expanded by air to two or three times its diameter. At the same time, the cooled air chills the web to a solid state. The degree of blowing or stretch determines the balance and level of tensile and impact properties. The point of air impingement and the velocity and temperature of the air must all be controlled to give the optimum physical properties to the film. With some polymers, an internal air cooling ring is used as well, in order to increase throughput rates and optical quality. Rapid cooling is essential to achieve the crystalline structure necessary to give clear, glossy films.

The film tube is collapsed within a V-shaped frame of rollers and is nipped at the end of the frame to trap the air within the bubble. The nip rolls also draw the film away from the die. The draw rate is controlled to balance the physical properties with the transverse properties achieved by the blow draw ratio. The tube may be wound as such or may be slit and wound as a single-film layer onto one or more rolls. The tube may also be directly processed into bags. The blown film method is used principally to produce polyethylene film. It has occasionally been used for polypropylene, poly(ethylene terephthalate), vinyls, nylon, and other polymers.

Downward extrusion of a bubble into a water bath and over an inner water-cooled mandrel is used in a few instances for polypropylene and polyesters. The water is removed prior to slitting and winding.

The double-bubble process may be used to produce biaxially oriented film, primarily polypropylene. In this process the first bubble formation is similar to the conventional blown film, except that the bubble is not collapsed. Rather it is reheated to the orientation temperature and blown and drawn further in a second stage. It is then collapsed, slit, and wound. This process is generally limited to a final film thickness of less than 24 μm.

3.1.2. Coextrusion

An increasingly popular technique to produce tailored film or sheet products is to coextrude one or more polymer types in two or more layers of melt (6). In this fashion the benefits of specific polymer types or formulations may be combined. Thus high cost barrier resins may be combined with a low cost thicker layer of standard resin to achieve an optimum barrier film at lower cost. Thin slip-control layers may be used on the surface of a bulk layer of optically clear resin to obtain an aesthetic film with good handleability. Lower melting outer layers may be used to provide heat sealing for polymers that seal with difficulty by themselves.

The layers of the different polymers or resins may be combined in one of two ways. One is to use a combining block prior to the slot extrusion die. Parallel openings within the block are fed from two or more extruders, one for each resin. The melts flow in laminar fashion through the die and onto the quench drum. The film is processed conventionally or may then be oriented. Careful control of resin viscosity must be obtained to provide smooth flow, and the resins must be compatible in order to bond together properly. The second method uses a multimanifold die to bring the melt streams together within the die. This allows use of resins with a wider difference in viscosity since fewer changes in flow patterns are necessary. Multimanifold dies may be flat or tubular. The most common types of coextrusion are AB, ABA, or ABC where A is one polymer system, B is another (of the same polymer type or different), and C is a third polymer type. Coextrusions of many, many layers lead to film products with a pearlescent appearance. Where two polymers may not adhere sufficiently, it is possible to extrude a tie or adhesive layer in the coextrusion. Ionomer resins are often used as such tie layers.

The process can be used to recover scrap or low quality resins by using them as the core layer, and using outer layers of virgin resins designed for the specific functional needs of the product such as slip or gloss and appearance. The inner core may be a foamed resin with surface layers of superior finish resins. Coextruded films often eliminate the need for costly lamination processes.

3.2. Calendering

Calendering is the process whereby a polymer is heated on hot rolls and squeezed between two or more parallel rolls into a thin web or sheet (Fig. 4) (8). The polymer is blended and masticated in preliminary operations and then fed to a rolling nip between hot, temperature-controlled rolls. The polymer mass is worked further in the nip and flows out to a uniform sheet as it passes through the nip. The web is nipped again and drawn down

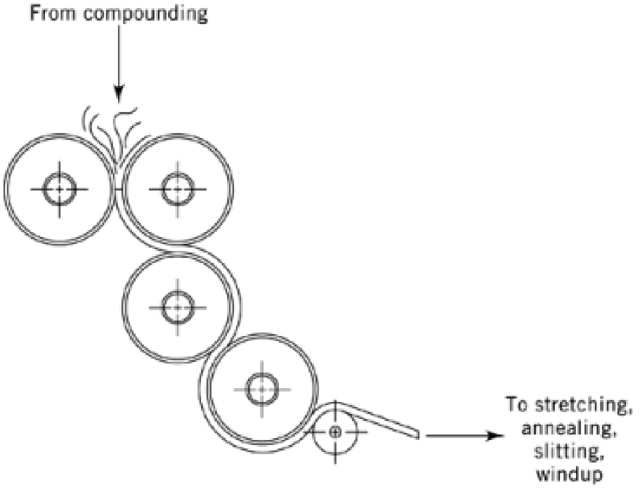

Fig. 4. Melt extrusion, calendering.

to a thinner sheet or film, and may undergo a third such step. Draw may be imparted to the web by a slight overdrive between nips. Since the surface of the film tends to take on the nature of the hot nip rolls, special surfaces such as high polish, matte, or embossing may be achieved by changing the rolls in the calender. The film and sheet properties are controlled by the resin composition (polymer–copolymer ratios, use of plasticizers or impact modifiers, stabilizers, molecular weight), by the amount of prework, by the temperature of plastic melt, by the amount of squeeze in each nip, and by the degree of draw imparted to the film (9).

Calendering is used principally for poly(vinyl chloride) film and sheet, both flexible and rigid. The use of the process had been in decline since the 1970s, but since 1986 sales have improved so that in 1993 12% of all PVC resin is used in calendering operations. The main products of calendering are flexible sheet for combination with textile backing for use in seating and wall coverings, flooring, and packaging. Rigid vinyl sheet is used for credit cards and packaging.

3.3. Biaxial Orientation

Many polymer films require orientation to achieve commercially acceptable performance (10). Orientation may be uniaxial (generally in the machine direction [MD]) or biaxial where the web is stretched or oriented in the two perpendicular planar axes. The biaxial orientation may be balanced or unbalanced depending on use, but most preferably is balanced. Further, this balance of properties may relate particularly to tensile properties, tear properties, optical birefringence, thermal shrinkage, or a combination of properties. A balanced film should be anisotropic, although this is difficult to achieve across the web of a flat oriented film.

There have been many methods and types of equipment developed to orient films, but only two are of real significance. One, the double-bubble process, is mentioned above; the other is the tenter process. In the latter process, a cast amorphous heavy-gauge film is drawn in the machine direction by passing it over heating rolls and then stretching it by speeding up the rolls at a point in the process where the web has reached the proper draw temperature. Immediately upon stretching the web is cooled and then fed into a tenter frame to achieve transverse draw. Here the edges of the film are engaged by a continuous chain of metal chips that tightly grip the film. The film enters an oven where it is reheated to the requisite second draw temperature. At this point the track for the chains of clip diverge, causing the film to stretch in the transverse direction (TD). The drawn web then enters a hotter section of the oven to heat-set or anneal the film. In this step, stresses are relieved

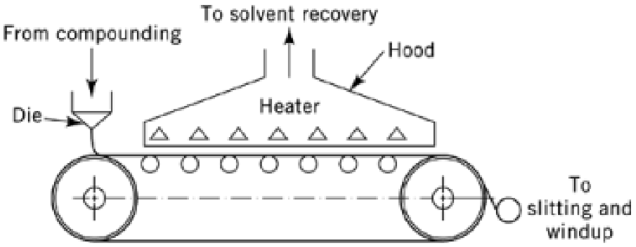

Fig. 5. Solvent casting on a belt.

and crystallization of the polymer may occur. The web is then cooled and the heavy edges that were within the clips are trimmed off. The film is then wound onto rolls for shipment or reslitting. The amount of stretch in each direction varies by polymer type and with the property balance that is desired in the product. Stretch ratios of from 3-to-1 up to 9-to-1 or more may be used. The degree of heat-set controls the crystallinity of the polymer and the amount and force of shrinkage when the free film is later heated.

In conventional tenter orientation, the sequence of steps is as described above (MD–TD). In some cases it is advantageous to reverse the draw order (TD–MD) or to use multiple draw steps, eg, MD–TD–MD. These other techniques are used to produce "tensilized" films, where the MD tensile properties are enhanced by further stretching. The films are generally unbalanced in properties and in extreme cases may be fibrillated to give fiber-like elements for special textile applications. Tensilized poly(ethylene terephthalate) is a common substrate for audio and video magnetic tape and thermal transfer tape.

Biaxially oriented films have excellent tensile strength properties and good tear and impact properties. They are especially well regarded for their brilliance and clarity. Essentially all poly(ethylene terephthalate) film is biaxially oriented, and more than 80% of polypropylene film is biaxially oriented. Polystyrene film is oriented, and a lesser amount of polyethylene, polyamide, poly(vinyl chloride), and other polymers are so processed. Some of the specialty films, like polyimides (qv), are also oriented.

3.4. Solution Casting

The production of unsupported film and sheet by solution casting has generally passed from favor and is used only for special polymers not amenable to melt processes. The use of solvents was generally very hazardous because of their flammability or toxic nature. The cost of recovery and disposal of solvents became prohibitive for many lower price film applications. The nature of the drying operations leads to problems with solvent migration and retention that are not problems with melt-processed polymers.

For solvent casting (Fig. 5), the resin is dissolved in the chosen solvent, along with the required stabilizers, modifiers, plasticizers, dyes, or other additives. Concentration of resin and temperature are critical factors to the film-forming process. The resin solution is pumped through filters to a hopper or die. It emerges onto a belt or drum for continuous processing, or may be passed into a cell or mold for *in situ* sheet production. When continuously cast, the solution is dried under rigorously controlled conditions of temperature and air flow. Care must be taken to avoid forming a skin of dried polymer on the surface which may impede further solvent migration. Also, gradients of solvent retention through the thickness are undesirable. In some processes, once the web is sufficiently strong, it may be removed from the drum or belt and then passed through a festoon dryer where both surfaces are exposed to the drying air flow. When drying is complete, the web is cooled, trimmed, and wound in conventional fashion. Band casting is used to produce cellulose acetate or triacetate film and sheet, and for specialized resins such as polysulfone.

Acrylic resins are often cell-cast (11). In this process no solvent is used, but the fluid monomers are passed into a cell or mold where polymerization takes place to form a solid sheet. Heavy sections can be produced in this fashion. Formation of cast acrylic is moving toward modified continuous-based casting to increase productivity. Drum casting on a commercial scale has almost disappeared.

3.5. Regeneration

The regeneration process is the oldest of the film-forming processes and was used exclusively for the manufacture of regenerated cellulose (cellophane) film from viscose. Highly purified cellulose is made into viscose by first converting it to alkali cellulose in strong caustic soda solution, pressing, and drying it into fluff. The fluff is aged, then treated with carbon disulfide to form cellulose xanthate, which is dissolved in dilute caustic to produce viscose solution (12). The cellophane is produced by extruding the viscose solution through a slot die of controlled gap size into a regeneration bath consisting of dilute sulfuric acid and sodium sulfate salt, where the viscose coagulates and the cellulose is regenerated. The web then passes through a series of baths where it is washed to remove acid, salts, and other materials. It is desulfurized, washed, bleached, washed again, and then sent to a conditioning bath where glycerol solution is added to plasticize the web. It is then dried to a desired moisture level. Each step of the process must be carefully controlled since the film properties and performance may be influenced by the type and molecular weight of cellulose, the effectiveness of washing out of impurities, the plasticizer added, the rates of regeneration, the degree of stretching and orientation, and the moisture level.

Almost all cellophane is coated with either a moisture barrier or heat-sealable coating. This is generally done in tower coaters after film production.

3.6. Casting and Lamination

Film and sheet are often coated or laminated to enhance their functional performance. Coatings may be applied by melt extrusion, solvent-based solution, water-based solution or emulsions, or vacuum deposition, in-line during the film- or sheet-forming process, or off-line as a secondary step (13). In-line coating has gained favor because it offers improved bonding, lower coating weights, and improved economics. Off-line coating may be done by the film or sheet manufacturer, but is more frequently done by their customers. Lamination is the combination of two or more web materials by melt or adhesive bonding.

In extrusion coating a polymer is extruded from a slot die into the nip of two rolls where it is bonded to a substrate under pressure (Fig. 6). A corona discharge may be applied to the substrate just prior to the nip to enhance adhesion. Polyethylene or ionomer are the most common resins used in extrusion coatings. They provide improved moisture barrier (on paper), or sealability (on foil, polypropylene, or polyester). When a second substrate is introduced to the nip, laminated structures may be produced.

Solution or emulsion coatings are used to produce film or sheet materials with special characteristics. The coatings that may be applied include a broad range of polymers, metals, oxides, light-sensitive compounds, pigments, inks, etc. They are designed to improve such properties as adhesion, printability, slip or handleability, sealability, antistatic behavior, water-vapor barrier, gas and odor barrier, opacity, color, conductivity, release characteristics, magnetic susceptibility, light sensitivity, light resistance, and selective absorption or reflection. Such coatings may be in one or several layers, and vary from 1 nm in thickness to a fraction of a mm.

These coatings (qv) are applied to the substrate using gravure roll coaters, reverse roll coaters, wire-wound rod coaters, knife coaters, kiss coaters, or spray coaters, to name a few methods (see Coating processes). Excess coatings are metered or doctored off the web, and then the solvent is removed by drying in an oven. Radiation drying may also be used, and often the coating is cured or cross-linked to make it permanent. The web may be supported on rollers, a drum, continuous belt, or by air-flotation during drying, depending on the number of sides coated and the nature of the coating system.

The use of vacuum-based systems to apply ultrathin coatings to various film and sheet substrates has grown in importance in recent years, and represents an area where new technology is still appearing. The film

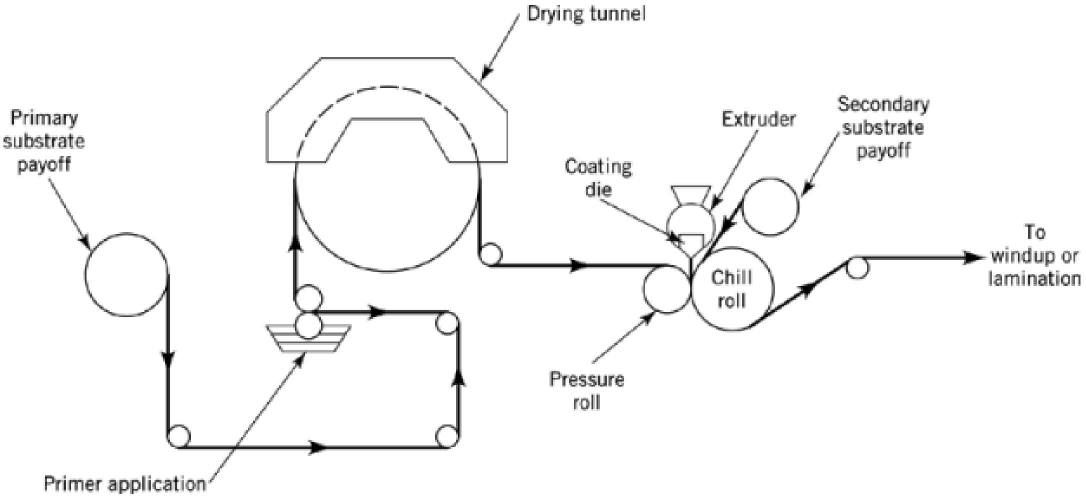

Fig. 6. Extrusion coating on a substrate.

is placed in a chamber and a high vacuum is drawn. The film is unwound and passed through one or more zones in which the vaporized coating is applied. Metals may be vaporized by use of resistance heat or ionizing radiation and deposited on the surface to give metallized film products. In other processes, plasmas are used to activate coatings that result in oxides or nitrides being deposited on the film that are useful in selective light-absorption coating. Ion implantation is another technique available. Sputtering of a material may be used to vaporize it for deposition on the substrate surface.

4. Economic Aspects

Table 6 shows the sales estimates for principal film and sheet products for the year 1990 (14). Low density polyethylene films dominate the market in volume, followed by polystyrene and the vinyls. High density polyethylene, poly(ethylene terephthalate), and polypropylene are close in market share and complete the primary products. A number of specialty resins are used to produce 25,000–100,000 t of film or sheet, and then there are a large number of high priced, high performance materials that serve niche markets. The original clear film product, cellophane, has fallen to about 25,000 t in the United States, with only one domestic producer. Table 7 lists some of the principal film and sheet material manufacturers in the United States.

Packaging (qv) represents the largest market area for film and sheeting materials (15). It is a complex market with so many categories that it is difficult to get an accurate measure of end usage for specific materials (16). The structure of the marketplace which uses both monolayers of film, as well as converted composite structures and laminates, adds to the complexity. The ultimate user or packager may purchase raw film directly from a manufacturer, or use the same film laminated to one or more other films or substrates through a converter. The converter may buy film or extrude his own supply. Resin sales to film producers do not always correlate with their film sales, because of scrap and yield losses.

Food packaging, in turn, constitutes a significant segment of the packaging market. Films or sheeting materials are used to package meat and poultry, snack foods, baked goods, dairy products, prepared foods, frozen foods, produce, cereals, and tobacco, to list some of the market areas. Each category has its own requirements

Table 6. U.S. Film and Sheet Sales,[a] 1990, 10^3 t

	Film			
Material	Packaging	Other	Sheet	Total
acrylics				
cell-cast			42	42
continuous cast			30	30
extruded		2	93	95
cellulosics		20[b]	7	27
cellophane	24	5		29
HDPE	345	70	150	565
LDP	1700	1140	118	2956
LLDP	560	730	8	1298
polypropylene	180	60	60	300
polyester (PET)	22	265	57	344
nylon	24	6	5	35
polycarbonate		15	54	69
polystyrene				
crystal		20	600	620
foam			335	335
poly(vinyl chloride)				
calendered				475
extruded	140		23	164
poly(vinyl alcohol)	2			2
ionomer	12			12
polyimide		1		1
fluorocarbons		6		6

[a] Based on estimates of resin sales for film and sheet.

[b] Includes estimate of captive use for photographic film and pressure-sensitive tape.

for protection and preservation of its food contents, which makes necessary the diverse line of products used for packaging.

Nonfood packaging categories include drugs and pharmaceuticals, textile goods, bags (merchandise, shipping, carry-out, T-shirt, and laundry), shrink wrap, stretch wrap, clear boxes, and many more.

The largest nonpackaging markets for film and sheet include agricultural (mulching) and construction film, trash liners and bags, pressure-sensitive tape base, insulation board, and diaper liners. These are relatively low cost, high volume uses. There are a large number of premium end uses for film and sheet that demand high performance, long life, or high purity. These uses are filled by higher value films such as polyester, BON, BOPP, polycarbonates, acrylics, fluorocarbons, polyurethanes, polysulfone, polyimides, and many new products. These markets include magnetic tape base, photographic film base, microfilm, drafting and layout bases, color separation films, cartoon cells, imaging films, electrical and electronic insulation or support films, capacitor dielectric, permanent labels, solar control window films, laminates for safety glazing, and high impact glazing.

Sheeting materials are utilized in a wide variety of applications (17). About 30% of the sheet market is foamed sheet, mostly all polystyrene, used for egg trays, food and drink containers, and insulation. About 10% of the market for solid sheeting is used for glazing, lighting, and outdoor signs. This market has seen growth with the need for high security, impact-resistant glazing for banks, storefronts, ice rinks, and transportation. Polycarbonate, acrylics, and cellulosics dominate these markets. Thermoformed applications account for about 40% of the use for sheet. Vacuum-formed or pressure-formed products include blister and skin packaging, food and drink containers (cups, tubs, trays, and bowls for single use), toys, auto and appliance parts, and luggage. Polystyrene, polypropylene, HDPE, thermoplastic polyester, ABC, and vinyls are used in these thermoforming markets.

Table 7. U.S. Manufacturers or Distributors of Film and Sheet

Material	Manufacturer	Trade name
acrylic film and sheet	CYRO Industries	
	Bristech Chemical Corp.	
	Polycast Technology Corp.	
cellophane	E. I. du Pont de Nemours & Co., Inc.	
cellulosics	Eastman Kodak Co.	Kodacel
	Flex-O-Glass, Inc.	
	Technical Plastics Extruders	
	Polymer Extruded Products	
fluoroplastics	Allied Signal Corp.	Aclar
	E. I. du Pont de Nemours & Co., Inc.	Tedlar, Tefrel, Teflon
	Fluoro Plastics Inc.	
nylon	Allied Signal	Capran
	E. I. du Pont de Nemours & Co., Inc.	Dartak
polycarbonate	General Electric Co.	Lexan
	Miles Inc.	Makofol
polyester	E. I. du Pont de Nemours & Co., Inc.	Mylar
		Hostaphan
	Hoechst Diafoil	Melinex
	ICI Americas, Inc.	Lumirror
	Toray	
polyethylene	Exxon Chemical Co., Film Products	
	Bemis Co., Inc., Film Division	
	AEP Industries, Inc.	
	Presto Products Co.	
	James River Corp.	
	Cryovac Division, W. R. Grace & Co.	
	Continental Extrusion Corp.	
	Georgia Pacific	
	Mobil Chemical Co.	
polypropylene	Hercules, Inc.	Bicor
	Mobil Chemical Co.	
	Quantum Performance Films	
	Toray Plastics America, Inc.	
polystyrene	Dow Chemical Co.	Opticite
	Mobil Chemical Co.	
poly(vinyl chloride)	Borden Packaging & Industrial Products	
	Hüls America, Inc.	
	American Mirex Corp.	
	Klockner Pentaplast of America, Inc.	
polyimides	E. I. du Pont de Nemours & Co., Inc.	Kapton
		Apecal
	Allied Signal Corp.	Upilex
	ICI Americas, Inc.	

Typical area yields and pricing (1990) are shown in Table 8. Conventional converting practice considers area yield, ie, area per weight of film of specified thickness. In this fashion easy comparison between materials or combinations of material can be made to determine cost of packaging materials. As film thickness diminishes for a given material, price per given weight may increase dramatically to cover production costs and lower production yields. Area pricing is affected to a lesser extent.

Table 8. Area Yields and Pricing,[a] 1990

Film material	Density, g/mL	Area yield,[b] m^2/kg^c	Pricing By weight, \$/kg	 By area, ¢/m^{2d}
acrylic	1.26	31.2	13.20	42.3
cellulose acetate	1.30	30.3	7.15	23.6
cellophane	1.44	27.3	4.77	17.5
HDPE	0.95	41.4	2.99	7.2
LDPE	0.915	43.0	1.32–2.20	3.1–5.1
polypropylene				
OPP	0.905	43.5	3.85	8.9
BOPP	0.89	44.2	2.53	5.7
polyester	1.39	28.3	4.84	17.1
nylon	1.13	34.8	7.37	21.2
polycarbonate	1.20	32.8	9.13	27.9
PVC-shrink	1.30	30.3	5.50	18.2
polystyrene	1.05	37.5	2.97	7.9
ionomer	0.95	41.4	3.63	8.8
fluorocarbons	2.20	17.9	22.00	123
polysulfone	1.30	30.3	33.00	109
polyimide	1.42	27.7	128	461

[a] Price vary by grades, special treatments, or other variables.

[b] Film thickness = 25.4 μm = 1 mil.

[c] To convert m^2/kg to 1000 $in.^2$/lb, multiply by 0.705.

[d] To convert ¢/m^2 to ¢/1000 $in.^2$, multiply by 0.645.

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