SECTION 18 DESIGN OF PLASTIC GEARS

18.1 General Considerations Of Plastic Gearing

Plastic gears are continuing to displace metal gears in a widening arena of applications. Their unique characteristics are also being enhanced with new developments, both in materials and processing. In this regard, plastics contrast somewhat dramatically with metals, in that the latter materials and processes are essentially fully developed and, therefore, are in a relatively static state of development.

Plastic gears can be produced by hobbing or shaping, similarly to metal gears or alternatively by molding. The molding process lends itself to considerably more economical means of production; therefore, a more in-depth treatment of this process will be presented in this section.

Among the characteristics responsible for the large increase in plastic gear usage, the following are probably the most significant:

1. Cost effectiveness of the injection-molding process.
2. Elimination of machining operations; capability of fabrication with inserts and integral designs.
3. Low density: lightweight, low inertia.
4. Uniformity of parts.
5. Capability to absorb shock and vibration as a result of elastic compliance.
6. Ability to operate with minimum or no lubrication, due to inherent lubricity.
7. Relatively low coefficient of friction.
8. Corrosion-resistance; elimination of plating, or protective coatings.
9. Quietness of operation.
10. Tolerances often less critical than for metal gears, due in part to their greater resilience.
11. Consistency with trend to greater use of plastic housings and other components.
12. One step production; no preliminary or secondary operations.

At the same time, the design engineer should be familiar with the limitations of plastic gears relative to metal gears. The most significant of these are the following:

1. Less load-carrying capacity, due to lower maximum allowable stress; the greater compliance of plastic gears may also produce stress concentrations.
2. Plastic gears cannot generally be molded to the same accuracy as high-precision machined metal gears.
3. Plastic gears are subject to greater dimensional instabilities, due to their larger coefficient of thermal expansion and moisture absorption.
4. Reduced ability to operate at elevated temperatures; as an approximate figure, operation is limited to less than 120ºC. Also, limited cold temperature operations.
5. Initial high mold cost in developing correct tooth form and dimensions.
6. Can be negatively affected by certain chemicals and even some lubricants.
7. Improper molding tools and process can produce residual internal stresses at the tooth roots, resulting in over stressing and/or distortion with aging.
8. Costs of plastics track petrochemical pricing, and thus are more volatile and subject to increases in comparison to metals.

18.2 Properties Of Plastic Gear Materials

Popular materials for plastic gears are acetal resins such as DELRIN*, Duracon M90; nylon resins such as ZYTEL*, NYLATRON**, MC901 and acetal copolymers such as CELCON***. The physical and mechanical properties of these materials vary with regard to strength, rigidity, dimensional stability, lubrication requirements, moisture absorption, etc. Standardized tabular data is available from various manufacturers' catalogs. Manufacturers in the U.S.A. provide this information in units customarily used in the U.S.A. In general, the data is less simplified and fixed than for the metals. This is because plastics are subject to wider formulation variations and are often regarded as proprietary compounds and mixtures. **Tables 18-1** through **18-9** are representative listings of physical and mechanical properties of gear plastics taken from a variety of sources. All reprinted tables are in their original units of measure.

Table 18-1 Physical Properties of Plastics Used in Gears

Material	Tensile Strength (psi x 10^3)	Flexural Strength (psi x 10^3)	Compressive Modulus (psi x 10^3)	Heat Distortion Temperature (°F @ 264psi)	Water Absorption (% in 24 hrs)	Rockwell Hardness	Mold Shrinkage (in./in.)
						M94	
Acetal	8.8 – 1.0	13 – 14	410	230 – 255	0.25	R120	0.022
							0.003
ABS	4.5 – 8.5	5 – 13.5	120 – 200	180 – 245	0.2 – 0.5	R80 – 120	0.007
							0.007
Nylon 6/6	11.2 – 13.1	14.6	400	200	1.3	R118 – 123	0.015
Nylon 6/10	7 – 8.5	10.5	400	145	0.4	R111	0.015
						M70	0.005
Polycarbonate	8 – 9.5	11 – 13	350	265 – 290	0.15	R112	0.007
							0.003
High Impact							
Polystyrene	1.9 – 4	5.5 – 12.5	300 – 500	160 – 205	0.05 – 0.10	M25 – 69	0.005
						M29	
Polyurethane	4.5 – 8	7.1	85	160 – 205	0.60 – 0.80	R90	0.009
Polyvinyl							0.002
Chloride	6 – 9	8 – 15	300 – 400	140 – 175	0.07 – 0.40	R100 – 120	0.004
						M69	
Polysulfone	10.2	15.4	370	345	0.22	R120	0.0076
MoS_2–Filled							
Nylon	10.2	10	350	140	0.4	D785	0.012

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* Registered trademark, E.I. du Pont do Nemours and Co., Wilmington, Delaware, 19898.
** Registered trademark, The Polymer Corporation, P.O. Box 422, Reading, Pennsylvania, 19603.
***Registered trademark, Celanese Corporation, 26 Main St., Chatham, N.J. 07928.

Table 18-2 Property Chart for Basic Polymers for Gearing

	Water Absorp. 24hrs.	Mold Shrinkage	Tensile Strength * Yield •Break	Flexural Modulus	Izod Impact Strength Notched	Deflect. Temp. @264psi	Coeff. of Linear Thermal Expan.	Specific Gravity
Units	**%**	**in./in.**	**psi**	**psi**	**ft.lb/in.**	**ºF**	**10^{-5} ºF**	
ASTM	**D570**	**D955**	**D638**	**D790**	**D256**	**D648**	**D696**	**D792**
1. Nylon 6/6	1.5	.015/.030	*11,200	175,000	2.1	220	4.5 varies	1.13/1.15
2. Nylon 6	1.6	.013/.025	*11,800	395,000	1.1	150	4.6	1.13
3. Acetal	0.2	.016/.030	*10,000	410,000	1.4/2.3	255	5.8	1.42
4.Polycarbonate 30% G/F, 15%PTFE	0.06	.0035	*17,500	1,200,000	2	290	1.50	1.55
5. Polyester (thermoplastic)	0.08	.020	*8,000 •12,000	340,000	1.2	130	5.3	1.3
6.Polyphenylene sulfide 30% G/F 15%PTFE	0.03	.002	*19,000	1,300,000	1.10	500	1.50	1.69
7. Polyester elastomer	0.3	.012	*3,780 •5,500	-	-	122	10.00	1.25
8. Phenolic (molded)	0.45	.007	•7,000	340,000	.29	270	3.75	1.42

* These are average values for comparison purpose only.
Source: Clifford E. Adams, Plastic Gearing, Marcel Dekker Inc., N.Y. 1986. Reference 1.

Table 18-3 Physical Properties of DELRIN Acetal Resin and ZYTEL Nylon Resin

Properties-Units	ASTM	"DELRIN" 500	"DELRIN" 100	"ZYTEL" 101 .2% Moisture	"ZYTEL" 101 2.5% Moisture
Yield Strength, psi	D638*	10,000		11,800	8,500
Shear Strength, psi	D732*	9,510		9,600	
Impact Strength (Izod)	D256*	1.4	2.3	0.9	2.0
Elongation at Yield,%	D638*	15	75	5	25
Modulus of Elasticity, psi	D790*	410,000		410,000	175,000
Hardness, Rockwell	D785*	M 94, R 120		M79 R118	M 94, R 120, etc.
Coefficient of Linear Thermal Expansion, in./in.ºF	D696	4.5 x 10^{-5}		4.5 x 10^{-5}	
Water Absorption					
24 hrs. %	D570	0.25		1.5	
Saturation, %	D570	0.9		8.0	
Specific Gravity	D792	1.425		1.14	1.14

* Test conducted at 73ºF
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Table 18-4 Properties of Nylatron GSM Nylon

Property	Units	ASTM No.	Value
Specific Gravity	–	D 792	1.15 - 1.17
Tensile Strength, 73°F	psi	D 638	11,000 - 14,000
Elongation, 73°F	%	D 638	10 - 60
Modulus of Elasticity, 73°F	psi	D 638	350,000 - 450,000
Compressive Strength	psi	D 695	
@ 0.1% Offset			9,000
@ 1.0% Offset			12,000
Shear Strength, 73°F	psi	D 732	10,500 - 11,500
Tensile Impact, 73°F	ft.lb./in.²	–	80 - 130
Deformation Under Load 122°F, 2000psi	%	D 621	0.5 - 1.0

Property	Units	ASTM No.	Value
Hardness (Rockwell), 73°F	–	D-785	R112 - 120
Coefficient of Friction (Dry vs Steel) Dynamic	–	–	.15 - .35
Heat Distortion Temp.			
66 psi	°F	D-648	400 - 425
264psi	°F	D-648	200 - 425
Melting Point	°F	D-789	430 ±10
Flammability	–	D-635	Self-extinguishing
Coefficient of Linear Thermal Expansion	in./in.°F	D-696	5.0 x 10^{-5}
Water Absorption			
24 Hours	%	D-570	.6 - 1.2
Saturation	%	D-570	5.5 - 6.5

Resistant to: Common Solvents, Hydrocarbons, Esters, Ketones, Alkalis, Diluted Acids
Not Resistant to: Phenol, Formic Acid, Concentrated Mineral Acid
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Table 18-5 Typical Thermal Properties of "CELCON" Acetal Copolymer

Property	ASTM Test Method	Units	M Series	GC-25A
Flow, Softening and Use Temperature				
Flow Temperature	D 569	ºF	345	-
Melting Point	-	ºF	329	331
Vicat Softening Point	D1525	ºF	324	324
Unmolding Temperature[1]	-	ºF	320	-
Thermal Deflection and Deformation				
Deflection Temperature	D648			
@264 psi		ºF	230	322
@66 psi		ºF	316	
Deformation under Load (2000 psi @122ºF)	D621	%	1.0	0.6
Miscellaneous				
Thermal Conductivity	-	BTU/hr./ft^2/Fº/in.	1.6	-
Specific Heat	-	BTU/lb./ºF	0.35	-
Coefficient of Linear Thermal Expansion (Range:- 30ºC to + 30ºC.)	D696	in./in.ºF		
Flow direction			4.7×10^{-5}	2.2×10^{-5}
Traverse direction			4.7×10^{-5}	4.7×10^{-5}
Flammability	D635	in./min.	1.1	-
Average Mold Shrinkage[2]	-	in./in.		
Flow direction			0.022	0.004
Transverse direction			0.018	0.018

[1]Unmolding temperature is the temperature at which a plastic part loses its structural integrity (under its own weight) after a half-hour exposure.
[2]Data Bulletin C3A, "Injection Molding Celcon," gives information of factors which influence mold shrinkage. Reprinted with the permission of Celanese Plastics and Specialties Co.; see Reference 3.

Table 18-6 Mechanical Properties of Nylon MC9O1 and Duracon M90

Properties	Testing Method ASTM	Unit	Nylon MC901	Duracon M90
Tensile Strength	D 638	kgf/cm^2	800-980	620
Elongation	D638	%	10-50	60
Modules of Elasticity (Tensile)	D638	10^3kgf/cm^2	30-35	28.8
Yield Point (Compression)	D638	kgf/cm^2	940-1050	-
5% Deformation Point	D638	kgf/cm^2	940-970	-
Modules of Elasticity (Compress)	D638	10^3kgf/cm^2	33-36	-
Shearing Strength	D732	kgf/cm^2	735-805	540
Rockwell Hardness	D785	R scale	115-120	980
Bending Strength	D790	kgf/cm^2	980-1120	980
Density (23ºC)	D792	-	1.15-1.17	1.41
Poisson's Ratio	-	-	0.40	0.35

Table 18-7 Thermal Properties of Nylon MC9O1 and Duracon M90

Properties	Testing Method ASTM	Unit	Nylon MC901	Duracon M90
Thermal Conductivity	C177	10^{-1}Kcal/mhrºC	2	2
Coeff. of Linear Thermal Expansion	D696	10^{-5}cm/cm/ºC	9	9-13
Specifical Heat (20ºC)		cal/ºCgrf	90.4	0.35
Thermal Deformation Temperature (18.5 kgf/cm^2)	D648	ºC	160-200	110
Thermal Deformation Temperature (4.6 kgf/cm^2)	D648	ºC	200-215	158
Antithermal Temperature (Long Term)		ºC	120-150	-
Deformation Rate Under Load (140 kgf/cm^2, 50ºC)	D621	%	0.65	-
Melting Point		ºC	220-223	165

Table 18-8 Typical Physical/Mechanical Properties of CELCON® Acetal Copolymer

Property English Units (Metric Units)	ASTM Test Method	Nominal Specimen Size	Temp.	M-Series Values	GC-25A Values	Temp.	M-Series Values	GC-25A Values
Specific Gravity	D 792			1.41	1.59		1.41	1.59
Density lbs/in³ (g/cm³)				0.0507	0.057			
Specific Volume lbs/in³ (cm³/g)				19.7	17.54		0.71	0.63
Tensile Strength at Yield lbs/in² (kg/cm²)	D 638 Speed B	Type I 1/8"	-40 °F 73 °F 160 °F	13,700 8,800 5,000	16,000 (at break)	-40 °C 23 °C 70 °C	965 620 350	1120 (at break)
Elongation at Break %	D 638 Speed B	Type I 1/8" Thick	-40 °F 73 °F 160 °F	M25/30 M90/20 M270/15 M25/75 M90/60 M270/40 250	2 – 3	-40 °C 23 °C 70 °C	M25/30 M90/20 M270/15 M25/75 M90/60 M270/40 250	2 – 3
Tensile Modulus lbs/in² (kg/cm²)	D 638	Type I 1/8" Thick		410,000	1.2 x 10⁶		28,800	84,500
Flexural Modulus lbs/in² (kg/cm²)	D 790	5" x 1/2" x 1/8" Thick	73 °F 160 °F 220 °F	375,000 180,000 100,000	1.05x10⁶ 0.7x10⁶ 0.5x10⁶	23 °C 70 °C 105 °C	26,400 12,700 7,000	74,000 50,000 35,000
Flexural Stress at 5% Deformation lbs/in² (kg/cm²)	D 790	5" x 1/2" x 1/8" Thick		13,000			915	
Compressive Stress at 1% Deflection lbs/in² (kg/cm²) at 10% Deflection lbs/in² (kg/cm²)	D 695	1" x 1/2" x 1/2"		4,500 16,000			320 1,100	
Izod Impact Strength (Notched) ft–lb/in.notch (kg·cm/cm notch)	D 256	2 1/2" x 1/2" x 1/8" machined notch	-40 °F 73 °F	M25/1.2 M90/1.0 M270/0.8 M25/1.5 M90/1.3 M270/1.0	1.1	-40 °C 23 °C	M25/6.5 M90/5.5 M270/4.4 M25/8.0 M90/7.0 M270/5.5	6.0
Tensile Impact Strength ft–lb/in² (kg·cm/cm²)	D 1822	L–Specimen 1/8" Thick		M25/90 M90/70 M270/60	50		M25/190 M90/150 M270/130	110
Rockwell Hardness M Scale	D 785	2" x1/8" Disc		80			80	
Shear Strength lbs/in² (kg/cm²)	D 732	2"x1/8" Disc	73 °F 120 °F 160 °F	7,700 6,700 5,700	8,300	23 °C 50 °C 70 °C	540 470 400	584
Water Absorption 24 – hr. Immersion %	D 570	2" x 1/8" Disc		0.22	0.29		0.22	0.29
Equilibrium, 50% R.H. %				0.16			0.16	
Equilibrium, Immersion				0.80			0.80	
Taper Abrasion 1000 g Load CS–17 Wheel	D 1044	4" x 4"		14mg per 1000 cycles			14mg per 1000 cycles	
Coefficient of Dynamic Friction • against steel, brass and aluminum • against Celcon	D 1894	3" x 4"		0.15 0.35			0.15 0.35	

Many of the properties of thermoplastics are dependent upon processing conditions, and the test results presented are typical values only. These test results were obtained under standardized test conditions, and with the exception of specific gravity, should not be used as a basis for engineering design. Values were obtained from specimens injection molded in unpigmented material. In common with other thermoplastics, incorporation into Celcon of color pigments or additional U.V. stabilizers may affect some test results. Celcon GC25A test results are obtained from material predried for 3 hours at 240ºF (116ºC) beforemolding. All values generated at 50% r.h. & 73ºF(23ºC)unless indicated otherwise.

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Table 18-9 Water and Moisture Absorption Property of Nylon MC9O1 and Duracon M90

Conditions	Testing Method ASTM	Unit	Nylon MC901	Duracon M90
Rate of Water Absorption (at room temp. in water, 24 hrs.)	D 570	%	0.5 - 1.0	0.22
Saturation Absorption Value (in water)		%	5.5 - 7.0	0.80
Saturation Absorption Value (in air, room temp.)		%	2.5 - 3.5	0.16

It is common practice to use plastics in combination with different metals and materials other than plastics. Such is the case when gears have metal hubs, inserts, rims, spokes, etc. In these cases, one must be cognizant of the fact that plastics have an order of magnitude different coefficients of thermal expansion as well as density and modulus of elasticity. For this reason, **Table 18-10** is presented.

Other properties and features that enter into consideration for gearing are given in **Table 18-11** (Wear) and **Table 18-12** (Poisson's Ratio).

Table 18-10 Modulus of Elasticity, Coefficients of Thermal Expansion and Density of Materials

Material	Modulus of Elasticity (flexural) (lb/in.^{2})	Coefficient of Thermal Expansion (per °F)	Temperature Range of Coefficient (°F)	Density (lb/in^3)
Ferrous Metals				
Cast Irons:				
Malleable	25 to 28 x 10^6	6.6 x 10^{-6}	68 to 750	.265
Gray cast	9 to 23 x 10^6	6.0 x 10^{-6}	32 to 212	.260
Ductile	23 to 25 x 10^6	8.2 x 10^{-6}	68 to 750	.259
Steels:				
Cast Steel	29 to 30 x 10^6	8.2 x 10^{-6}	68 to 1000	.283
Plain carbon	29 to 30 x 10^6	8.3 x 10^{-6}	68 to 1000	.286
Low alloy,cast and wrought	30 x 10^6	8.0 x 10^{-6}	0 to 1000	.280
High alloy	30 x 10^6	8 to 9 x 10^{-6}	68 to 1000	.284
Nitriding , wrought	29 to 30 x 10^6	6.5 x 10^{-6}	32 to 900	.286
AISI 4140	29 x 10^6	6.2 x 10^{-6}	32 to 212	.284
Stainless:				
AISI 300 series	28 x 10^6	9.6 x 10^{-6}	32 to 212	.287
AISI 400 series	29 x 10^6	5.6 x 10^{-6}	32 to 212	.280
Nonferrous Metals:				
Aluminum alloys, wrought	10 to 10.6 x 10^6	12.6 x 10^{-6}	68 to 212	.098
Aluminum, sand–cast	10.5 x 10^6	11.9 to 12.7 x 10^{-6}	68 to 212	.097
Aluminum, die–cast	10.3 x 10^6	11.4 to 12.2 x 10^{-6}	68 to 212	.096
Beryllium copper	18 x 10^6	9.3 x 10^{-6}	68 to 212	.297
Brasses	16 to 17 x 10^6	11.2 x 10^{-6}	68 to 572	.306
Bronzes	17 to 18 x 10^6	9.8 x 10^{-6}	68 to 572	.317
Copper, wrought	17 x 10^6	9.8 x 10^{-6}	68 to 750	.323
Magnesium alloys, wrought	6.5 x 10^6	14.5 x 10^{-6}	68 to 212	.065
Magnesium, die–cast	6.5 x 10^6	14 x 10^{-6}	68 to 212	.065
Monel	26 x 10^6	7.8 x 10^{-6}	32 to 212	.319
Nickel and alloys	19 to 30 x 10^6	7.6 x 10^{-6}	68 to 212	.302
Nickel, low–expansion alloys	24 x 10^6	1.2 to 5 x 10^{-6}	–200 to 400	.292
Titanium, unalloyed	15 to 16 x 10^6	5.8 x 10^{-6}	68 to 1650	.163
Titanium alloys, wrought	13 to 17.5 x 10^6	5.0 to 7 x 10^{-6}	68 to 572	.166
Zinc, die–cast	2 to 5 x 10^6	5.2 x 10^{-6}	68 to 212	.24
Powder Metals:				
Iron (unalloyed)	12 to 25 x 10^6	—	—	.21 to .27
Iron–carbon	13 x 10^6	7 x 10^{-6}	68 to 750	.22
Iron–copper–carbon	13 to 15 x 10^6	7 x 10^{-6}	68 to 750	.22
AISI 4630	18 to 23 x 10^6	—	—	.25
Stainless steels:				
AISI 300 series	15 to 20 x 10^6	—	—	.24
AISI 400 series	14 to 20 x 10^6	—	—	.23
Brass	10 x 10^6	—	—	.26
Bronze	8 to 13 x 10^6	10 x 10^{-6}	68 to 750	.28
Nonmetallics:				
Acrylic	3.5 to 4.5 x 10^5	3.0 to 4 x 10^{-5}	0 to 100	.043
Delrin (acetal resin)	4.1 x 10^5	5.5 x 10^{-5}	85 to 220	.051
Fluorocarbon resin (TFE)	4.0 to 6.5 x 10^4	5.5 x 10^{-5}	–22 to 86	.078
Nylon	1.6 to 4.5 x 10^5	4.5 to 5.5 x 10^{-5}	–22 to 86	.041
Phenolic laminate:				
Paper base	1.1 to 1.8 x 10^5	0.9 to 1.4 x 10^{-5}	–22 to 86	.048
Cotton base	0.8 to 1.3 x 10^5	0.7 to 1.5 x 10^{-5}	–22 to 86	.048
Linen base	0.8 to 1.1 x 10^5	0.8 to 1.4 x 10^{-5}	–22 to 86	.049
Polystyrene (general purpose)	4.0 to 5 x 10^5	3.3 to 4.4 x 10^{-5}	–22 to 86	.038

Source: Michalec, G.W., *Precision Gearing*, Wiley 1966

Table 18-11 Wear Characteristics of Plastics

Material	Steel	Brass	Polyurethane	Polycarbonate	MoS_2-Filled Nylon	Nylon 6/10	Nylon 6/6	Polystirene	ABS	Acetal
Acetal	F	P	G	F	G	G	G	F	F	G
ABS	P	P	G	G	G	G	G	P	F	
Polystyrene	P	P	F	F	G	F	F	F		
Nylon 6-6	E	F	E	F	E	G	G			
Nylon 6-10	E	F	E	F	E	G				
MoS_2-Filled Nylon	E	G	E	F	E					
Polycarbonate	G	F	G	G						
Polyurethane	E	F	G							
Brass	G	P								
Steel	F									

Key
E — Excellent
G — Good
F — Fair
P — Poor

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Table 18-12 Poisson's Ratio μ for Unfilled Thermoplastics

Polymer	μ
Acetal	0.35
Nylon 6/6	0.39
Modified PPO	0.38
Polycarbonate	0.36
Polystyrene	0.33
PVC	0.38
TFE (Tetrafluorethylene)	0.46
FEP (Fluorinated Ethylene Propylene)	0.48

Source: Clifford E. Adams, Plastic Gearing, Marcel Dekker Inc., New York 1986. Reference 1.

Moisture has a significant impact on plastic properties as can be seen in **Tables 18-1** thru **18-5**. Ranking of plastics is given in **Table 18-13**. In this table, rate refers to expansion from dry to full moist condition. Thus, a 0.20% rating means a dimensional increase of 0.002 mm/mm. Note that this is only a rough guide, as exact values depend upon factors of composition and processing, both the raw material and gear molding. For example, it can be seen that the various types and grades of nylon can range from 0.07% to 2.0%.

Table 18-13 Material Ranking by Water Absorption Rate

Material	Rate of Change %
Polytetrafluoroethylene	0.0
Polyethylene: medium density	< 0.01
high density	< 0.01
high molecular weight	< 0.01
low density	< 0.015
Polyphenylene sulfides (40% glass filled)	0.01
Polyester: thermosetting and alkyds	
low shrink	0.01 – 0.25
glass – preformed chopping roving	0.01 – 1.0
Polyester: linear aromatic	0.02
Polyphenylene sulfide: unfilled	0.02
Polyester: thermoplastic (18% glass)	0.02 – 0.07
Polyurethane: cast liquid methane	0.02 – 1.5
Polyester synthetic: fiber filled – alkyd	0.05 – 0.20
glass filled – alkyd	0.05 – 0.25
mineral filled – alkyd	0.05 – 0.50
glass–woven cloth	0.05 – 0.50
glass–premix, chopped	0.06 – 0.28
Nylon 12 (30% glass)	0.07
Polycarbonate (10–40% glass)	0.07 – 0.20
Styrene–acrylonitrile copolymer (20–33% glass filled)	0.08 – 0.22
Polyester thermoplastic:	0.09
thermoplastic PTMT (20% asbestos)	0.10
glass sheet molding	0.10 – 0.15
Polycarbonate <10%glass	0.12
Phenolic cast: mineral filled	0.12 – 0.36
Polyester alkyd: asbestos filled	0.14
Polycarbonate: unfilled	0.15 – 0.18
Polyester cast: rigid	0.15 – 0.60
Acetal: TFE	0.20
Nylon 6/12 (30–35% glass)	0.20
6/10 (30–35% glass)	0.20
Polyester alkyd vinyl ester thermoset	0.20
Styrene–acrylonitrile copolymer: unfilled	0.20 – 0.30
Polycarbonate ABS alloy	0.20 – 0.35
Phenolic cast: unfilled	0.20 – 0.40
Acetal copolymer	0.22
homopolymer	0.25
Nylon 12 (unmodified)	0.25
Acetal (20% glass)	0.25 – 0.29
Poly (ancide–imide)	0.28
Acetal (25% glass)	0.29
Nylon 11 (unmodified)	0.30
Polyester elastomer	0.30 – 0.60
Polyamide	0.32
Nylon: 6/12 (unmodified)	0.40
6/10 (unmodified)	0.40
Polyester-thermosetting and alkyds (cast flexible)	0.50 – 2.50
Nylon 6 (cast)	0.60 – 1.20
Polyurethane elastomer thermoplastic	0.70 – 0.90
Nylon 6/6: MoS_2	0.80 – 1.10
30 – 35% glass	0.90
unmodified	1.10 – 1.50
nucleated	1.10 – 1.50
Nylon 6 (30 – 35% glass)	1.30
unmodified	1.30 – 1.90
nucleated	1.30 – 1.90
Nylon 6/6 – 6 (copolymer)	1.50 – 1.20

Source: Clifford E. Adams, *Plastic Gearing*, Marcel Dekker, Inc., New York, 1986. Reference 1.

Table 18-14 lists safe stress values for a few basic plastics and the effect of glass fiber reinforcement.

It is important to stress the resistance to chemical corrosion of some plastic materials. These properties of some of materials used in the products presented in this catalog are further explored.

Nylon MC9O1

Nylon MC901 has almost the same level of antichemical corrosion property as Nylon resins. In general, it has a better antiorganic solvent property, but has a weaker antiacid property. The properties are as follows:

- For many nonorganic acids, even at low concentration at normal temperature, it should not be used without further tests.

Table 18-14 Safe Stress

Plastic	Safe stress, psi	
	Unfilled	Glass-reinforced
ABS Resins	3000	6000
Acetal	5000	7000
Nylon	6000	12000
Polycarbonate	6000	9000
Polyester	3500	8000
Polyurethane	2500	

Source: Clifford E. Adams, *Plastic Gearing*, Marcel Dekker Inc.,New York 1986. Reference 1.

- For nonorganic alkali at room temperature, it can be used to a certain level of concentration.
- For the solutions of nonorganic salts, we may apply them to a fairly high level of temperature and concentration.
- MC901 has better antiacid ability and stability in organic acids than in nonorganic acids, except for formic acid.
- MC901 is stable at room temperature in organic compounds of ester series and ketone series.
- It is also stable in mineral oil, vegetable oil and animal oil, at room temperature.

Duracon M90

This plastic has outstanding antiorganic properties. However, it has the disadvantage of having limited suitable adhesives. Its main properties are:

- Good resistance against nonorganic chemicals, but will be corroded by strong acids such as nitric, sulfuric and chloric acids.
- Household chemicals, such as synthetic detergents, have almost no effect on M90.
- M90 does not deteriorate even under long term operation in high temperature lubricating oil, except for some additives in high grade lubricants.
- With grease, M90 behaves the same as with oil lubricants. Gear designers interested in using this material should be aware of properties regarding individual chemicals. Plastic manufacturers' technical information manuals should be consulted prior to making gear design decisions.

18.3 Choice Of Pressure Angles And Modules

Pressure angles of 14.5º, 20º and 25º are used in plastic gears. The 20º pressure angle is usually preferred due to its stronger tooth shape and reduced undercutting compared to the 14.5º pressure angle system. The 25º pressure angle has the highest load-carrying ability, but is more sensitive to center distance variation and hence runs less quietly. The choice is dependent on the application.

The determination of the appropriate module or diametral pitch is a compromise between a number of different design requirements. A larger module is associated with larger and stronger teeth. For a given pitch diameter, however, this also means a smaller number of teeth with a correspondingly greater likelihood of undercut at very low number of teeth. Larger teeth are generally associated with more sliding than smaller teeth.

On the other side of the coin, smaller modules, which are associated with smaller teeth, tend to provide greater load sharing due to the compliance of plastic gears. However, a limiting condition would eventually be reached when mechanical interference occurs as a result of too much compliance. Smaller teeth are also more sensitive to tooth errors and may be more highly stressed.

A good procedure is probably to size the pinion first, since it is the more highly loaded member. It should be proportioned to support the required loads, but should not be overdesigned.

18.4 Strength Of Plastic Spur Gears

In the following text, main consideration will be given to Nylon MC901 and Duracon M90, However, the basic equations used are applicable to all other plastic materials if the appropriate values for the factors are applied.

18.4.1 Bending Strength of Spur Gears

Nylon MC901

The allowable tangential force F (kgf) at the pitch circle of a Nylon MC9O1 spur gear can be obtained from the Lewis formula.

$F = m y b \sigma_b K_V$ (kgf) (18-1)

where:
m = Module (mm)
y = Form factor at pitch point (see **Table 18-15**)
b = Teeth width (mm)
σ_b = Allowable bending stress (kgf/mm²) (see **Figure 18-1**)
K_V= Speed factor (see **Table 18-16**)

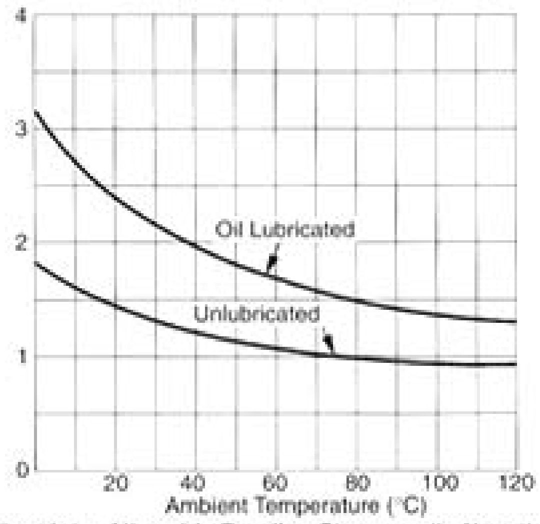

Fig. 18-1 Allowable Bending Stress, σ_b (kgf/mm²)

Table 18-15 Form Factor, y

Number of teeth	Form Factor		
	14.5º	**20ºStandardTooth**	**20ºStubTooth**
12	0.355	0.415	0.496
14	0.399	0.468	0.540
16	0.430	0.503	0.578
18	0.458	0.522	0.603
20	0.480	0.544	0.628
22	0.496	0.559	0.648
24	0.509	0.572	0.664
26	0.522	0.588	0.678
28	0.535	0.597	0.688
30	0.540	0.606	0.698
34	0.553	0.628	0.714
38	0.565	0.651	0.729
40	0.569	0.657	0.733
50	0.588	0.694	0.757
60	0.604	0.713	0.774
75	0.613	0.735	0.792
100	0.622	0.757	0.808
150	0.635	0.779	0.830
300	0.650	0.801	0.855
Rack	0.660	0.823	0.881

Table 18-16 Speed Factor, K_V

Lubrication	Tangential Speed (m/sec)	FactorK_V
Lubricated	Under 12	1.0
	Over 12	0.85
Unlubricated	Under 5	1.0
	Over 5	0.7

Duracon M90

The allowable tangential force F (kgf) at pitch circle of a Duracon M90 spur gear can also be obtained from the Lewis formula.

$F = m y b \sigma_b$ (kgf) (18-2)

where:
m = Module (mm)
y = Form factor at pitch point (see **Table 18-15**)
b = Teeth width (mm)
σ_b = Allowable bending stress (kgf/mm²)

The allowable bending stress can be calculated by **Equation (18-3)**:

$$\sigma_b = \sigma_b' \frac{K_V K_T K_L K_M}{C_S} \qquad (18\text{-}3)$$

where:
σ_b' = Maximum allowable bending stress under ideal condition (kgf/mm²) (see **Figure 18-2**)
C_S = Working factor (see **Table 18-17**)
K_V = Speed factor (see **Figure 18-3**)
K_T = Temperature factor (see **Figure 18-4**)
K_L = Lubrication factor (see **Table 18-18**)
K_M = Material factor (see **Table 18-19**)

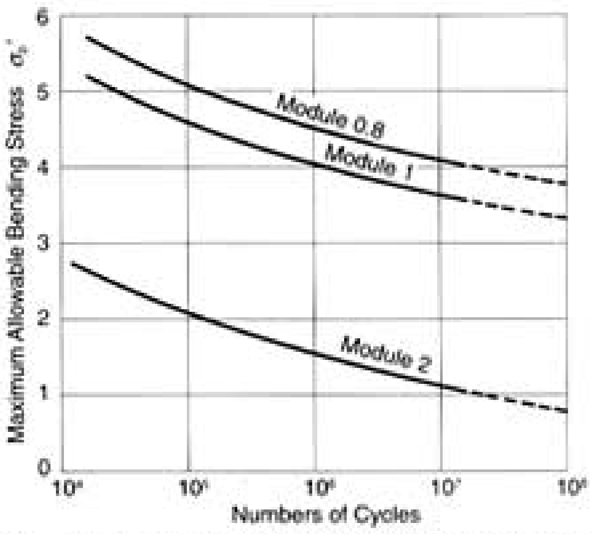

Fig. 18-2 Maximum Allowable Bending Stress under Ideal Condition, σ_b' (kgf/mm²)

Table 18-17 Working Factor, C_S

Types of Load	Daily Operating Hours			
	24 hrs./day	8-10 hrs./day	0.5 hrs./day	3 hrs./day
Uniform Load	1.25	1.00	0.80	0.50
Light Impact	1.50	1.25	1.00	0.80
Medium impact	1.75	1.50	1.25	1.00
Heavy Impact	2.00	1.75	1.50	1.25

Table 18-18 Lubrication Factor. KL

Lubrication	K_L
Initial Grease Lubrication	1
Continuous Oil Lubrication	1.5-3.0

Table 18-19 Material Factor, KM

Material Combination	K_M
Duracon vs. Metal	1
Duracon vs. Duracon	0.75

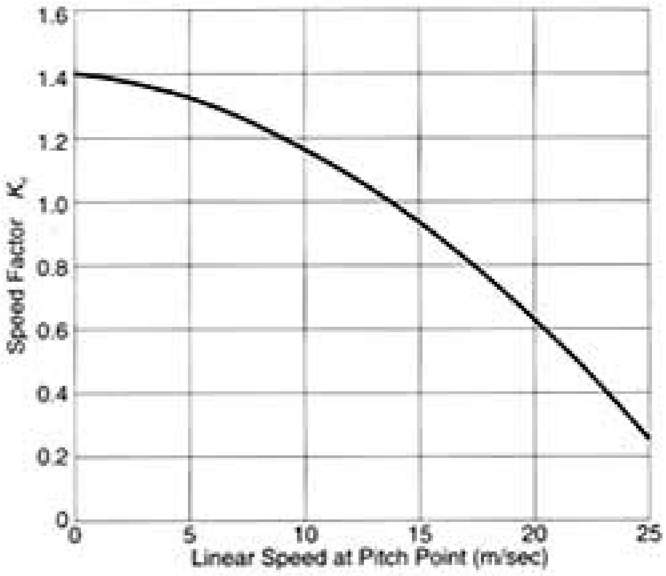

Fig. 18-3 Speed Factor, K_v

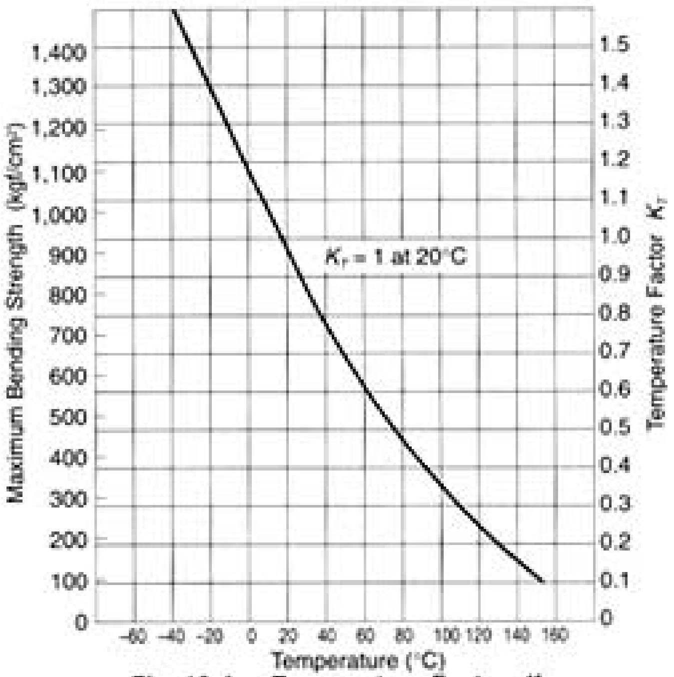

Fig. 18-4 Temperature Factor, K_T

Application Notes

In designing plastic gears, the effects of heat and moisture must be given careful consideration. The related problems are:

1. Backlash

Plastic gears have larger coefficients of thermal expansion. Also, they have an affinity to absorb moisture and swell. Good design requires allowance for a greater amount of backlash than for metal gears.

2. Lubrication

Most plastic gears do not require lubrication. However, temperature rise due to meshing may be controlled by the cooling effect of a lubricant as well as by reduction of friction. Often, in the case of high-speed rotational speeds, lubrication is critical.

3. Plastic gear with metal mate

If one of the gears of a mated pair is metal, there will be a heat sink that combats a high temperature rise. The effectiveness depends upon the particular metal, amount of metal mass, and rotational speed.

18.4.2 Surface Strength of Plastic Spur Gears

Duracon M90

Duracon gears have less friction and wear when in an oil lubrication condition. However, the calculation of strength must take into consideration a no-lubrication condition. The surface strength using Hertz contact stress, S_C, is calculated by **Equation (18-4)**.

$$S_c = \sqrt{\frac{F}{bd_1}\,\frac{u+1}{u}} \cdot \sqrt{\frac{1.4}{\left(\frac{1}{E_1}+\frac{1}{E_2}\right)\sin 2\alpha}} \quad (\text{kgf/mm}^2) \qquad \textbf{(18-4)}$$

where:
F = Tangential force on surface (kgf)
b = Tooth width (mm)
d_1 = Pitch diameter of pinion (mm)
u = Gear ratio $= z_2/z_1$
E = Modulus of elasticity of material (kgf/mm²) (see **Figure 18-5**)
α = Pressure angle

If the value of Hertz contact stress, S_C is calculated by **Equation (18-4)** and the value falls below the curve of **Figure 18-6**, then it is directly applicable as a safe design. If the calculated value falls above the curve, the Duracon gear is unsafe.

Figure 18-6 is based upon data for a pair of Duracon gears: m = 2, v = 12 m/s, and operating at room temperature. For working conditions that are similar or better, the values in the figure can be used.

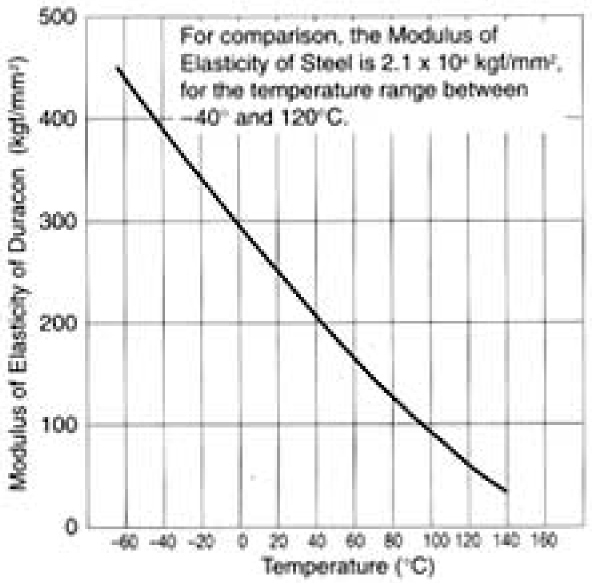

Fig. 18-5 Modulus of Elasticity in Bending of Duracon

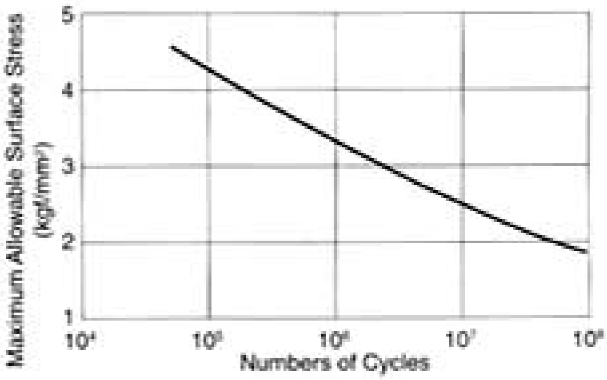

Fig. 18-6 Maximum Allowable Surface Stress (Spur Gears)

18.4.3 Bending Strength of Plastic Bevel Gears

Nylon MC901

The allowable tangential force at the pitch circle is calculated by **Equation (18-5)**.

$$F = m\frac{R_a - b}{R_a} yb\sigma_b K_v \qquad (18\text{-}5)$$

where:

y = Form factor at pitch point (by equivalent spur gear from **Table 18-15**)

$$z_v = \frac{z}{\cos\delta} \qquad (18\text{-}6)$$

where:

R_a = Outer cone distance

δ = Pitch cone angle (degree)

Z_V = Number of teeth of equivalent spur gear

Other variables may be calculated the same way as for spur gears.

Duracon M90

The allowable tangential force F(kgf) on pitch circle of Duracon M90 bevel gears can be obtained from **Equation (18-7)**.

$$F = m\frac{R_a - b}{R_a} yb\sigma_b \qquad (18\text{-}7)$$

where:

$$\sigma_b = \sigma_b' \cdot \frac{K_V K_T K_L K_M}{C_S}$$

and y = Form factor at pitch point, which is obtained from **Table 18-15** by computing the number of teeth of equivalent spur gear via **Equation (18-6)**.

Other variables are obtained by using the equations for Duracon spur gears.

18.4.4 Bending Strength of Plastic Worm Gears

Nylon MC901

Generally, the worm is much stronger than the worm gear. Therefore, it is necessary to calculate the strength of only the worm gear.

The allowable tangential force F (kgf) at the pitch circle of the worm gear is obtained from **Equation (18-8)**.

$F = m_n y b \sigma_b K_V$ (kgf) (18-8)

where: m_n = Normal module (mm)

y = Form factor at pitch point, which is obtained from Table 18-15 by first computing the number of teeth of equivalent spur gear using **Equation (18-9)**.

$$z_V = \frac{z}{\cos^3\gamma} \qquad (18\text{-}9)$$

Worm meshes have relatively high sliding velocities, which induces a high temperature rise. This causes a sharp decrease in strength and abnormal friction wear. This is particularly true of an all plastic mesh. Therefore, sliding speeds must be contained within recommendations of **Table 18-20**.

$$\text{Sliding speed } v_s = \frac{\pi d_1 n_1}{60000\cos\gamma} \quad \text{(m/s)}$$

Lubrication of plastic worms is vital, particularly under high load and continuous operation.

18.4.5 Strength of Plastic Keyway

Fastening of a plastic gear to the shaft is often done by means of a key and keyway. Then, the critical thing is the stress level imposed upon the keyway sides. This is calculated by **Equation (18-10)**.

$$\sigma = \frac{2T}{d\,l\,h} \quad (\text{kgf/cm}^2) \qquad (18\text{-}10)$$

where: σ = Pressure on the keyway sides(kgf/cm²)

T = Transmitted torque (kgf.m)

d = Diameter of shaft (cm)

ι = Effective length of keyway (cm)

h = Depth of keyway (cm)

The maximum allowable surface pressure of MC901 is 200 kgf/cm², and this must not be exceeded. Also, the keyways corner must have a suitable radius to avoid stress concentration. The distance from the root of the gear to the bottom of the keyway should be at least twice the tooth whole depth, h.

Keyways are not to be used when the following conditions exist:

- Excessive keyway stress
- High ambient temperature
- High impact
- Large outside diameter gears

When above conditions prevail, it is expedient to use a metallic hub in the gear. Then, a keyway may be cut in the metal hub.

A metallic hub can be fixed in the plastic gear by several methods:

- Press the metallic hub into the plastic gear, ensuring fastening with a knurl or screw.
- Screw fasten metal discs on each side of the plastic gear.
- Thermofuse the metal hub to the gear.

18.5 Effect Of Part Shrinkage On Plastic Gear Design

The nature of the part and the molding operation have a significant effect on the molded gear. From the design point of view, the most important effect is the shrinkage of the gear relative to the size of the mold cavity.

Gear shrinkage depends upon mold proportions, gear geometry, material, ambient temperature and time. Shrinkage is usually expressed in millimeters per millimeter. For example, if a plastic gear with a shrinkage rate of 0.022 mm/mm has a pitch diameter of 50 mm while in the mold, the pitch diameter after molding will be reduced by (50)(0.022) or 1.1 mm, arid becomes

Table 18-20 Material Combination and Limits of Sliding Speed

Material of Worm	Material of Worm Gear	Lubrication Condition	Sliding Speed
"MC" Nylon	"MC" Nylon	No Lubrication	Under 0.125 m/s
Steel	"MC" Nylon	No Lubrication	Under 1 m/s
Steel	"MC" Nylon	Initial Lubrication	Under 1.5 m/s
Steel	"MC" Nylon	Condition Lubrication	Under 2.5 m/s

48.9 mm after it leaves the mold.

Depending upon the material and the molding process, shrinkage rates ranging from about 0.001 mm/mm to 0.030 mm/mm occur in plastic gears (see Table 18-1 and Figure 18-7). Sometimes shrinkage rates are expressed as a percentage. For example, a shrinkage rate

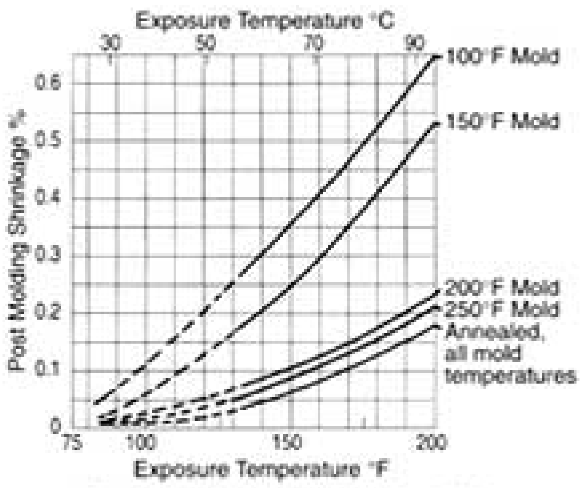

Fig. 18-7 Shrinkage for Delrin in Air
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of 0.0025 mm/mm can be stated as a 0.25% shrinkage rate.

The effect of shrinkage must be anticipated in the design of the mold and requires expert knowledge. Accurate and specific treatment of this phenomenon is a result of years of experience in building molds for gears; hence, details go beyond the scope of this presentation.

In general, the final size of a molded gear is a result of the following factors:

1. Plastic material being molded.
2. Injection pressure.
3. Injection temperature.
4. Injection hold time.
5. Mold cure time and mold temperature.
6. Configuration of part (presence of web, insert, spokes, ribs, etc.).
7. Location, number and size of gates.
8. Treatment of part after molding.

From the above, it becomes obvious that with the same mold - by changing molding parameters - parts of different sizes can be produced.

The form of the gear tooth itself changes as a result of shrinkage, irrespective of it shrinking away from the mold, as shown in Figure 18-8. The resulting gear will be too thin at the top and too thick at the

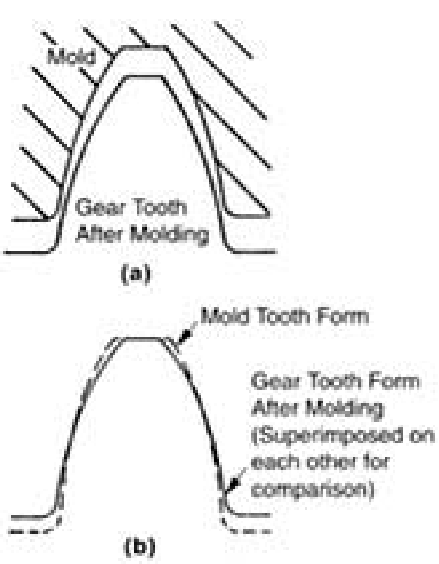


Fig. 18-8 Change of Tooth Profile

base. The pressure angle will have increased, resulting in the possibility of binding, as well as greater wear.

In order to obtain an idea of the effect of part shrinkage subsequent to molding, the following equations are presented where the primes refer to quantities after the shrinkage occurred:

$$\cos\alpha' = \frac{\cos\alpha}{1 + s^*} \qquad (18\text{-}11)$$

$$m' = (1 - s^*)m \qquad (18\text{-}12)$$

$$d' = zm' \qquad (18\text{-}13)$$

$$p' = \pi m' \qquad (18\text{-}14)$$

where: s^* = shrinkage rate (mm/mm)
m = module
a = pressure angle
d = pitch diameter (mm)
p' = circular pitch (mm)
z = number of teeth

It follows that a hob generating the electrode for a cavity which will produce a post shrinkage standard gear would need to be of a nonstandard configuration.

Let us assume that an electrode is cut for a 20° pressure angle, module 1, 64 tooth gear which will be made of acetal (s^* = 0.022) and will have 64 mm pitch diameter after molding.

$$\cos\alpha = \cos\alpha'(1 + s^*) = 0.93969262\ (1 + 0.022) = 0.96036$$

therefore, a = 16°11' pressure angle

$$m = \frac{m}{1 - s^*} = \frac{1}{1 - 0.022} = 1.0225$$

The pitch diameter of the electrode, therefore, will be:

$$d = zm = 64 \times 1.0225 = 65.44\text{mm}$$

For the sake of simplicity, we are ignoring the correction which has to be made to compensate for the electrode gap which results in the cavity being larger than the electrode.

The shrinking process can give rise to residual stresses within the gear, especially if it has sections of different thicknesses. For this reason, a hubless gear is less likely to be warped than a gear with a hub.

If necessary, a gear can be annealed after molding in order to relieve residual stresses. However, since this adds another operation in the manufacturing of the gear, annealing should be considered only under the following circumstances:

1. If maximum dimensional stability is essential.
2. If the stresses in the gear would otherwise exceed the design limit.
3. If close tolerances and high-temperature operation makes annealing necessary.

Annealing adds a small amount of lubricant within the gear surface region. If the prior gear lubrication is marginal, this can be helpful.

18.6 Proper Use Of Plastic Gears

18.6.1 Backlash

Due to the thermal expansion of plastic gears, which is significantly greater than that of metal gears, and the effects of tolerances, one should make sure that meshing gears do not bind in the course of service. Several means are available for introducing backlash into the system. Perhaps the simplest is to enlarge center distance. Care must be taken, however, to ensure that the contact ratio remains adequate.

It is possible also to thin out the tooth profile during manufacturing, but this adds to the manufacturing cost and requires careful consideration of the tooth geometry.

To some extent, the flexibility of the bearings and clearances can compensate for thermal expansion. If a small change in center distance is necessary and feasible, it probably represents the best and least expensive compromise.

18.6.2 Environmental and Tolerances

In any discussion of tolerances for plastic gears, it is necessary to distinguish between manufacturing conditions tolerances and dimensional changes due to environmental conditions.

As far as manufacturing is concerned, plastic gears can be made to high accuracy, if desired . For injection molded gears, Total Composite Error can readily be held within a range of roughly 0.075-0.125 mm, with a corresponding Tooth-to-Tooth Composite Error of about 0.025-0.050 mm. Higher accuracies can be obtained if the more expensive filled materials, mold design, tooling and quality control are used.

In addition to thermal expansion changes, there are permanent dimensional changes as the result of moisture absorption. Also, there are dimensional changes due to compliance under load. The coefficient of thermal expansion of plastics is on the order of four to ten times those of metals (see Tables 18-3 and 18-10). In addition, most plastics are hygroscopic (i.e., absorb moisture) and dimensional changes on the order of 0.1% or more can develop in the the course of time, if the humidity is sufficient. As a result, one should attempt to make sure that a tolerance which is specified is not smaller than the inevitable dimensional changes which arise as a result of environmental conditions. At the same time, the greater compliance of plastic gears, as compared to metal gears, suggests that the necessity for close tolerances need not always be as high as those required for metal gears.

18.6.3 Avoiding Stress Concentration

In order to minimize stress concentration and maximize the life of a plastic gear, the root fillet radius should be as large as possible, consistent with conjugate gear action. Sudden changes in cross section and sharp corners should be avoided, especially in view of the possibility of additional residual stresses which may have occurred in the course of the molding operation.

18.6.4 Metal Inserts

Injection molded metal inserts are used in plastic gears for a variety of reasons:

1. To avoid an extra finishing operation.
2. To achieve greater dimensional stability, because the metal will shrink less and is not sensitive to moisture; it is, also, a better heat sink.
3. To provide greater load-carrying capacity.
4. To provide increased rigidity.
5. To permit repeated assembly and disassembly.
6. To provide a more precise bore to shaft fit.

Inserts can be molded into the part or subsequently assembled. In the case of subsequent insertion of inserts, stress concentrations may be present which may lead to cracking of the parts. The interference limits for press fits must be obeyed depending on the material used; also, proper minimum wall thicknesses around the inserts must be left. The insertion of inserts may be accomplished by ultrasonically driving in the insert. In this case, the material actually melts into the knurling at the insert periphery.

Inserts are usually produced by screw machines and made of aluminum or brass. It is advantageous to attempt to match the coefficient of thermal expansion of the plastic to the materials used for inserts. This will reduce the residual stresses in the plastic part of the gear during contraction while cooling after molding.

When metal inserts are used, generous radii and fillets in the plastic gear are recommended to avoid stress concentration. It is also possible to use other types of metal inserts, such as self-threading, self-tapping screws, press fits and knurled inserts. One advantage of the first two of these is that they permit repeated assembly and disassembly without part failure or fatigue.

18.6.5 Attachment of Plastic Gears to Shafts

Several methods of attaching gears to shafts are in common use. These include splines, keys, integral shafts, set screws, and plain and knurled press fits. Table 18-21 lists some of the basic characteristics of each of these fastening methods.

18.6.6 Lubrication

Depending on the application, plastic gears can operate with continuous lubrication, initial lubrication, or no lubrication. According to L.D. Martin ("Injection Molded Plastic Gears", Plastic Design and Processing, 1968; Part 1, August, pp 38-45; Part 2, September, pp. 33-35):

1. All gears function more effectively with lubrication and will have a longer service life.
2. A light spindle oil (SAE 10) is generally recommended as are the usual lubricants; these include silicone and hydrocarbon oils, and in some cases cold water is acceptable as well.
3. Under certain conditions, dry lubricants such as molybdenum disulfide, can be used to reduce tooth friction.

Ample experience and evidence exist substantiating that plastic gears can operate with a metal mate without the need of a lubricant, as long as the stress levels are not exceeded. It is also true that in the case of a moderate stress level, relative to the materials rating, plastic gears can be meshed together without a lubricant. However, as the stress level is increased, there is a tendency for a localized plastic-to-plastic welding to occur, which increases friction and wear. The level of this problem varies with the particular type of plastic.

Table 18-21 Characteristics of Various Shaft Attachment Methods

Nature of Gear-shaft Connection	Torque Capacity	Cost	Disassembly	Comments
Set Screw	Limited	Low	Not good unless threaded metal insert is used	Questionable reliability, particularly under vibration or reversing drive
Press fit	Limited	Low	Not Possible	Residual stresses need to e considered
Knurled Shaft Connection	Fair	Low	Not possible	A permanent assembly
Spline	Good	High	Good	Suited for close tolerances
Key	Good	Reasonably Low	Good	Requires good fits
Integral Shaft	Good	Low	Not Possible	Bending load on shaft needs to be watched

A key advantage of plastic gearing is that, for many applications, running dry is adequate. When a situation of stress and shock level is uncertain, using the proper lubricant will provide a safety margin and certainly will cause no harm. The chief consideration should be in choosing a lubricants chemical compatibility with the particular plastic. Least likely to encounter problems with typical gear oils and greases are: nylons, Delrins (acetals), phenolics, polyethylene and polypropylene. Materials requiring caution are: polystyrene, polycarbonates, polyvinyl chloride and ABS resins.

An alternate to external lubrication is to use plastics fortified with a solid state lubricant. Molybdenum disulfide in nylon and acetal are commonly used. Also, graphite, colloidal carbon and silicone are used as fillers.

In no event should there be need of an elaborate sophisticated lubrication system such as for metal gearing, If such a system is contemplated, then the choice of plastic gearing is in question. Simplicity is the plastic gear's inherent feature.

18.6.7 Molded vs. Cut Plastic Gears

Although not nearly as common as the injection molding process, both thermosetting and thermoplastic plastic gears can be readily machined. The machining of plastic gears can be considered for high precision parts with close tolerances and for the development of prototypes for which the investment in a mold may not be justified.

Standard stock gears of reasonable precision are produced by using blanks molded with brass inserts, which are subsequently hobbed to close tolerances.

When to use molded gears vs. cut plastic gears is usually determined on the basis of production quantity, body features that may favor molding, quality level and unit cost. Often, the initial prototype quantity will be machine cut, and investment in molding tools is deferred until the product and market is assured. However, with some plastics this approach can encounter problems.

The performance of molded vs. cut plastic gears is not always identical. Differences occur due to subtle causes. Bar stock and molding stock may not be precisely the same. Molding temperature can have an effect. Also, surface finishes will be different for cut vs. molded gears. And finally, there is the impact of shrinkage with molding which may not have been adequately compensated.

18.6.8 Elimination of Gear Noise

Incomplete conjugate action and/or excessive backlash are usually the source of noise. Plastic molded gears are generally less accurate than their metal counterparts. Furthermore, due to the presence of a larger Total Composite Error, there is more backlash built into the gear train.

To avoid noise, more resilient material, such as urethane, can be used. Figure 18-9 shows several gears made of urethane which, in mesh with Delrin gears, produce a practically noiseless gear train. The face width of the urethane gears must be increased correspondingly to compensate for lower load carrying ability of this material.

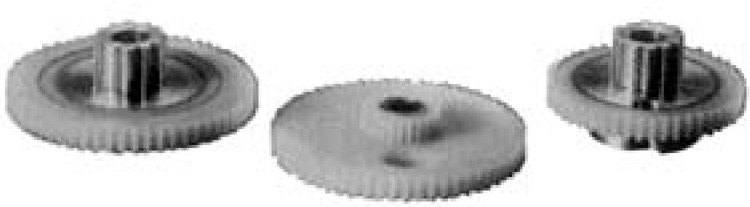


Fig. 18-9 Gears Made of Urethane

18.7 Mold Construction

Depending on the quantity of gears to be produced, a decision has to be made to make one single cavity or a multiplicity of identical cavities. If more than one cavity is involved, these are used as "family molds" inserted in mold bases which can accommodate a number of cavities for identical or different parts.

Since special terminology will be used, we shall first describe the elements shown in Figure 18-10.

1. Locating Ring is the element which assures the proper location of the mold on the platen with respect to the nozzle which injects the molten plastic.
2. Sprue Bushing is the element which mates with the nozzle. It has a spherical or flat receptacle which accurately mates with the surface of the nozzle.
3. Sprue is the channel in the sprue bushing through which the molten plastic is injected.
4. Runner is the channel which distributes material to different cavities within the same mold base.
5. Core Pin is the element which, by its presence, restricts the flow of plastic; hence, a hole or void will be created in the molded part.
6. Ejector Sleeves are operated by the molding machine. These have a relative motion with respect to the cavity in the direction which will cause ejection of the part from the mold.
7. Front Side is considered the side on which the sprue bushing and the nozzle are located.
8. Gate is the orifice through which the molten plastic enters the cavity.
9. Vent (not visible due to its small size) is a minuscule opening through which the air can be evacuated from the cavity as the molten plastic fills it. The vent is configured to let air escape, but does not fill up with plastic.

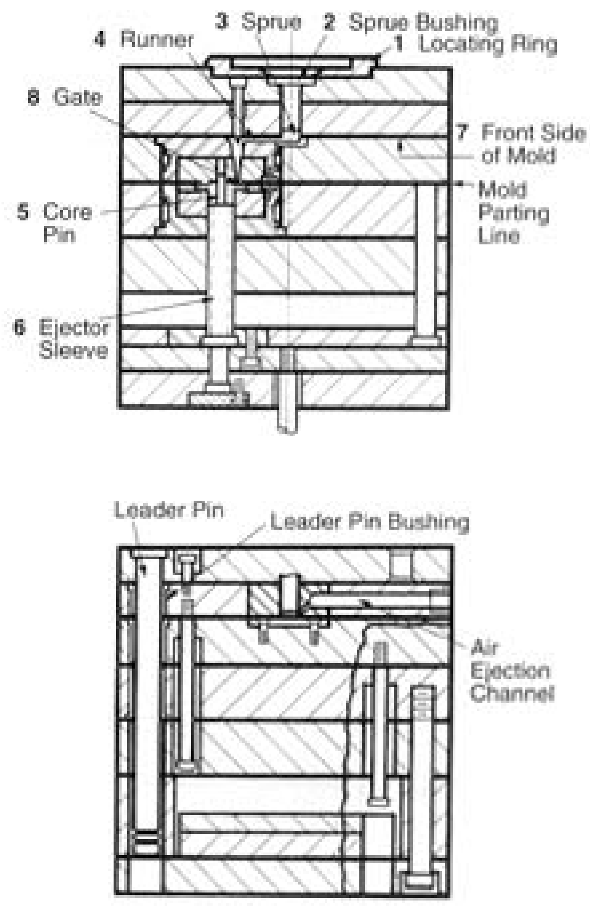


Fig. 18-10 Mold Nomenclature

The location of the gate on the gear is extremely important. If a side gate is used, as shown in Figure 18-11, the material is injected in one spot and from there it flows to fill out the cavity. This creates a weld line opposite to the gate. Since the plastic material is less fluid at that point in time, it will be of limited strength where the weld is located.

Furthermore, the shrinkage of the material in the direction of the flow will be different from that perpendicular to the flow. As a result, a side-gated gear or rotating part will be somewhat elliptical rather than round.

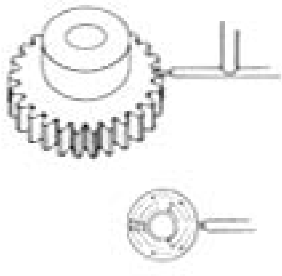


Fig. 18-11 Side Gating

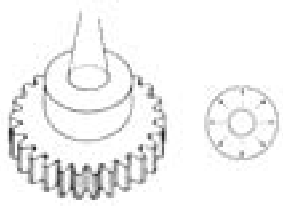


Fig. 18-12 Diaphragm Gating

In order to eliminate this problem, "diaphragm gating" can be used, which will cause the injection of material in all directions at the same time (Figure 18-12). The disadvantage of this method is the presence of a burr at the hub and no means of support of the core pin because of the presence of the sprue.

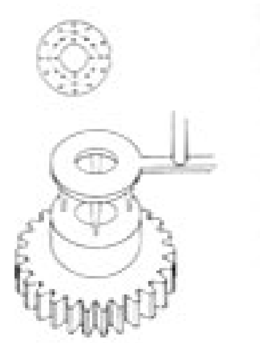
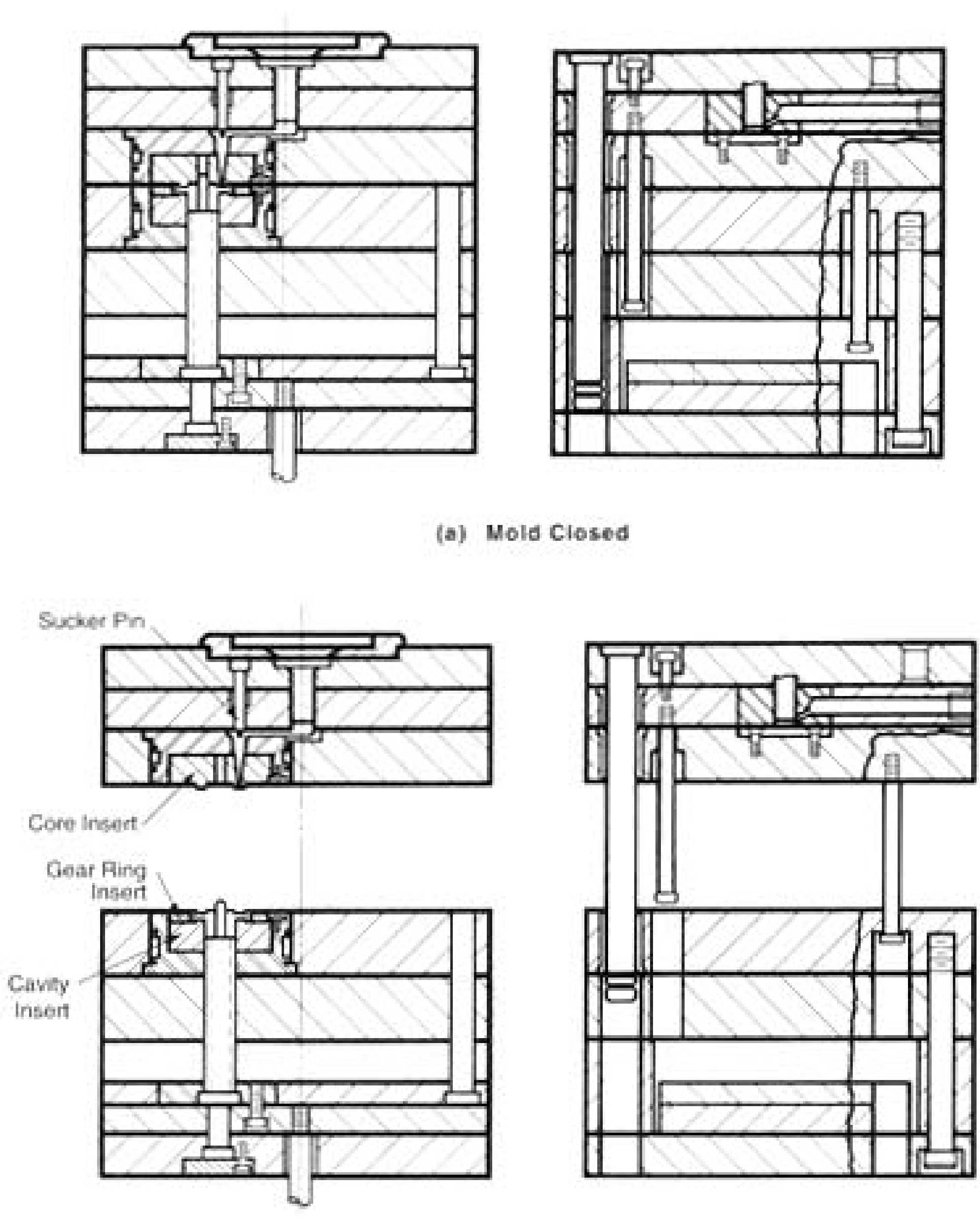


Fig. 18-13 Multiple Pin Gating

The best, but most elaborate, way is "multiple pin gating" (Figure 18-13). In this case, the plastic is injected at several places symmetrically located. This will assure reasonable viscosity of plastic when the material welds, as well as create uniform shrinkage in all directions.
The problem is the elaborate nature of the mold arrangement - so called 3-plate molds, in Figure 18-14 - accompanied by high costs. If precision is a requirement, this way of molding is a must, particularly if the gears are of a larger diameter.

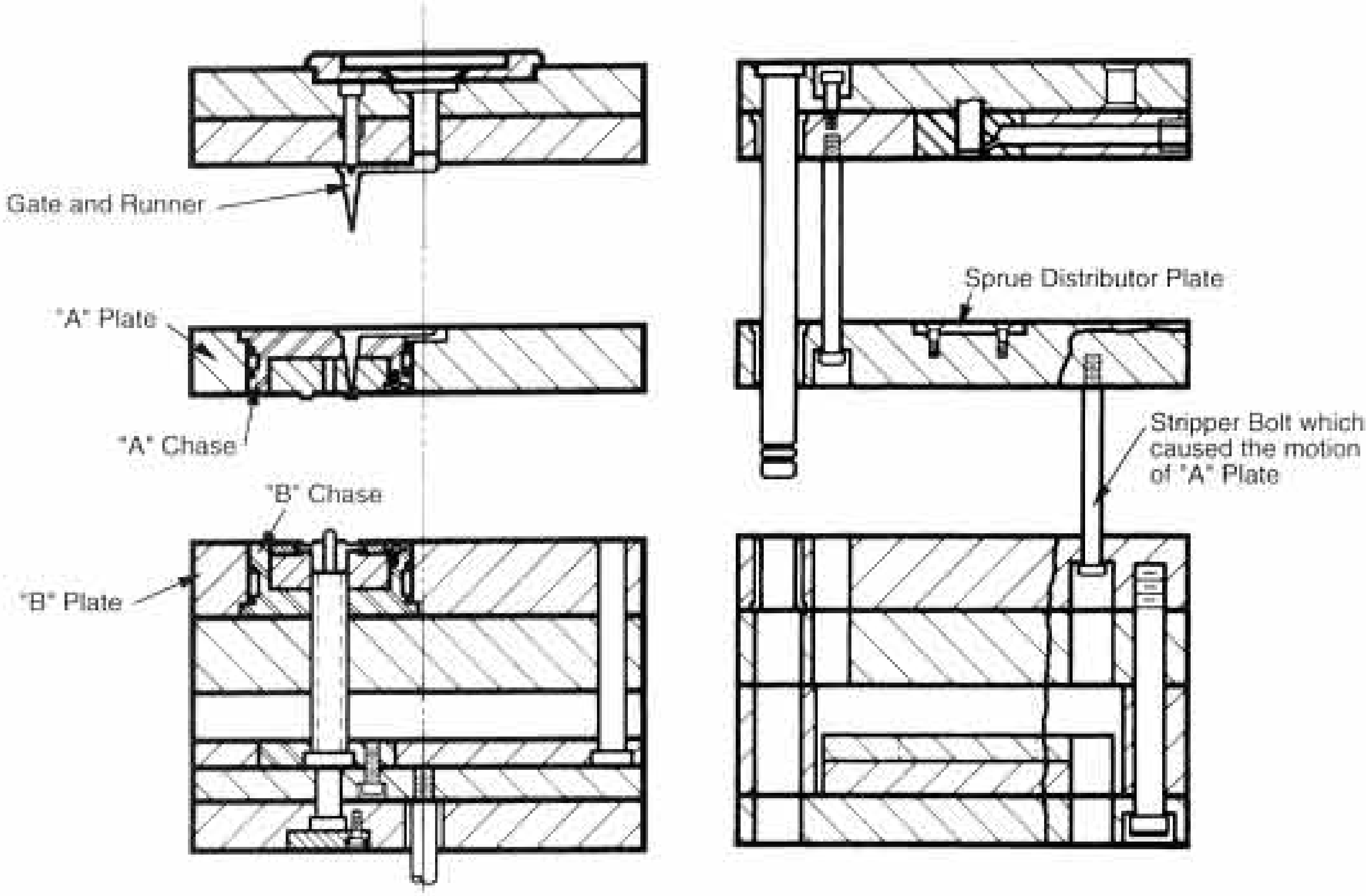
To compare the complexity of a 3-plate mold with a 2-plate mold, which is used for edge gating, Figure 18-15 can serve as an illustration.



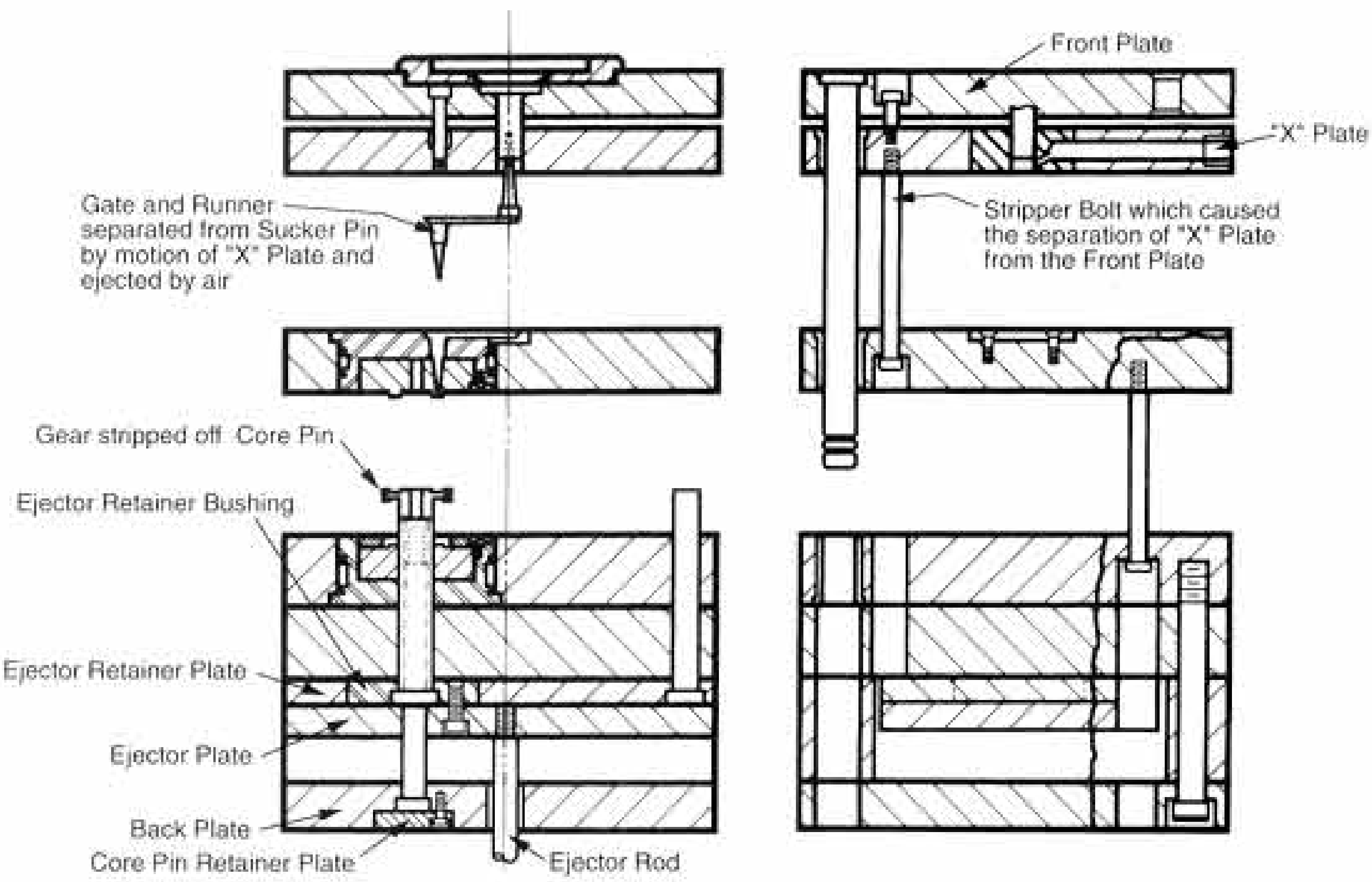
(a) Mold Closed

(b) Gates Separated from Molded Parts

Fig. 18-14 Three-Plate Mold

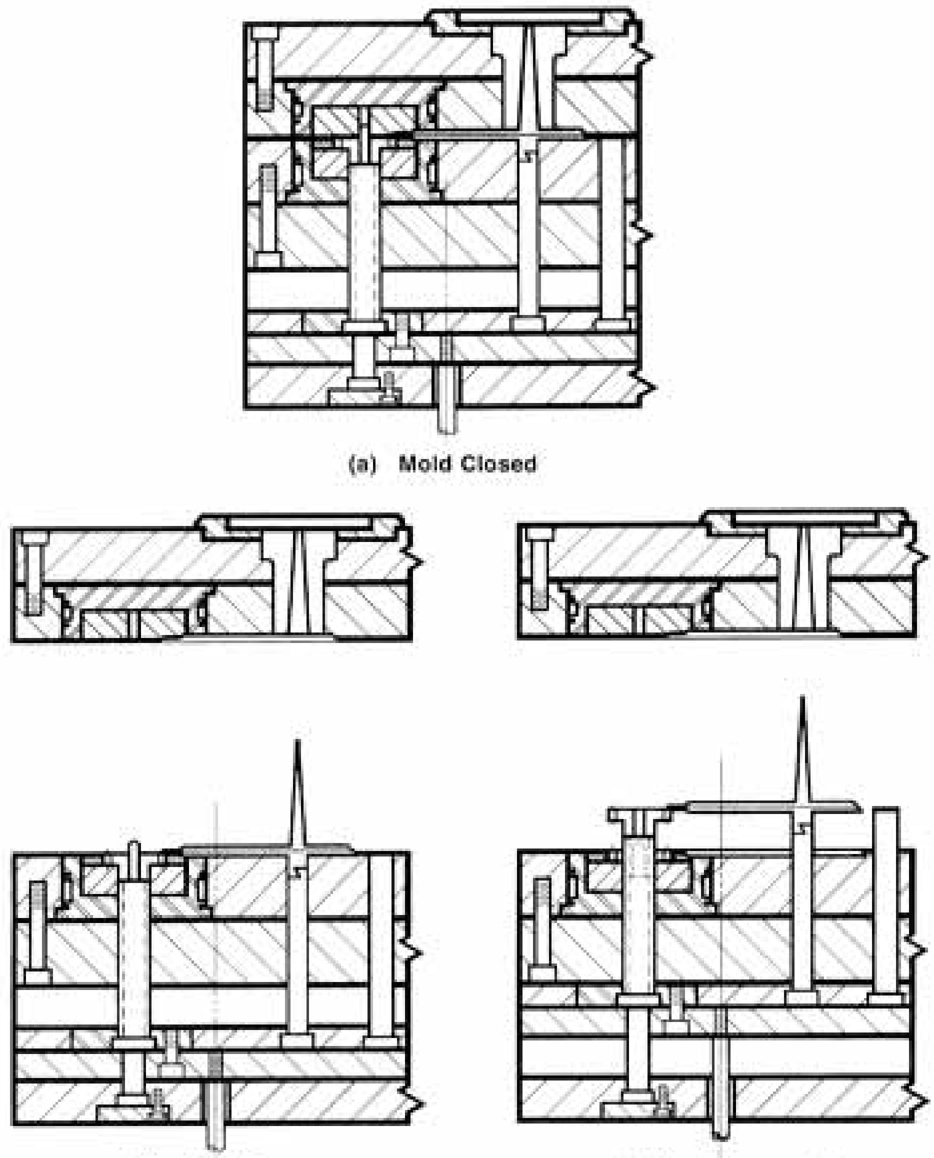


(c) Gate and Runner Exposed



(d) Mold Open

Fig. 18-14 (Cont.) Three-Plate Mold



(a) Mold Closed

(b) Mold Open

(c) Part, Runners & Sprue Ejected

Fig. 18-15 Two-Plate Mold

SECTION 19 FEATURES OF TOOTH SURFACE CONTACT

Tooth surface contact is critical to noise, vibration. efficiency, strength, wear and life. To obtain good contact, the designer must give proper consideration to the following features:

- Modifying the Tooth Shape
  Improve tooth contact by crowning or relieving.
- Using Higher Precision Gear
  Specify higher accuracy by design. Also, specify that the manufacturing process is to include grinding or lapping.
- Controlling the Accuracy of the Gear Assembly
  Specify adequate shaft parallelism and perpendicularity of the gear housing (box or structure).

Surface contact quality of spur and helical gears can be reasonably controlled and verified through piece part inspection. However, for the most part, bevel and worm gears cannot be equally well inspected. Consequently, final inspection of bevel and worm mesh tooth contact in assembly provides a quality criterion for control. Then, as required, gears can be axially adjusted to achieve desired contact.

JIS B 1741 classifies surface contact into three levels, as presented in Table 19-1.

The percentage in Table 19-1 considers only the effective width and height of teeth.

Table 19-1 Levels of Gear Surface Contact

Level	Types of Gear	Levels of Surface Contact	
		Tooth Width Direction	Tooth Height Direction
A	Cylindrical Gears	More than 70%	More than 40%
	Bevel Gears	More than 50%	
	Worm Gears		
B	Cylindrical Gears	More than 50%	More than 30%
	Bevel Gears	More than 35%	
	Worm Gears		
C	Cylindrical Gears	More than 35%	More than 20%
	Bevel Gears	More than 25%	
	Worm Gears	More than 20%	