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 of 0.0025 mm/mm can be stated as a 0.25% shrinkage rate.

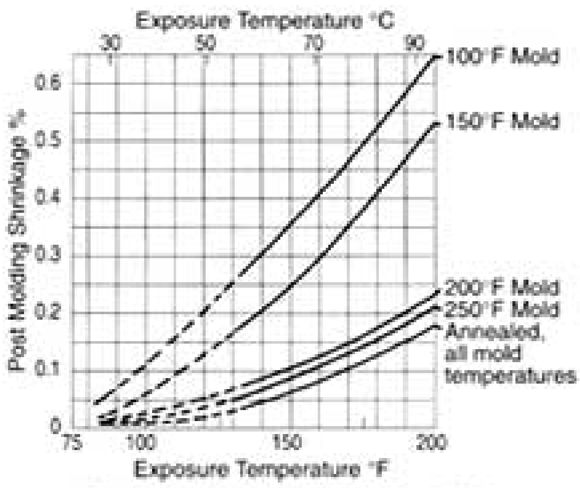

Fig. 18-7 Shrinkage for Delrin in Air
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The effect of shrinkage must be anticipated in the design of the mold and requires expert knowledge. Accurate and specific treatment of this phenomenon is a result of years of experience in building molds for gears; 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 base. The pressure angle will have increased, resulting in the possibility of binding, as well as greater wear.

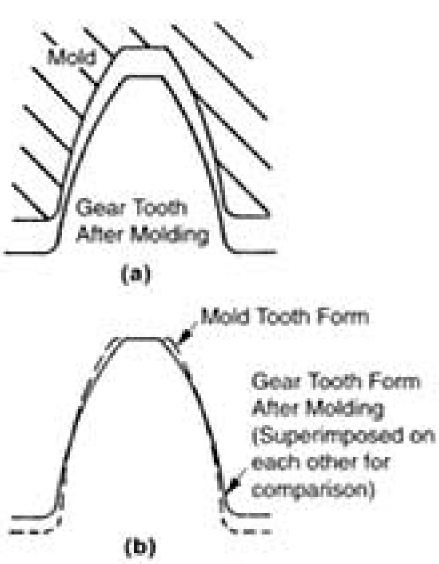


Fig. 18-8 Change of Tooth Profile

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.

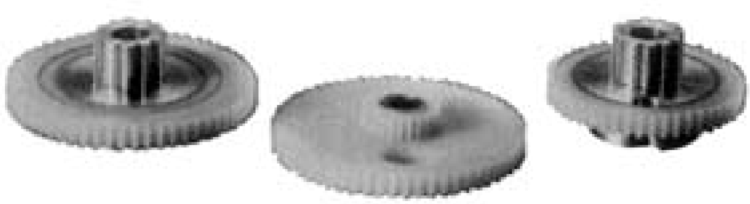


Fig. 18-9 Gears Made of Urethane

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.

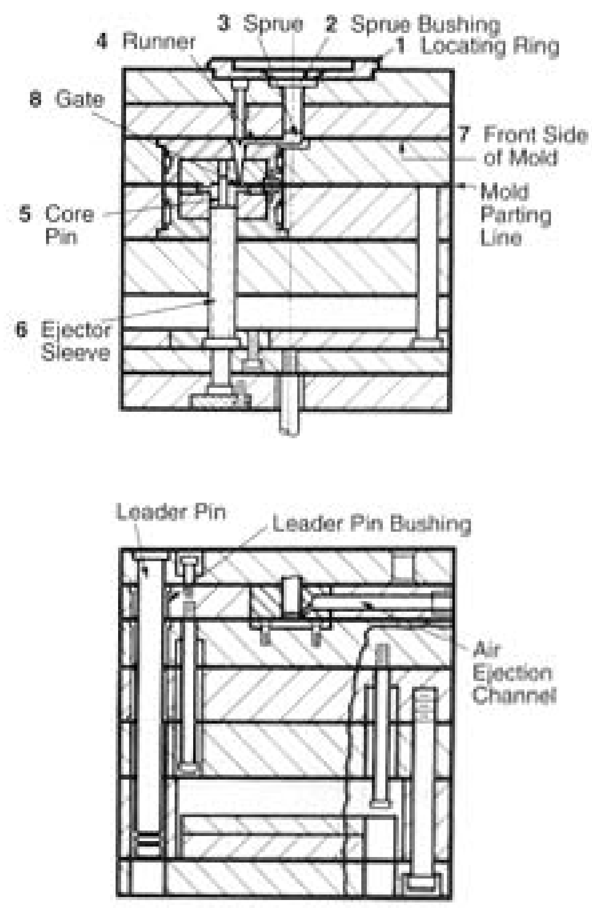


Fig. 18-10 Mold Nomenclature

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.

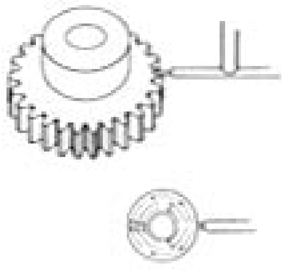


Fig. 18-11 Side Gating

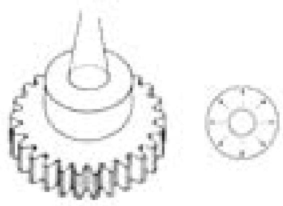


Fig. 18-12 Diaphragm Gating

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.

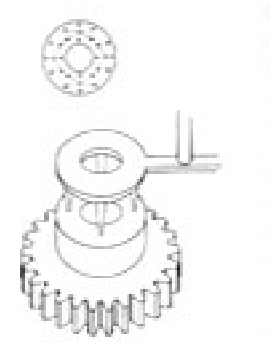
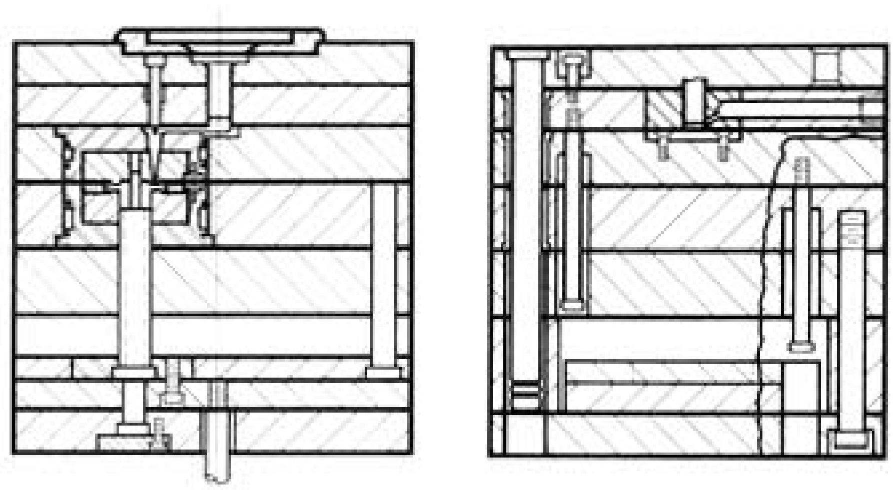


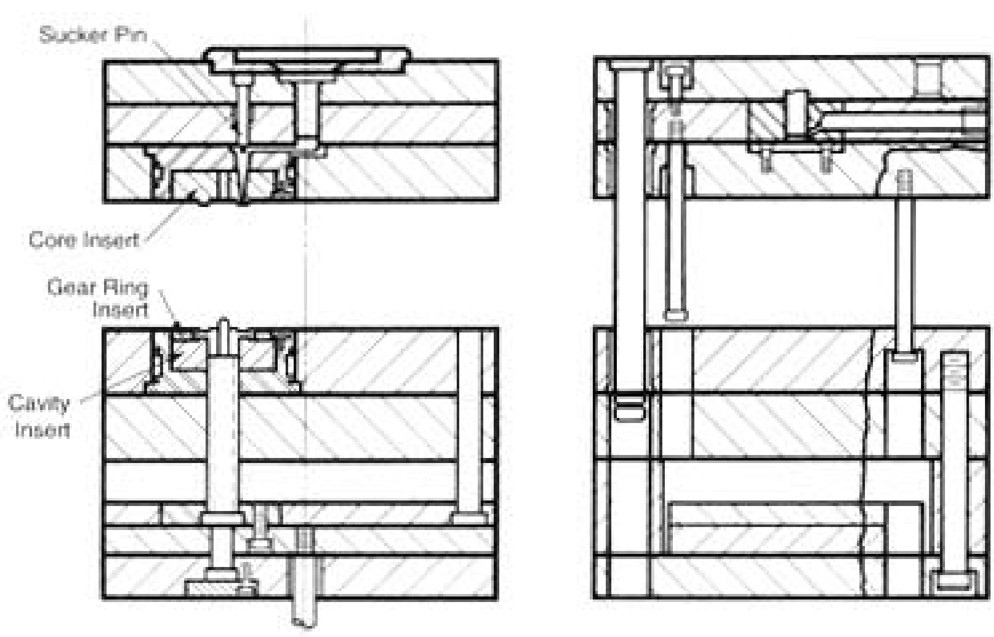
Fig. 18-13 Multiple Pin Gating

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.

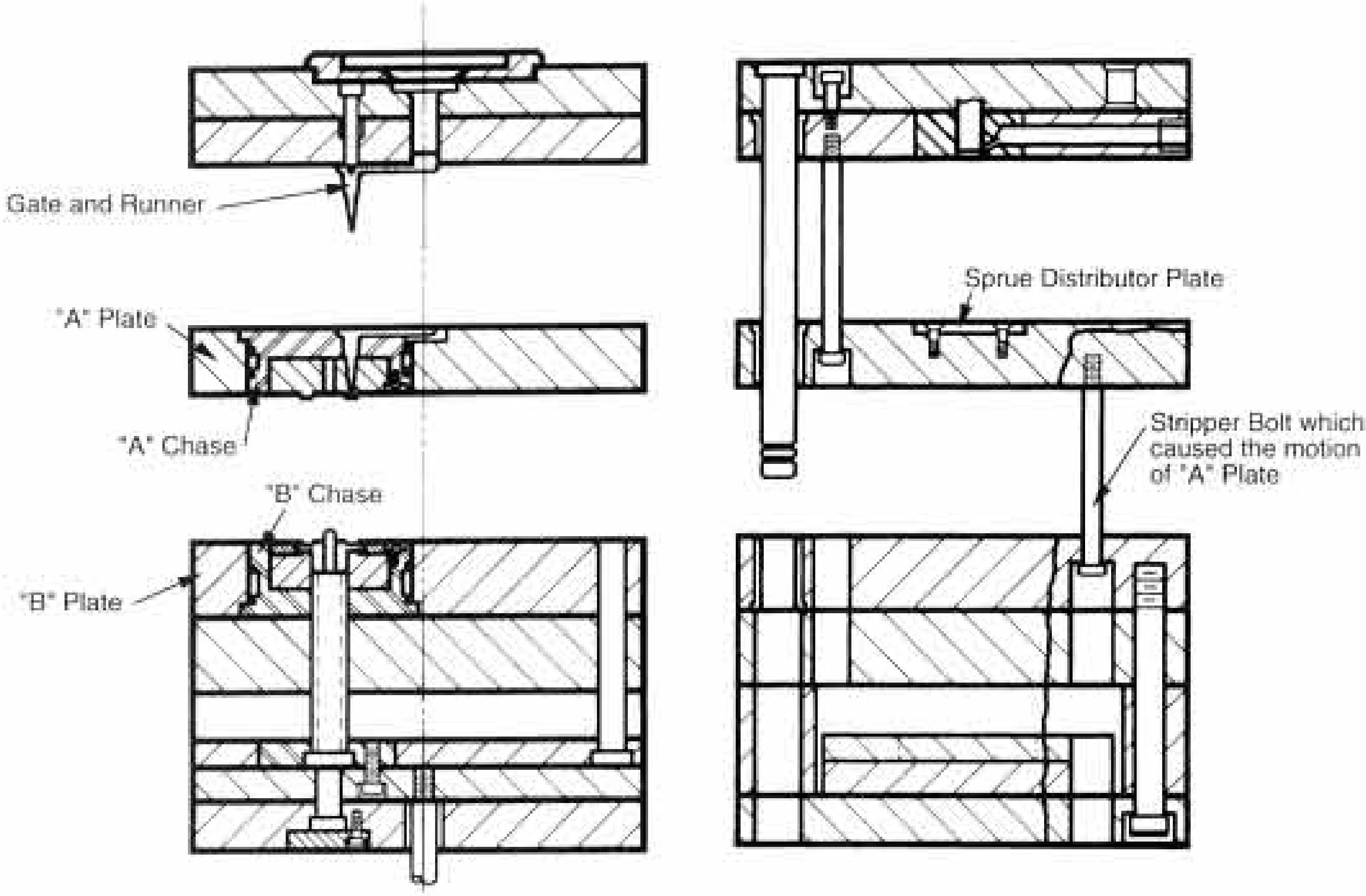


(a) Mold Closed

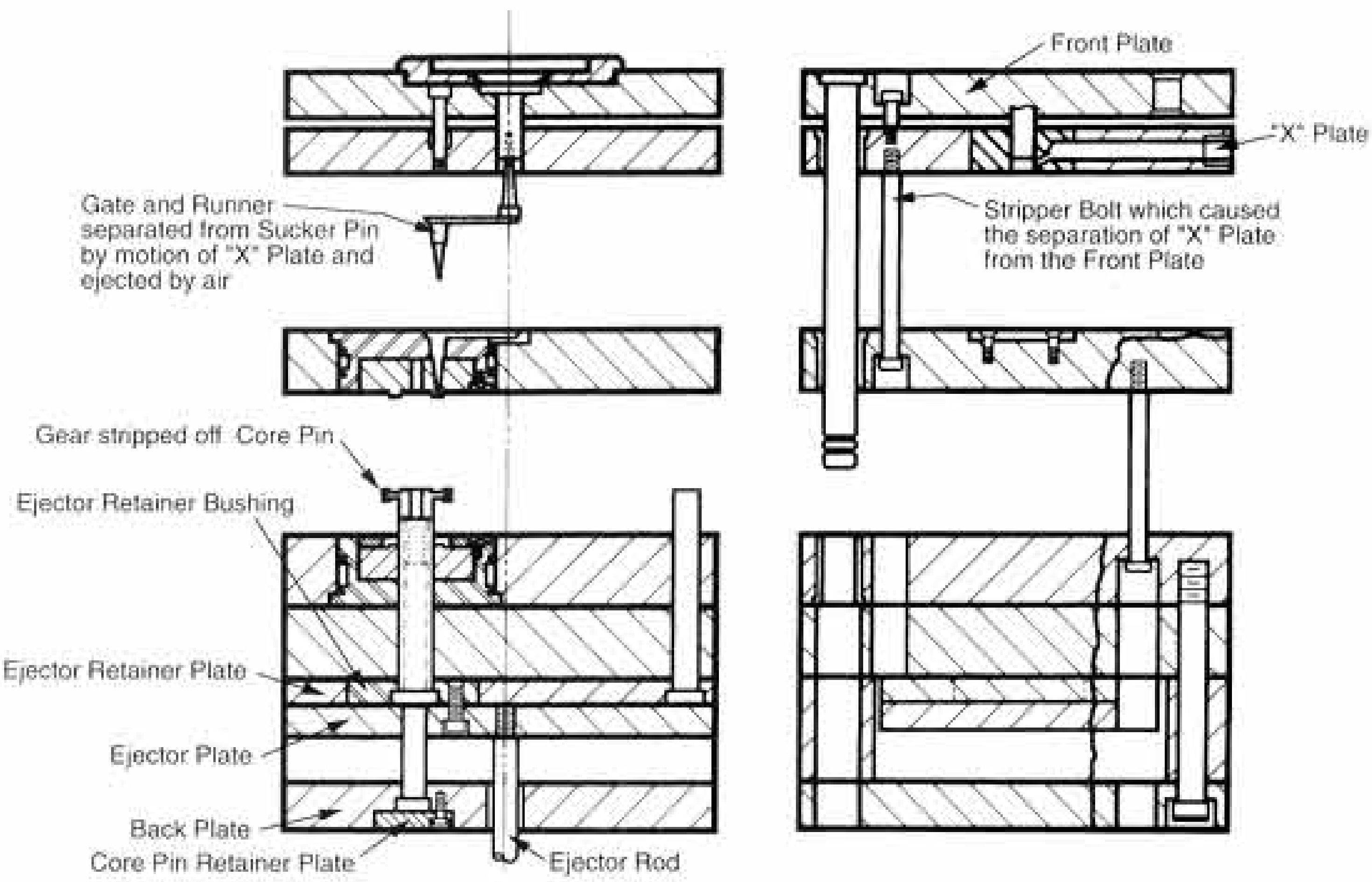


(b) Gates Separated from Molded Parts

Fig. 18-14 Three-Plate Mold



(c) Gate and Runner Exposed



(d) Mold Open

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