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Small Motor, Gearmotor and Control Handbook
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Electric motor design involves complex calculations that take into account the physical laws of magnetism and numerous empirical factors in order to arrive at an optimal combination of materials for use in motor construction. A given motor design is expected to deliver a range of specified output torques and speeds while operating within various physical, environmental and cost constraints. Since the output of the motor is determined by the characteristics of its magnetic circuits, the magnetic materials used in its construction are of primary importance.

5.1 MAGNETIC MATERIALS AND MOTOR DESIGN

Electric machines are designed to convert electrical energy into mechanical energy to perform work. The force necessary to do this work is typically derived from two or more magnetic fields set in opposition to each other. The strength of these opposing fields relative to each other determines the turning force or torque produced.

In Chapter 3 (Fig. 3-1c), we learned that if a current-carrying conductor loop is suspended in an air gap at a right angle to a magnetic field, and current flows in one end and out the other, the forces that result generate a torque. Since the force is partially dependent on flux density, a change in the permeability of the material used in the field and armature core can alter motor performance.

Practical motor design requires that strong magnetic fields be produced and distributed in a precise fashion across an air gap which allows the movement of one member relative to the other (Fig. 5-1). While current flowing through isolated conductors will produce a magnetic field, the additional heat generated by the increased current density needed to produce useful flux levels results in practical limitations. The most effective way to produce magnetic fields 15 to 20 times as strong as that generated by conductors alone is to surround them with a ferromagnetic material.
Electric motors may contain either a stationary field or a rotating field. The actual configuration depends on several factors: the supplied current (AC or DC), the type of commutation (mechanical or electronic), and the source of the field and armature flux (wound field or permanent magnet).

In electric motors, magnetic materials are used in three ways:

1) to form the core around which electrical conductors are wound,
2) to replace the coil structure as the source of the magnetic field, and
3) to assist the return of magnetic flux to its source.

Suitability for these tasks depends on whether the material qualifies as “hard” or “soft.” Soft magnetic materials, such as iron, nickel-iron and silicon steels, magnetize and demagnetize easily with very little energy loss when cycled. Soft materials make excellent cores and flux return rings.

Hard magnetic materials, such as ferrite, alnico and samarium cobalt, require more energy to magnetize and demagnetize. Hard materials (also called permanent magnets) are used to replace wound coils in many applications.

Motor designs must take into account all of the practical behaviors of magnetic materials. In addition to the hysteresis losses described in Section 1.2 (Basic Magnetism), alternating and cyclic magnetization found in AC and DC motors and gearmotors produces an unwanted by-product called “eddy current effect” which can seriously impair the performance of medium and high speed motors.

Eddy currents are induced in the core material itself and flow in a direction that counteracts the primary flux change in the core. To counteract this effect, the core material can be divided into equal slices (laminations), bonded together and electrically insulated from one another as shown in Fig. 5-2. When divided into laminations, the flux in each represents only a portion of the total and the maximum induced voltage is correspondingly reduced. The greater the number of laminations, the lower the voltage and corresponding losses. Eddy current loss becomes more significant in high speed and high frequency applications, since the eddy loss is found to increase in proportion to the square of the frequency of the cyclic flux. Laminations, materials selection and techniques which increase the resistance of the eddy current path all help reduce eddy current loss.

New magnetic materials offer opportunities for more efficient motor design that seemed unthinkable a decade ago. Neody-
mium-ironboron and other alloys promise magnets that are five times stronger than common ferrite magnets. Amorphous soft magnetic alloy ribbons can reduce core losses by as much as 70% when substituted for silicon steel laminations. While both soft and hard materials deliver a magnetic flux to the air gap, the effects which govern the behavior of each type of material make it practical to treat each separately.

**Soft Magnetic Materials**

Soft magnetic materials (iron, nickel-iron and silicon steels) are very easy to magnetize and demagnetize, a characteristic which makes them ideal for use in brush-type armature and field cores as well as induction rotors and stators. Soft magnetic materials may also be used as structural elements or enclosures that either carry flux between the source and load or act as shielding.

When specifying soft magnetic materials in motor design, factors such as mechanical strength, machinability, corrosion resistance, hysteresis loss, eddy current loss, permeability and the impact on magnetic properties of stamping or forming operations must be considered.

Figure 5-3 shows a comparison of the hysteresis loops for three common soft magnetic materials. Soft iron (Fig. 5-3a) provides low hysteresis loss (the area within the loop) with relatively high flux-conducting capability (permeability). Hard steel (Fig. 5-3b) exhibits higher hysteresis loss, but somewhat lower maximum permeability. Soft ferrites (Fig. 5-3c) have lower saturation and lower permeability, but can be magnetized and demagnetized very quickly, which makes them excellent for use in equipment requiring quick response time such as computer peripherals. Figure 5-4 shows a further comparison of soft magnetic materials.

**Low Carbon Iron:** The popularity of low carbon iron as a core material can be explained by its combination of very high permeability, low coercive force, low hysteresis loss, high saturation and low cost. The maximum permeability of low carbon iron ranges from 2 to 7.5 kilogauss per oersted (kG/Oe). The low carbon level, however, reduces the material's strength.
and toughness. Iron cores are used primarily in the manufacture of relays.

**Iron-Silicon Alloys:** Iron-silicon alloys (silicon steels) contain nominally 1, 2.5 and 4% silicon. They were developed to enhance both mechanical strength and magnetic properties, and have been the most common soft materials used in motor core laminations. The trend is to minimize the amount of iron-silicon used because of cost. Many motor cores are produced using cold rolled electrical steel with less than 0.15% iron-silicon content. These materials can also be optimized for maximum permeability and minimum core losses by hot rolling, annealing and cooling them rapidly. Oriented four percent silicon steels may reach a maximum permeability of 55 kG/Oe.

**Amorphous Alloys:** Produced by cooling molten metals before they can form crystalline structures, these glass-like materials combine ease of magnetization with high strength and low melting points. Amorphous materials may provide up to 70% reductions in core loss with significant improvements in efficiency. In spite of their many advantages, these materials exhibit much higher hardness (brittleness) than silicon steels and may require radically different motor lubrication techniques to be used. Their characteristic brittleness when annealed also makes them difficult to machine.

**Soft Ferrites:** The most common ceramic soft magnetic materials are made from sintering the powders of iron oxides, manganese, zinc and also nickel, cobalt and cadmium. Ferrites may reach a maximum permeability of 600 kG / Oe.

**Hard Magnetic Materials**

Since permanent magnets provide the magnetic flux for either the rotating or stationary member of a permanent magnet motor, they must provide a sufficiently high flux density to satisfy machine requirements. In addition, they must retain this flux in the presence of a demagnetizing field at reasonably high operating temperatures.

Hard materials typically depend on cobalt as an alloying element. Higher concentrations provide both a high energy product (B x H) and high Curie temperature at which a material loses its magnetic properties). With the introduction of high energy rare earth products and neodymium-iron-boron alloys, significant savings in motor size and weight may offset the higher cost of these materials. Figure 5-5 shows a comparison of hard magnetic materials.

**Magnetic Steels:** Cobalt steel (36% cobalt, 3 to 5% chromium, 3% tungsten, 0.85% carbon) is easily magnetized and demagnetized. The addition of cobalt...
significantly increases both coercivity and the available energy product. Cobalt steels are not commonly used due to their expense, lack of a domestic source of cobalt, and their tendency to react to strong demagnetizing fields.

**Aluminum-Nickel-Cobalt-Iron Alloys (Alnico):** Alloys of Al, Ni, Co, Cu, Fe and Ti, alnico magnets are formed either by powdered metal processes or by casting. Alnico (alcomax in England) materials must be cooled at a controlled rate in a strong magnetic field to develop their outstanding magnetic qualities. These materials have a high flux density and are relatively easy to magnetize and demagnetize. Alnico is thermally stable and may be used at high temperatures. However, it tends to be extremely brittle and difficult to machine. Alnico is used extensively in stepper motors and other applications requiring a high performance coefficient (strength of the magnetic field vs. breadth of the air gap between magnetic poles).

**Rare Earth-Cobalt Alloys:** Like many newer magnetic materials, rare earth magnets are produced with powdered metallurgy techniques. Alloys of cobalt and samarium, lanthanum, yttrium, cerium and praseodymium provide excellent magnetic qualities and temperature stability. A very high energy product allows for compact magnet structures, excellent resistance to demagnetization and good temperature stability. Typically bonded to rotor structures in brushless motors, these materials are extremely costly even in small quantities.

**Neodymium-Iron-Boron (NdFeB):** Instabilities in the supply of cobalt have led researchers to substitute neodymium in order to obtain an alloy element which is both readily available and provides the high coercivity of the rare earth-cobalt magnets. Produced by quenching molten alloy on the edge of a rotating substrate disk, NdFeB alloys produce an energy product as high as 40 MGOe with a coercivity of 15 kOe. Although they promise to be important new materials in magnet design, neodymium alloys have relatively low Curie temperatures. With the addition of small amounts (6%) of cobalt, Curie temperatures can be raised to safe levels.

**Ferrites:** With more than 40% of the market for magnetic materials, ceramic ferrites are the mature entry in the magnet field. Developed after World War II, these

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy Product (MGOe)</th>
<th>Coercive Force (Oe)</th>
<th>Remanence (G)</th>
<th>$\text{ Cost Per Lb.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Steels</td>
<td>0.1</td>
<td>50</td>
<td>10,000</td>
<td>3.00</td>
</tr>
<tr>
<td>Alnico</td>
<td>2 - 10</td>
<td>600 - 2,000</td>
<td>6,000-13,000</td>
<td>12.00</td>
</tr>
<tr>
<td>Ferrites</td>
<td>3 - 5</td>
<td>1,600 - 2,400</td>
<td>2,000 - 4,000</td>
<td>1.40</td>
</tr>
<tr>
<td>Samarium-Cobalt</td>
<td>14 - 30</td>
<td>7,000 - 9,000</td>
<td>7,500 - 11,000</td>
<td>90.00-160.00</td>
</tr>
<tr>
<td>Neodymium</td>
<td>26 - 40</td>
<td>9,000 - 15,000</td>
<td>10,000-13,000</td>
<td>90.00-115.00</td>
</tr>
</tbody>
</table>

*Fig. 5-5: Comparison of hard magnetic materials.*
nonmetallic oxides of iron and other metals are pressed in powder form to the shape and size required, and are then heat-treated at temperatures between 1000°C and 1300°C. They are readily available and inexpensive, exhibit high resistivity to demagnetization and show full magnetic stability at greatest maximum field strength.

5.2 BEARINGS

In order to meet the often severe conditions of operation, a motor or gearmotor must be equipped with correct bearings. Since metal-to-metal contact during rotation causes friction and heat, the type of bearings used in a drive unit plays an essential role in the life and effectiveness of any driven machine.

Among the many considerations which affect the choice of bearings are: speed requirements, temperature limits, lubrication, load capacity, noise and vibration, tolerance, space and weight limitations, end thrust, corrosion resistance, infiltration of dirt or dust, and of course, cost. Because of the many factors which enter into bearing selection, it is evident that one bearing design cannot possibly meet all criteria and the choice must represent the most desirable compromise.

There are two principle types of bearing supports used in fractional horsepower motors: sleeve (journal) and ball. Gearheads use sleeve, ball, tapered roller, needle thrust and drawn-cup full-complement needle bearings. Figure 5-6 shows a representative sample of bearing types. In addition, the table in Fig. 5-7 outlines the characteristics of ball and sleeve bearings.

**Sleeve (Journal) Bearings:**
Sleeve or journal bearings are the simplest in construction and therefore, the most widely used bearing when low initial cost is a factor. They are quiet in operation, have fair radial load capacity, and may be used over a fairly wide temperature range. Sleeve bearings also have virtually unlimited storage life if the motor is to remain unused for extended periods. They show good resistance to humidity, mild dirt infiltration and corrosion (when made of bronze). Under light loads, static friction of sleeve bearings is nearly as low as grease-packed ball bearings (although it is higher than oil-lubricated ball bearings).

The principle disadvantages of sleeve bearings are their need for relubrication and size. They are, by necessity, longer than ball types, and in general, add something to the overall length of the motor. **Sleeve bearings cannot be allowed to run dry.** An oil reservoir (or felt or similar oil-retaining material) must also be incorporated into the end shield and the lubricating oil periodically replenished.

A variation of the ordinary sleeve bearing, the graphited self-lubricating bearing, is made of solid bronze, with graphite-filled inner recesses (often in the shape of two figure eights). It may also employ graphite-filled holes to conduct oil between the reservoir and the inner bearing surface. The bronze body of such bearings provides strength and resistance to shock or vibration, while the presence of graphite helps to form a lubricating film on the bearing...
The graphite in the bearing will also act as an emergency lubricant if the oil level is allowed to run low. It should be noted, however, that it is not safe to depend on the graphite and allow the motor to run dry. Graphited bearings will also usually withstand higher operating temperatures than ordinary sleeve bearings.

Oil-lubricated motors or gearmotors should not be mounted in a vertical shaft configuration except for right angle gearmotors designed for this purpose. When the oil reservoir is mounted above the motor, gravity may cause oil leakage into windings, causing subsequent motor failure and hazards to personnel. Although generally specified for radial loads, sleeve bearings can also be designed to cope with thrust loads or angle mounting. For this purpose, they may be supplied in the flange or “spool” configuration. In place of the

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Sleeve Bearing</th>
<th>Ball Bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load:</strong></td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Unidirectional</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Cyclic</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Starting and Stopping</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Unbalanced</td>
<td>Fair</td>
<td>Excellent</td>
</tr>
<tr>
<td>Shock</td>
<td>Fair</td>
<td>Excellent</td>
</tr>
<tr>
<td>Thrust</td>
<td>Fair</td>
<td>Excellent</td>
</tr>
<tr>
<td>Overhung</td>
<td></td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>Speed Limited by:</strong></td>
<td>Turbulence of oil. Usual limit 5000 RPM max.</td>
<td>20,000 RPM max.</td>
</tr>
<tr>
<td><strong>Misalignment Tolerance</strong></td>
<td>Poor (unless of the self-alignment type)</td>
<td>Fair</td>
</tr>
<tr>
<td><strong>Starting Friction</strong></td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Space Requirements:</strong></td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>Radial</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Axial</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Damping of Vibration</strong></td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td><strong>Type of Lubrication</strong></td>
<td>Oil</td>
<td>Oil or Grease</td>
</tr>
<tr>
<td><strong>Quantity of Lubricant</strong></td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>Quiet</td>
<td>Depends upon quality of bearing and resonances of mounting.</td>
</tr>
<tr>
<td><strong>Low Temperature Starting</strong></td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td><strong>High Temperature Operation</strong></td>
<td>Limited by lubricant</td>
<td>Limited by lubricant</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>Periodic relubrication</td>
<td>Occasional relubrication. Greased bearings often last the life of the application without attention.</td>
</tr>
</tbody>
</table>

**Fig. 5-7: Comparison of ball and sleeve bearing characteristics.**
flange, thrust forces may also be accommodated by a hardened steel ball and disc at the end of the shaft (which can also be adjusted to control lengthwise shaft play and heavy thrusts with low friction).

Another type of self-lubricating sleeve bearing is constructed from porous bronze. The porous bronze sleeve bearing is oil-impregnated and can be used with a felt washer around its periphery to hold additional oil in suspension (eliminating the need for frequent relubrication).

Porous bronze bearings are more compact and offer more freedom from attention than solid bronze bearings. Their porous feature is achieved by powder metal fabricating techniques. Porous bronze bearings are often constructed to be self-aligning, and to reduce friction and shaft binding. The porous bearing is generally more economical than the graphited or solid bronze types and given proper design, will carry loads as well.

**Ball Bearings:** Ball bearings can be used for virtually all types and sizes of electric motors. They exhibit low friction loss (especially when oil-lubricated), are suited for high speed operation, and can be used for relatively wide ranges of temperatures. Ball bearings can also accommodate thrust loads, and permit end play to be conveniently minimized. Compared to sleeve bearings, ball bearings require significantly less maintenance (especially if grease-packed).

On the other hand, ball bearings are slightly more expensive. Due to the nature of the rolling action, they will also tend to be noisier than their sleeve bearing counterparts. Ball bearing manufacturers have developed special processing techniques for ball bearings used in electric motors. As a result, the difference in noise levels of sleeve and ball bearings has become minimal.

Since they are made of steel, ball bearings are more susceptible to rust. However, moisture access to the ball bearings can be precluded by proper design techniques. Grease-packed ball bearings may also have a limited storage life (motors which have been kept in storage for some time or exposed to low temperatures may show a tightening of the shaft due to lubricant hardening). This factor may require that sleeve bearings be chosen over otherwise more suitable ball bearings in some instances. In some cases, simply giving the motor some warm-up time will “rejuvenate” the ball bearing grease to a suitable condition. In recent years, greases which have long storage life have also been developed, but this advantage has been gained at the expense of limiting the rating at low temperatures.

**Needle Bearings:** In many gearheads, full-complement drawn-cup needle bearings may be used as supports for the gearshafts. This bearing type has a much higher length-to-diameter ratio than caged roller bearings and is generally lubricated by the lubricant in the gearhead. Compared with “pure” roller bearings, needle bearings have much smaller rollers and the highest radial load capacity of all rolling element bearings.

Needle bearings must, however, be used with a hardened steel shaft because the shaft becomes the inner race of the bearing. Maximum operating speeds are also much lower than those for ball or pure roller bearings. Their principle advantage comes with their high-load-capability-to-size ratio, providing the ability to support relatively severe radial and overhung loads in high torque, compact gearmotor drives. Needle bearings are not suitable for motor shafts chiefly because their noise levels increase somewhat exponentially with speed.

A variation, the needle thrust bearing, is also used in gearmotor application (prin-
They employ the same type of rolling elements arranged like spokes emanating from a central hub. Set in a wafer-like retainer, needle thrust bearings can operate at reasonably high speeds with high static and dynamic load capacities.

**Thrust Washers:** It is common in small motors and gearmotors for thrust accommodation and/or tolerance adjustment washers to be used in situations where the thrust forces are light to moderate. Such washers are made of many materials, some of them having self-lubricating properties. Steel, nylon and graphite-impregnated materials are common. In noise-critical applications, the nonmetallic materials are favored.

### 5.3 BRUSHES

Since they form the vital link between the power supply and the armature coils in a DC motor, brushes have always been an important consideration in DC and universal motor design. Viewed as a system, the commutator and brushes act as a rotary switching mechanism which distributes current from the power supply to the desired armature windings at the appropriate time.

Brushes must not only efficiently conduct line current to and from the armature conductors. They must also resist destruction from voltages induced in the armature coils undergoing commutation, and have sufficient bearing qualities to minimize friction and wear at surface speeds which may exceed 5000 ft/min. Almost all of the important limitations on brush performance are in some way related to the dynamic interface of brushes and the commutator. For example, friction generated at high speeds can cause sparking and nonconductive films to be formed between the brushes and the commutator if the brushes are not properly matched to the motor type and function.

While there is no magic formula for selecting the most suitable brush grade for a particular application, brush and motor manufacturers work together to narrow the choices from the many thousands of brush grades and materials available. Their final choice is based on the specific motor type and actual application parameters (since the commutation characteristics will vary depending on how the motor is to be applied).

A brush grade is considered to be ideal for a given application if it meets the following criteria:

1. long life,
2. minimum sparking,
3. minimum commutator wear,
4. minimum electrical and mechanical losses, and
5. quiet operation.

Since there are only a few brush grades that will deliver long life and proper commutation in any given application, proper brush selection is critical to motor performance.

To minimize electrical losses, it would seem reasonable to select brushes with low bulk resistance and a low voltage drop (contact drop) between the brush and the commutator. This approach is appropriate for low voltage motors where power-robbing voltage drops cannot be tolerated. However, it can cause excessive sparking and commutator surface damage in motors with high armature coil inductance. In these situations, brushes with high resistance and high contact drops will improve commutator and brush life by dissipating the energy in the short-circuited commutator coils and reducing the short-circuit current during switching, thus improving the overall efficiency. Mechanical factors such as commutator surface speed, wear properties of the insulation between the commutator segments (flush or undercut), and brush...
dimensions must also be considered. Dimensions are particularly important because the cross-sectional contact area is proportional to the amperage-carrying ability of a given brush material.

Other motor design details such as winding type, current rating, ampere-turns ratio and type of commutator can affect brush selection in a number of specific ways. For example, series motors often operate more efficiently when designed with a lower than usual ampere-turns ratio. But, if a “normal” brush grade is used, sparking will be more pronounced and the commutator will become blackened and burned. For low ampere-turns ratio motors, a harder grade of brush with a slight cleaning action can be specified which will effectively counteract this condition.

Application parameters like frequent starting and stopping (or reversing), overload capacity, need for high efficiency, the presence of vibration or the minimizing of brush noise will all influence brush selection. In some cases requirements may be contradictory, forcing a compromise in the ultimate selection. For all practical purposes, there are four popular groupings of brush materials, covered below.

**Carbon and Carbon Graphite Brushes:** Amorphous carbon (which is relatively hard) and crystalline carbon or graphite (which has good lubricating qualities) are used in varying percentages in this brush classification. The two materials are mixed and bonded together. Hard carbon and carbon graphite brushes are particularly well-adapted for use with motors having flush mica commutators (where appreciable polishing action is required to keep the mica flush with the copper bars). Their high coefficient of friction, however, generally restricts their use to slow speed motors having peripheral speeds below an upper limit of approximately 4500 ft/min (1370 m/min).

In addition, the resistance of the carbon and carbon graphite brushes limits their current density to 35-45 amperes/in² (5.4 to 7.0 amp/cm²). This characteristic generally restricts the application of this brush type to low current fractional horsepower motors.

**Electro-Graphitic Brushes:** The electro-graphitic brush is made by subjecting carbon to intense heat (2500°C). The conversion to crystalline carbon or graphite is a physical (not a chemical) change.

This group of brush materials has a lower coefficient of friction than the carbon and carbon graphite class of brush and is therefore better suited for use at higher commutator peripheral speeds. The preferred average speed application is about 6500 ft/min (1980 m/min). This material is less abrasive than carbon graphite. It is also tougher, and has greater current density capability, with 75 amp/in² (11.6 amp/cm²) being fairly standard. The electro-graphitic group of brush materials is most often used to solve difficult commutation problems.

**Graphite Brushes:** Natural graphite is a mined product. Graphite brushes, as a class, are characterized by more polishing action than electro-graphitic grades. Their frictional properties are usually very low and their characteristic softness gives them good sliding qualities, adapting them for use at commutator peripheral speeds as high as 8000 ft/min (2440 m/min).

Due to the ability to orient the flake graphite during the manufacturing process, this material’s specific resistance can be maintained at a very high level in one direction and yet achieve a current density in the range from 50-65 amp/in² (7.7-10.0 amp/cm²) in the other direction. This feature results in very favorable commutation.
characteristics because short-circuited coil currents are limited during commutation, while still providing a low resistance path for the active motor current. Sparking and noise are generally low with this brush type. However, the softness, which produces quiet operation, also limits the life of these brushes.

**Metal-Graphite Brushes:**
Metal-graphite brushes normally contain copper and graphite in varying percentages. The two materials are either mixed and bonded together or the graphite is impregnated with molten metal.

The most important characteristic of this brush class is its extremely high current-carrying capacity, varying almost directly with the percentage of copper content (the higher the copper content, the greater the current-carrying capacity and the lower the contact drop). A brush containing in excess of 50% copper may have current-carrying capacity greater than 100 amp/in² (15.5 amp/cm²). Normal speed limits are 5000 ft/min (1520 m/min).

The life of such brushes is relatively low because of the wear properties of copper brushes sliding on copper commutators. Therefore, copper-graphite brushes are usually employed only in high-current low-voltage motors where no other brush choice is possible.

General brush application guidelines include:

1) **Shunt-wound DC motors generally exhibit better brush life than series wound motors** due primarily to their lower average speeds. However, poor commutation can result even with a standard brush if resistance is inserted into the shunt field to weaken the field strength and increase motor speed. This additional resistance alters the ampere-turns ratio relationship of the field and armature so that the armature coils are commutated in a less favorable position in relation to the magnetic flux. This factor must be considered in alternate brush selection.

2) **Frequent starting and stopping** imposes challenges on brushes because of the higher starting currents involved. This factor has a particularly pronounced effect with high voltage shunt motors. Also, starting friction considerations play a role in performance. Selection of a high contact-drop brush (one with a voltage-drop of one volt or more) may be more suitable.

3) **Quietsness of brush operation** is dependent primarily on the maintenance of uninterrupted, smooth surface contact between the brushes and the commutator. Concentricity of the commutator, brush spring pressure and fit of the brushes in their brush holders also relate to quietness. When quietness is of prime importance, the normally-used brush can be replaced with a softer grade with enough spring pressure to ensure adequate commutator contact.

4) **Humidity levels affect brush wear.** Low wear rates are dependent upon the formation of a conductive lubricating film on the commutator. Applications that are subjected to an environment of extremely low humidity (high altitudes) cause high brush friction and relatively rapid brush wear because of insufficient moisture to form the required film. Special grades of brushes are available and should be selected for low humidity applications. High humidity, on the other hand, may increase the electrolytic action on the brushes. To improve commutation in high-humidity applications, brushes with a certain degree of abrasiveness are normally specified.
5) **The presence of chemical fumes, dirt or dust** will also be a deciding factor in brush selection. Recommendations for brush grades to be used in environments subjected to those contaminants usually include brushes with some cleaning action. The use of totally-enclosed motors also helps to prevent contaminants from reaching the commutator and brushes.

6) **The nature of the commutator surface affects brush operation.** Satisfactory service requires that a smooth surface of uniform finish and concentricity be maintained. A change in the character of the commutator surface, for any reason, is almost certain to result in a noticeable effect on brush and commutator system performance.

7) **Springs.** The pressure exerted by springs holding the brushes against the commutator surface is an important consideration in the total commutation system. While specific spring composition details will not be discussed here, there are three basic spring types in general use:
   a) **Coil Type**—Inexpensive and most popular, but contact pressure decreases as the brush wears, because the spring exerts less force as it uncoils.
   b) **Roll Type**—Expensive, but contact pressure is constant throughout the life of the brush due to the constant force exerted by this spring type as it coils or uncoils.
   c) **Lever Action Type**—The pressure exerted vs. distance traveled curve of this spring type falls somewhere in between the two previously mentioned types.

8) **Preventive Maintenance.** The wear rate of brushes is dependent upon many parameters (armature speed, amperage conducted, duty cycle, humidity, etc.). For best performance, brush-type motors and gearmotors need periodic maintenance. The maintenance interval is best determined by the user.

   **SAFETY NOTE:** Always disconnect power to the motor before inspecting or replacing brushes. Follow instructions in motor manufacturer’s documentation or contact the motor manufacturer before attempting preventive maintenance.

   Typical maintenance procedures include:
   〈 Inspecting brushes regularly for wear (replace in same axial position),
   〈 Replacing brushes when their length is less than 1/4 inch (7 mm.),
   〈 Periodically removing carbon dust from commutator and inside the motor. This can be accomplished by occasionally wiping them with a clean, dry, lint-free cloth. Do not use lubricants or solvents on the commutator. If necessary, use No. 0000 or finer sandpaper only to dress the commutator. Do not use solvents on a nonmetallic end shield if the product is so equipped.

In conclusion, the motor manufacturer has considered many factors in specifying the brushes for a particular motor design and application. For this reason, it is important to replace worn brushes with the original type (available from qualified service centers).

**5.4 INSULATION SYSTEMS**

An insulation system, as defined by the National Electrical Manufacturers Associa-
tion (NEMA) Standard MG-1, is “an assembly of insulating materials in association with the conductors and the supporting structural parts” of a motor. The stationary parts of a motor represent one insulation system and the rotating parts make up another.

**Coil Insulation:** All of the insulating materials that surround the current-carrying conductors and their associated turns and strands and which separate them from the motor structure are part of the coil insulation. These include: varnish, wire coatings, encapsulants, slot fillers and insulators, tape, phase insulation, pole-body insulation and retaining ring insulators.

**Connection and Winding Support Insulation:** All of the insulation materials that surround the connections which carry current from coil to coil, and which form rotary or stationary coil terminals or lead wires for connection to external circuits, as well as the insulation for any metallic supports for the windings, are considered part of the connection and winding support insulation system.

**Associated Structural Parts:** Slot wedges, spacers and ties for positioning the ends of the coils and their connections, as well as any non-metallic winding supports or field coil flanges, make up this insulation system.

Insulation systems are rated by temperature and divided into classes according to the maximum operating temperature they can safely endure for extended periods of time. The four classes of insulation most commonly found in motors are Classes A, B, F and H. The table in Fig. 5-8 shows the hot spot temperatures for these and other classes of insulation systems.

The hot spot operating temperature is a theoretical value. Under normal conditions, a motor is operated at a temperature less than the values shown in Fig. 5-8. Various end-use standards for different types of motors and controls use different methods to measure the hot spot temperature for a given insulation system.

### 5.5 ENVIRONMENTAL PROTECTION

The environmental conditions in which a motor will operate are critical factors to consider when selecting a motor for a specific application. Some types of motors are more suited for specific conditions than others and some may perform well under a variety of conditions.

In some applications, the service conditions may constitute a hazard such as areas where flammable vapors accumulate and create an explosive situation. Another example would be an application which requires the motor to operate within a high ambient temperature environment for prolonged periods, increasing the risk of fire or motor failure.

NEMA has defined usual and unusual service conditions for motors. They are categorized by environmental and operating conditions as shown below:

**Usual Environmental Conditions:**

1. Exposure to ambient temperatures between 0° and 40°C,
2. Operation at altitudes less than 3300 ft. (1000 meters),

<table>
<thead>
<tr>
<th>Insulation Class</th>
<th>Maximum Hot Spot Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>A</td>
<td>105</td>
</tr>
<tr>
<td>E</td>
<td>120</td>
</tr>
<tr>
<td>B</td>
<td>130</td>
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<tr>
<td>F</td>
<td>155</td>
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<td>H</td>
<td>180</td>
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<tr>
<td>N</td>
<td>200</td>
</tr>
<tr>
<td>R</td>
<td>220</td>
</tr>
<tr>
<td>S</td>
<td>240</td>
</tr>
<tr>
<td>C</td>
<td>Over 240</td>
</tr>
</tbody>
</table>

*Fig. 5-8: Maximum hot spot temperatures of insulation systems.*
3) Installation on a rigid mounting surface,
4) Installation in enclosures or areas that provide adequate ventilation, and
5) Most V-belt, fan belt, chain and gear drives.

**Unusual Environmental and Operating Conditions:**

1) Exposure to:
   a) combustible, explosive, abrasive or conducting dust,
   b) conditions which could interfere with normal ventilation,
   c) fumes, flammable or explosive gasses,
   d) nuclear radiation,
   e) steam, salt-laden air or oil vapors,
   f) very humid or very dry conditions, radiant heat, vermininfested areas, or areas conducive to fungus growth,
   g) abnormal shock, vibration or mechanical loading, and
   h) abnormal axial or side thrust applied to the motor shaft.

2) Operating:
   a) where there is excessive departure from rated voltage or frequency,
   b) where the deviation factor of the AC source exceeds 10%,
   c) where the AC supply voltage is unbalanced by more than 1%,
   d) from an unbalanced rectified DC supply,
   e) where low noise levels are required,
   f) at higher than rated speeds,
   g) in poorly ventilated surroundings,
   h) under torsional impact loads, repetitive abnormal overloads, reversing or electric braking,
   i) in a stalled condition with any winding continuously energized, and
   j) a DC motor at less than 50% of rated armature current for long periods of time.

Various definitions and classification of motors have been defined by NEMA in Standard MG-1 based on a motor’s ability to withstand environmental conditions. A brief summary of the environmental protection classifications for fractional horsepower motors and gearmotors is presented here.

**Open Motor:** One which has ventilator openings so air can flow over and around the windings for cooling.

**Drip-Proof:** An open motor with ventilator openings that will prevent liquids and solids dropped from an angle of 0° to 15° from vertical, from interfering with its operation.

**Splash-Proof:** An open motor with ventilator openings that will prevent liquids or solids that strike the machine at any angle of 100° or less from vertical, from interfering with its operation.

**Guarded:** An open motor surrounded by screens, baffles, grilles, expanded metal or other structures to prevent direct access to live metal or rotating parts through the ventilator openings.

**Semiguarded:** An open motor with ventilator openings that are partially guarded, usually on the top half.

**Open, Externally Ventilated:** A machine which is cooled by a separate motor-driven blower mounted on the machine enclosure.

**Weather-Protected:** An open motor with its ventilating passages constructed to minimize the entrance of rain, snow or other airborne particles.

**Totally-Enclosed Motor:** Motors that prevent the free flow of air from the inside of the motor enclosure to the outside.
**Totally-Enclosed, Nonventilated:** A totally-enclosed motor that is not equipped with an external cooling device.

**Totally-Enclosed, Fan-Cooled:** A totally-enclosed motor equipped with a separate external blower.

**Explosion-Proof Motor:** A totally-enclosed motor which will withstand an explosion of a specific vapor or gas within its housing, or which will prevent sparks or flashes generated within its housing from igniting a surrounding vapor or gas.

**Dust-Ignition-Proof:** A totally-enclosed motor which will not allow ignitable amounts of dust to enter the enclosure and cause performance loss, or which will not permit sparks or heat generated within the motor enclosure from igniting dust or other airborne particles which accumulate around the motor.

**Waterproof:** A motor which will exclude a stream of water from entering its enclosure from any angle.

**Encapsulated Windings:** Usually a squirrel cage motor with random windings filled with an insulating resin to form a protective coating against environmental contaminants.

**Sealed Windings:** Usually a squirrel cage motor with an insulation system that is protected from outside contaminants by using a combination of materials and processes to seal the windings.