Chapter 16

Cast Aluminum Rotors and Switchgear

Squirrel cage induction motors are the most popular form of motor design for both household appliances and heavy industrial equipment.

Before the advent of present aluminum die casting techniques, rotors for squirrel cage motors were built up in a step by step fashion using iron laminations and wound copper wire conductors or conducting rods of copper or bronze alloys welded to end-rings of copper or bronze.

Experimental work with aluminum castings conducted in the 1930’s focused serious attention on the lower cost and engineering advantages of making an integrally cast aluminum/iron lamination squirrel cage rotor.

The Cast Rotor

The cast rotor has two essential components. These are the punched iron disks or laminations containing the holes for the conducting bars, the shaft, and any cooling holes or vents, and the aluminum which is used in integrally casting the conductor bars and collector rings. A stack of laminations is assembled for a particular rotor, the diameter and height of which are determined by the motor design. The laminations may have either open or closed slots (See Fig. 16-1, A and B), however in recent years, the closed-slot design is much more commonly used.

The stack of laminations is placed in a permanent mold or die-casting die containing a space at the top and bottom for the simultaneous casting of end-rings. These end-rings serve to connect electrically all of the rotor bars. The mold is clamped together and the selected molten aluminum alloy is poured or forced into the mold. The resultant cast rotor is shown in Fig. 16-2. The particular rotor shown is of the open-slot type. If this particular rotor were of the closed-slot type, the flash would not be in evidence.

The rotor shaft may or may not be inserted in the rotor bore at this point, depending on the succeeding finishing steps required and the particular manufacturing process being used.

Fig. 16-3 shows a typical cast rotor from which all of the iron laminations have been eaten away by acid in order to reveal the interior construction.

Comparative Performance of Cast Aluminum Rotors

Casting rotors in aluminum makes it possible to fill all the conductor bar slots, bind the entire assembly together, and produce the end-rings and cooling fan vanes in a single economical operation. The resultant assembly is sturdier and less noisy than a copper-cage rotor. It gives motor designers greater latitude and makes better use of the slots by filling them completely. Because of this, a cast rotor should maintain its balance indefinitely whereas a welded, brazed or wound cage, in which the conductors do not fill the slots completely, may lose its balance in time.

Electrical Conductivity: In an induction motor, the higher the electrical conductivity of the rotor, the greater the efficiency of the motor under normal load. On the other hand, the lower the conductivity the higher the starting torque and the lower the starting current. The use to which the motor will be subjected determines motor design and selection of alloy for a desired conductivity. Since, on a volume basis, aluminum has lower conductivity than copper, the required conductivity in a cast aluminum rotor is achieved simply by increasing the size of the slots and of the end rings over that required by an equivalent copper-cage. The overall dimensions remain approximately the same.

Weight: Because of the relative densities of the two metals the weight of an aluminum conductor is half that of an equivalent copper conductor. This means that an aluminum rotor is subject to less stress from centrifugal forces, less starting inertia, less vibration while running and is more portable than an equivalent copper rotor.

Heat Capacity: Temperature rise is one of the limiting factors in motor design. The greater the heat capacity of the rotor the cooler it remains during temporary overloads. Pound for pound aluminum has more than twice the heat capacity of copper but, since its weight in a rotor is about half that of an equivalent copper-cage, heat capacity remains on an equivalent basis.

Thermal Conductivity: The higher the thermal conduc-
tivity the greater the ability of the rotor to dissipate heat. Aluminum has half the thermal conductivity of copper. On the other hand an equivalent aluminum cage has a relatively larger volume and better heat transmission conditions between conductor and core. In this respect, therefore, equivalent performance is attained.

**Alloy Selection**

Rotor casting demands relatively high conductivity for most applications, exceptionally clean metal that will completely fill the conductor-bar slots and form sound end-rings and fan vanes around the assembled core of steel laminations. The aluminum must solidify without cracks or excessive porosity to provide the necessary electrical circuits, and develop adequate strength to bind the entire unit together.

The important factors, therefore, in cast rotor alloy selection are: conductivity, castability, cleanliness and strength. Unfortunately not all of these factors are optimized by the same alloy composition. For most applications rotor manufacturers strive for maximum conductivity but as the size and complexity of the rotor increases some sacrifice is unavoidable if the needed castability and strength are to be secured.

Manufacturers generally provide several recommended aluminum rotor alloys whose use depends upon the size of the rotor. For smaller rotor sizes the aluminum content is higher and the conductivity approaches 59 to 60% IACS. For larger rotors a greater amount of alloyed silicon and iron is provided so that the conductivity may be from 54 to 57% IACS. The higher alloy content is controlled carefully and provides greater castability, greater freedom from hot cracking and shrinkage during casting. Manufacturers recommend the use of the higher iron/silicon alloy when one or more dimensions of the rotor is greater than five inches.

For a listing of rotor alloys and their chemical compo-

**Conductivity from Composition**: Conductivity measurements on the ingot itself are not a reliable measure of the conductivity of connector bars and collector rings because rotor casting processes affect such conductivity measurements. Yet rotor manufacturers need a means for identifying consistent electrical characteristics in the rotor metal they purchase. This is accomplished by specifying the chemical composition limits and a range or the minimum electrical conductivity of the ingot.

**Rotor Ingot**: Manufacturers of aluminum rotor alloys supply such metal in ingot form to specifications for composition and conductivity. The rotor alloys are particularly free from non-metallic and harmful oxide inclusions resulting in better fluidity and improved castability than commercial grades of unalloyed aluminum.

**Manufacture of Cast Aluminum Rotors**

**Melting and Metal Preparation Equipment**

Fuel fired, induction and electric resistance furnaces are used to melt and hold aluminum for the casting of motor rotors. The choice of melting equipment will depend on the type and volume of rotors to be cast and on the cost of fuel for any given locality.

The following types of furnace equipment can be used to melt and hold aluminum for motor rotors:

**Crucible Furnaces**: Underfired crucible furnaces are available with capacities that range from just a few pounds to 1500 pounds. Although it is possible to use the same crucible furnace for both the melting and casting processes, it is preferable to melt and flux in one unit and transfer the molten metal to a second furnace for casting. The use of a single furnace for melting and casting does not provide good temperature control since ingot and gates charged into the melt drop the temperature of the metal making it impossible to maintain a uniform
pouring or casting temperature. A single furnace for melting and holding also complicates the fluxing of the melt for cleaning the metal.

The use of a refractory crucible such as silicon carbide or clay graphite is recommended as iron pickup can result from the use of cast iron crucibles. Where cast iron crucibles are employed, they must be kept coated with a refractory pot wash to minimize iron pickup since iron is readily soluble in molten aluminum and reduces the electrical conductivity of aluminum. Proprietary salt fluxes are used to dry the surface skim on the melt and remove build up from crucibles.

Reverberatory Furnaces: Reverberatory furnaces may be built in sizes varying from about 1000 pounds capacity to as high as 100,000 pounds. The reverberatory furnace is usually employed as a “breakdown” furnace with the molten metal transferred to crucible type or induction holding furnaces at the casting machine. Reverberatory furnaces with a dipping well or wells are also employed as combination melt and hold furnaces. The advantage of the dip well type of furnace is in the elimination of molten metal transfer and a low cost for melting and holding. The principal disadvantage of this type of furnace, aside from its higher original cost, is that salt fluxing and cleaning of the furnace is more difficult than with the crucible type. In all rotor casting work, the degree of cleanliness of the melting and holding furnaces is an important factor in preventing low or variable conductivity and casting problems due to the occurrence of oxide inclusions in the rotor castings. The combination of rotor grades of ingot and clean furnaces provides optimum metal quality.

Induction Furnaces: Electric induction furnaces are employed by a number of motor rotor manufacturers for the melting and holding of aluminum. Induction furnaces provide a high quality melt with uniform composition and excellent temperature control; however, where ingot and scrap are charged into a single chamber induction furnace, some variation in metal temperature and oxide content can be expected.

Successful operation of core-type induction furnaces requires regular maintenance of the inductor channels. These channels usually require “rodming out” at regular intervals to prevent the channel from plugging up. The non-metallic deposit in the channels of an induction furnace consists of the oxides and nitrides of aluminum and other elements which are formed during continuous melting and holding. The non-metals are concentrated in the channels by the electromagnetic field and form a hard deposit. Complex intermetallic compounds of iron and impurities may also settle in the furnace channels if the original rotor alloy is contaminated with impurity elements.

The proprietary fluxing compounds required to clean crucible and reverberatory furnaces in induction furnaces have been shown to promote channel plugging. The metal salts in fluxing compounds form oxides which are deposited on the walls of the inductor channels. Where fluxing is deemed necessary, a degassing flux of the hexa-chloroethane type or chlorine-nitrogen gas mixture is recommended. With rotor grade ingots, it is not necessary to flux the melt when 100% ingot is charged. The charging of gates and the biscuits from the shot chamber may necessitate fluxing of the melt at times to cleanse the metal and the channels.

Casting Methods Employed for Aluminum Rotors

The horizontal cold chamber die-casting method is recommended for high volume production of fractional horsepower motor rotors. The die casting process provides a good quality rotor casting at a low unit cost. The process lends itself to automation providing further production economics. Multiple cavity dies are usually employed to cast several rotors of the same or different design at one time. In volume production the high original investment cost of the die casting machine, dies and suitable metal melting and holding equipment is justified. In the die-casting process, the steel lamination stack is usually loaded into the die without preheating. Conventional die casting practices are used to produce rotors.

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Fig. 16-2. A typical die-cast rotor of the open-slot type.

Fig. 16-3. Iron surrounding the cast-aluminum squirrel cage has been removed to reveal construction.
The vertical press method of pressure casting aluminum rotors has been used for many years to cast both fractional and large integral horsepower motor rotors. The original investment is lower than die casting equipment. In this process the lower platen of the press usually contains a round well or sump into which the molten metal is poured. The sump may be lined with mica and/or asbestos paper to prevent excessive metal temperature loss or is sometimes sprayed with an aqueous graphite or similar type coating to prevent the metal from sticking. The rotor mold and the laminating stack are mounted on the upper platen. The molten metal is forced by the stroke of the press through a series of small gates into the rotor die. The gates into the rotor usually consist of a number of tapered holes through the base plate of the mold into the collector ring part of the cavity. In this casting method, it is desirable to preheat the lamination stack to a temperature of from 400°-1000° F. prior to loading the stack into the casting die. The required preheat temperature of the laminations will vary depending on the size of the rotor to be cast and the size of the slots in the laminations.

Casting Problems

Problems usually show up as low conductance or high starting torque of the rotors. The major casting problem in the production of aluminum rotors is the presence of entrapped air and/or gas from the die lubricant. This type of defect manifests itself as a number of smooth rounded (or slightly elongated) gas holes within the end rings and conductor bars. This type of defect reduces the conductance of the rotor and the electrical efficiency of the motor. Some porosity of this type is experienced in varying degrees in all of the casting methods employed for rotors. This type of defect may be reduced by providing adequate venting of the die or mold during the casting cycle and by avoiding excessive use of die or mold lubricants. The rate of metal injection into the die can also influence the occurrence of this type of defect. The optimum metal injection rate must be determined by the producer as it will vary depending on the type of casting equipment, mold design and design of rotor being cast.

Other casting defects encountered in rotors are dross or oxide films, shrinkage, cracks and poor fill (usually in conductor bars). The dross defect can be the result of poor metal melting and handling practice and is discussed under the previous section on melting. Aluminum alloys undergo a 5 to 6 percent volume decrease in solidifying from the liquid state. Since it is impractical to supply molten metal to feed or make up for this volume change in most designs of cast rotors, some internal shrinkage porosity may occur, particularly in large integral rotors with heavy end rings. Cracks in the end rings or in the conductor bars are extremely detrimental to the service of the rotor. Unalloyed aluminum, 99.80 or 99.85, is more prone to cracks and shrinks than the rotor alloys. Other casting alloys such as 380.0 are prone to cracking in rotor casting because of their relatively long solidification range. In large rotors, it may be possible to provide excess metal in the form of risers to aid in overcoming the shrinkage tendency in the top ring. Careful control of the metal temperature and mold temperature is necessary in minimizing cracks and poor fill in 380.0 alloy rotors.

Loss of conductivity and poor casting characteristics may occur if the rotor alloy becomes contaminated with other metals. Iron is readily soluble in molten aluminum and iron contamination in the melt is quite often the cause of low conductivity and poor fill or cold shuts.

Steel Laminations: In the stamping of laminations the formation of burrs at the slot edges should be kept to a minimum by proper maintenance of punches and dies. Excessive burring can contribute to metallurgical bonding with the aluminum during casting, and lead to loss of motor efficiency.

To assist in the casting of sound conductor bars and end rings (whether by gravity, centrifugal or pressure die casting) it is recommended that the steel lamination stacks be preheated. This greatly facilitates metal flow and the filling of intricate passages. Preheating the laminations also oxidizes freshly sheared edges of the slots thereby reducing the tendency for metallurgical bonding to occur between the steel and aluminum. Preheating at 250-350°C for 1-2 hours is usually adequate though bulky lamination stacks may require higher temperatures for a somewhat longer period.

Casting: Casting temperatures for rotor metal may lie anywhere in the range 700-800°C (1290-1470°F) depending upon individual foundry practices. Once casting temperature is established it should be held within ±10°C. In production, uniform casting cycles should be maintained so as to properly control die and mold temperatures. Dies should be preheated to 250-300°C (480-570°F). Cold dies are the cause of scrap which can be reduced by maintaining uniform and continuous production cycling.

In pressure die-casting an important factor in the production of sound rotors is adequate venting of the cavity. Excessive use of die lubricants can lead to venting problems. If asbestos paper is used to line the mold (vertical pressure die casting of larger rotors) it should be thoroughly furnace dried just before use to eliminate this source of gas pick-up.

Thermal Treatment: Two considerations are important for the efficient electrical operation of a squirrel cage motor. These are (1) there should be a reasonably high inter-laminar resistance and (2) there should be a high resistance between the iron laminations and the die-cast aluminum conductors and end rings. The second item is particularly important and even a partial separation of aluminum from iron immediately results in noticeably better performance.

Thermal treatment of rotor castings, 1-2 hours at 300-450°C (570-840°F), is helpful in breaking metallurgical bonds between steel laminations and the aluminum conductor bars. This is due to a large differential in thermal expansion of the two metals. For pressure die cast rotors,
TABLE 16-1
Rotor Metal Alloys

<table>
<thead>
<tr>
<th>Alloy*</th>
<th>Aluminum Grade</th>
<th>Rated Conductivity</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Min. Purity*</td>
<td>% IACS — Min.</td>
</tr>
<tr>
<td>100.1</td>
<td>99.00%</td>
<td>54</td>
</tr>
<tr>
<td>130.1</td>
<td>99.30%</td>
<td>55</td>
</tr>
<tr>
<td>150.1</td>
<td>99.50%</td>
<td>57</td>
</tr>
<tr>
<td>170.1</td>
<td>99.70%</td>
<td>59</td>
</tr>
</tbody>
</table>

Chemical Composition of Rotor Alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Silicon</th>
<th>Iron</th>
<th>Copper</th>
<th>Manganese</th>
<th>Chromium</th>
<th>Zinc</th>
<th>Titanium</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Each</td>
<td></td>
<td></td>
<td>Each</td>
<td>Total</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100.1</td>
<td>0.15</td>
<td>0.6–0.8</td>
<td>0.10</td>
<td>(a)</td>
<td>(a)</td>
<td>0.05</td>
<td>(a)</td>
<td>0.03 (a)</td>
</tr>
<tr>
<td>130.1</td>
<td>(b)</td>
<td>(b)</td>
<td>0.10</td>
<td>(a)</td>
<td>(a)</td>
<td>0.05</td>
<td>(a)</td>
<td>0.03 (a)</td>
</tr>
<tr>
<td>150.1</td>
<td>(c)</td>
<td>(c)</td>
<td>0.05</td>
<td>(a)</td>
<td>(a)</td>
<td>0.05</td>
<td>(a)</td>
<td>0.03 (a)</td>
</tr>
<tr>
<td>170.1</td>
<td>(d)</td>
<td>(d)</td>
<td>------</td>
<td>(a)</td>
<td>(a)</td>
<td>0.05</td>
<td>(a)</td>
<td>0.03 (a)</td>
</tr>
</tbody>
</table>

(a) Manganese plus chromium plus titanium plus vanadium is 0.025% max.
(b) Iron to silicon ratio is 2.5 minimum.
(c) Iron to silicon ratio is 2.0 minimum.
(d) Iron to silicon ratio is 1.5 minimum.

*In judging the rotor alloy to be used, it should be noted that the highest purity alloy (170.1) is the most difficult to cast and is subject to a greater degree of shrink cracking. By contrast, the lesser purity 100.1 alloy is easier to cast with a minimum of cracks.

For high torque rotors (37% IACS — typical) the standard foundry alloy 443.0 (Nominal 5.2% Si) is applicable. Also for high torque 30% IACS conductivity, the standard foundry alloy 380.0 (Nominal 3.5% cu, 8.5% Si) is applicable.

treatment temperatures at the lower end of the indicated range are less likely to cause blistering. The heating also tends to introduce some further oxide film between the aluminum and iron thus assisting electrical isolation further.

Aluminum in Power Switchgear

Aluminum and its alloys have become increasingly important in the manufacture of all types of electrical switchgear. Its applications in switchgear vary from small rivets, sheet metal enclosures and hardware to important current-carrying and structural parts.

High electrical and thermal conductivity, high strength-to-weight ratio, excellent corrosion resistance, non-magnetic properties and superb fabrication capability are some of the most important characteristics favoring the use of aluminum.

Fig. 16-4 shows an example of modern switchgear using aluminum in various forms.
electromagnetic and other electrical applications of aluminum

Figure 16-4. Modern aluminum switch gear capable of handling 50,000 ampere short circuit current.