Chapter 14

Aluminum Magnet Conductor

During the 1950-1960 period when aluminum conductors began to displace copper in overhead transmission and distribution and a large effort was started to evaluate aluminum in the insulated cable field, some attention was also directed to aluminum magnet wire. These early efforts were confined to round 1350 aluminum wire in the fully annealed or partly annealed condition using conventional and new magnet wire insulations. Results from an economic viewpoint were only moderately successful and, in order to achieve better space factors, an anodized film was used as turn insulation. However, at almost this same time it became apparent that thin aluminum strip conductor in the form of anodized foil or foil interleaved with a suitable insulating film would eliminate many of the magnet wire problems previously experienced. The subsequent development of aluminum foil or strip magnet conductor has successfully achieved a new order of improvement in electromagnetic coil design.

In transformer practice, aluminum conductors have lower stray losses than copper conductors for a given size. This is because the eddy current losses are an inverse function of resistivity of the conductor. This advantage for aluminum is offset by the fact that larger conductor sizes are needed for equal resistances. On balance, aluminum windings, with resistances equal to copper windings of similar design, have about 3% lower stray losses.

Aluminum Magnet Wire (Round, Square, Rectangular)

As previously indicated, the first use of aluminum magnet wire was as a film-insulated round wire. This type of conductor is now available in virtually all AWG sizes as it is for copper magnet wire (No. 4 through No. 26 or finer AWG) and with all conventional insulation including class 105, class 130, class 155 and class 200.

Certain small, fractional horsepower motors, mainly in the washer and dryer appliance field, are designed now exclusively with round aluminum insulated wire. However, the greatest increase in growth has been in the use of rectangular and square aluminum magnet wire in distribution, small power and dry type transformers, both bare and tape insulated with Aramid, thermally upgraded paper and crepe paper. Tape-insulated aluminum, in comparison to film-insulated aluminum of the same temper, size and shape, usually has a higher tensile strength due to the tape. Film-insulated conductors must be processed through a curing oven which results in total or partial anneal of the wire. Therefore, taped conductor can have a higher temper which results in much higher tensile and yield strengths. Taped conductors also have greater resistance to mechanical stresses and abuse, making them easier to wind and more resistant to the effects of electrical short circuit forces at elevated temperatures. Many of these applications can be served by 1350 aluminum, but there is a substantial demand for commercially available alloys possessing higher yield strength while maintaining conductivity of 61 percent as a minimum.

Since annealed 1350 aluminum has a tensile strength of 12,000 psi as compared to 35,000 psi for annealed copper, coil winding operations must be modified somewhat but once the necessary adjustments have been made aluminum magnet wire may be handled readily and rapidly.

Conventional aluminum magnet wire possesses a number of advantages over copper in both economic and technical aspects.

Light Weight

Aluminum, with a density of 2.703 grams per cubic centimeter at 20°C has less than one-third the density of copper and weighs one-half as much as a copper conductor of equal resistance and equal length.

The lighter-weight conductor is of advantage in most electrical equipment for transformers, especially coils, and motors in portable equipment or in air-borne, missile, or space-vehicle applications where reduced component weight allows vital additional payload.

Generally superior performance can be expected when aluminum magnet wire is used for rotating and other moving windings. The lower mass of aluminum designs results in lower inertia—improving performance of a wide variety of equipment.

In rotary equipment, low mass simplifies dynamic balancing. Because vibration from dynamic imbalance is
electromagnetic and other electrical applications of aluminum

**TABLE 14-1**

Springback Comparison Chart

<table>
<thead>
<tr>
<th>Wire Size (AWG)</th>
<th>Degree of Angular Springback* (Typical figures)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td>AWG 18</td>
<td>54°</td>
</tr>
<tr>
<td>AWG 16</td>
<td>46°</td>
</tr>
<tr>
<td>AWG 14</td>
<td>38°</td>
</tr>
</tbody>
</table>

* In "degrees per turn" when tested per NEMA publication MW-1000/1967 Part 3, Par. 2.2.5.

Reduced, aluminum construction contributes to longer operating life of rotary apparatus.

Lower mass also results in higher sensitivity and response in moving coil applications. Manufacturers can take advantage of this characteristic in the design of electrical instruments and acoustical devices.

Significant weight reductions of coils can also lower shipping and handling costs. Dramatically lower spool weights reduce operator fatigue by making it easier to load the winding machines.

**Windability**

Because annealed aluminum magnet wire has a low yield strength (approximately 4000 psi), little strain energy is required to conform it to an arbor. This quality is noticeable in practice: rectangular coil sides have less bow than similar copper coils; end turns on a motor stator are shorter; all coils are more compact; and operator fatigue is reduced in hand winding operations. The most striking aspect of this lower springback is reduction in winding tension. Even though aluminum wire may be two gauges larger than copper, machines run faster, and they readily handle aluminum wire four sizes larger than the largest copper gauge they can handle. Operators have no problem threading machines or advancing the wire. Table 14-1 presents some comparative springback data provided by a manufacturer of magnet wire.

**Thermal Characteristics**

Tests indicate that insulations applied to aluminum can be expected to operate one IEEE temperature classification* higher than the same insulation applied to copper, and still have equal life; for example, a class 105 insulation for copper can be used as class 130 insulation for aluminum.

Insulations applied to aluminum have longer life at the same operating temperature than the same insulation applied to copper. The mechanical properties of insulation on thermally aged magnet wire show a marked advantage for aluminum. In certain applications, where electrical losses are not a problem, designers have used these advantages (higher temperature operation and good mechanical properties after aging) for both economic and space reasons by using aluminum magnet wire only one or one-and-a-half sizes larger than copper, rather than the rule-of-the-thumb two sizes.

Fig. 14-1 was provided by a manufacturer of aluminum magnet wire and gives data on the aging of aluminum vs. copper magnet wire insulated with a variety of materials.

**Economic Factors**

Through lower initial cost and other savings due to aluminum's advantages, manufacturers can realize significant improvements in product cost control.

In the size range No. 8 AWG through No. 24 AWG, aluminum film-insulated round magnet wire costs less per unit of length than its equivalent copper conductor. These savings run from 15 to 25 percent and more in the heavy gauges.

**Coil Design**

Engineering with aluminum magnet wire is not different fundamentally from engineering with copper wire, but some allowances do have to be made. Because aluminum has a lower conductivity than copper, designers often must find space to increase the wire gauge by two sizes. In changing from copper to aluminum, some engineers may prefer to develop an entirely new coil design. Sometimes modification of existing designs will be sufficient. Sometimes, it is discovered that an existing unit allows sufficient space to accommodate the larger aluminum coil without any major revisions. Usually, however, for optimum results it is necessary to redesign the unit (e.g., distribution transformer primaries).

**Apparatus with Stamped Laminations:** When there is insufficient space for an easy substitution of aluminum for copper, redesign of transformers and similar apparatus using scrapless laminations will usually involve one or two kinds of changes. It may be necessary to increase stack height to accommodate an aluminum coil of fewer turns of large wire, or a different lamination may be necessary. If the designer must change lamination size, he has, in effect, developed an entirely new design.

**Apparatus with Wound Cores:** For apparatus using wound cores the procedure is nearly the same as for scrapless lamination. However, considering the moderate increase in cost for special core designs, this family of electrical devices yields the greatest return when completely new designs are used.

Optimum designs for aluminum wire require different...
core dimensions than are used with copper. A typical copper design has a window area one-half of its central core area, stack height $1\frac{1}{2}$ times core width, and a window length $1\frac{1}{2}$ times window width. In the finished product, coil weight is about 33% of the total. Such a design probably is very close to minimum material costs.

But for aluminum, the window area is approximately 75% greater than core area, stack height 2 to $2\frac{1}{2}$ times core width and the window length 2 to $2\frac{1}{2}$ times window width. In the finished product, aluminum-coil weight would be approximately 40% of the total. Such a design, which constitutes a complete departure from standard practice, is most practical with tape-wound cores.

**Motors:** Many classes of motors lend themselves readily to redesign with aluminum magnet wire. In particular, shaded-pole types often have sufficient space for an easy substitution of aluminum. Induction motors may have space for a change in wire size of one or one-and-a-half gauges. This change together with shortened end turns may be sufficient for a simple substitution. As with transformers, stack length can be increased or a larger lamination can be used.

Other Devices: In general, the same information applies to all other magnetic devices which a designer wishes to convert to aluminum windings. If the necessary extra space does not already exist, it must be provided by modification or redesign on the entire device.

**Means of Minimizing Coil Size:** In copper-wound electromagnets, the design flux density of the pole piece is often conservative, and the pole-piece diameter can safely be reduced by 10 to 15 percent. This approach of reducing the inside diameter of the coil is better than increasing the outside coil diameter because it lowers the mean turn length while it provides the extra space required for larger gauge wire.

There are various measures available for minimizing size of wound coils. Coils can be precision wound instead of random wound. Bobbins can be made smaller—sometimes they can be eliminated altogether. Coil operating temperatures can be raised—with moderate temperature increases, aluminum coils still have longer life than copper coils. Finally, as a result of a thoroughgoing redesign particularly of an older item in a product line, the new device and its aluminum coil may operate cooler.

Often overlooked are the opportunities to modify existing windings, if only slightly, to take advantage of aluminum magnet wire’s economic benefits. Through close attention to coil configuration, the designer can employ previously wasted space to accommodate windings even though it may alter the basic shape of the coil. Sometimes, only one additional turn per layer or special contouring of the winding to fit special cavities will use a space for maxi-
electromagnetic and other electrical applications of aluminum


Since cases of redesign for aluminum wire are highly individual, some manufacturers maintain a coil-prototype laboratory to help customers with aluminum application designs by winding experimental coils and demonstrating techniques of joining.

**Coil Connections**

Joining aluminum coils to lead wires is not a laboratory curiosity; it is done in everyday production. The joining and termination of insulated aluminum wire—which has been a source of concern to many coil makers—can be easily done with mechanical connectors.

**Mechanical Termination:** Mechanical termination and splicing methods have been developed which are highly effective and low in cost. These methods employ machine-applied compression terminals with serrated barrels, such as those shown in Fig. 14-2.

This mechanical connection has numerous features that make it more efficient and more economical than conventional joining and termination methods. A one-step, machine-applied process combines low labor costs with high production speeds of up to 4000 terminations per hour. Top quality terminations and splices are exceptionally reproducible—and the resulting low rejection rate helps increase output while reducing scrap costs.

A considerable number of environmental tests, developed by the manufacturers, have proved this method to be highly reliable. Millivolt drops and temperature rise are essentially the same as the best of connections made carefully by other methods. There’s no damage to insulation from heat, stripper residues, or soldering fluxes.

**Soldering:** A secondary method of splicing and terminating is by soldering. Aluminum can be soldered using the same tools and techniques as copper, but requires special procedures and solder and flux. Information about procedures for soldering aluminum is available from various manufacturers on request.

**Aluminum Strip Magnet Conductor**

Strip conductor by definition is a flat, flexible metal strip usually produced by slitting a supply roll of proper gage metal into required widths for the finished product. The resulting conductor has a rectangular cross-section with a large width to thickness ratio; a broad range of widths and thicknesses are available.

Aluminum strip magnet conductor is usually made from either 1350 grade aluminum or 1235 aluminum alloy. Although 1350 grade metal will be principally discussed in what follows, technical data are included for both alloys and are compared to electrolytic copper.

**Strip Magnet Conductor Insulation**

Aluminum strip magnet conductor may be insulated by extremely thin, high dielectric strength anodized films; by interleaved (wider) films of a variety of high grade insulating materials; or by the deposition and bonding of insulating coatings. All of these methods require some special treatment of the strip surfaces and edges.

**Anodized Films:** Early developments by the aluminum industry clearly recognized the possibilities of using anodic films for the electrical insulation of aluminum conductors. Aluminum oxide exists to some extent on all aluminum in the form of a microscopically thin layer and provides aluminum with its excellent corrosion resistance. By the use of anodizing techniques, this thin layer can be expanded into a hard, inelastic and highly insulating film in the order of three ten-thousandths of an inch thick. This anodic film is desirable in many applications because of its hardness, abrasion resistance and high breakdown potential for a given thickness and high temperature rating.

Early work was directed at anodizing round aluminum conductors. A satisfactory film was obtained on straight conductor but bending sometimes resulted in crazing at
the outside radius of the bend and an actual extrusion of metal through similar cracks on the inside radius. Developments were directed toward anodizing a relatively wide and thin strip of aluminum having the same cross-sectional area as the round conductor. The bending problem was overcome by going to a strip, but the edges were almost impossible to anodize. By utilizing a chemical and mechanical treatment of the ragged, non-uniform edges, a surface that could be anodized adequately was obtained. The results of the fabrication process for anodized strip are considerably improved insulation efficiency and overall strength.

*Interleaved Insulation:* The thermal, mechanical, chemical and electrical requirements must be defined before an interleaving material can be selected.

Paper and polyester interleaves as thin as .0005 inch have been used as turn insulation in electromagnetic coils wound with edge-conditioned strip conductor.

The width of the interleave is usually about 0.125 inch wider than the strip. Of course, this dimension may vary considerably—depending on the interleaving material, the coil and the equipment used to wind the coil.

Paper: Paper has a thermal rating of 90°C (Class O) and 105°C (Class A) or better when submerged in oil or impregnated. Because it is able to withstand large compressive forces and has good dielectric strength, it is usually the interleaving material used in oil-filled transformers and in coils that do not operate above 105°C.

Polyester: Polyester interleaving materials have a thermal rating of approximately 150°C which is between Class B, 130°C and Class F, 155°C. They have excellent dielectric strength, resistance to most chemicals and solvents and very high tensile strength. Polyester films are not compatible with some varnishes and are not generally recommended for use in oil-filled equipment. Under certain electrostatic conditions they have a tendency to attract foreign matter while being wound.

Aramid: Polyamide, such as DuPont “Nomex,” has a thermal rating of 200°C (Class K). It is available in thicknesses of 2 mils and over. It has good abrasion resistance and can be wound on automatic equipment.

Asbestos: Asbestos treated with silicone or other high temperature varnish has a thermal rating of 220°C (Class H). It acts as a positive spacer and varnish absorbent. Silicone, polyester, epoxy and other varnishes are generally used to treat the asbestos fibers. (Lower thermal varnishes like epoxy bring the thermal rating down.) The use of this interleaving material is limited because it is a bulky insulation.

Teflon: Teflon has a thermal rating of 200°C per MIL-W-16878. (Teflon backed up by glass cloth to prevent cut-through has a much higher rating than 200°C.) It is very resistant to abrasion and has good chemical resistance and good dielectric strength. Teflon is more expensive than most other interleaving materials which limits its major application to aircraft and missile work.

Mica: Mica has a thermal rating of 220°C (Class C). It is sometimes used without a binder, but normally it is impregnated with silicone or other resins which may limit the temperature classification. Mica has good electrical properties but its tensile strength is low and it is bulky.

Glass: Glass has a thermal rating of 220°C (Class C). It also depends on binder thermal rating for its rating. It has excellent thermal endurance, acts as a positive spacer and is able to withstand the elements that deteriorate other insulations. It is used where dependability is an important factor. The major limitation is its poor space factor. Glass is sometimes used as a backing for other interleaving materials to provide tensile strength.

Coated Strip: Coated aluminum strip has also been developed for use in commercially available distribution transformers. Epoxy (Class B, 135°C), polyvinyl formal (Class A, 105°C), polyesters (Class F, 155°C), and the amid-imide polymer enamel coatings (200°C+) are used. Epoxy and polyamide-imide appear to be growing in favor.

Fig. 14-3. An aluminum to copper transition piece may be used to make aluminum to aluminum connection at the strip and to make a copper connection to a lead or terminal. The transition pieces are usually made by cold or flash welding.
Coil Design with Aluminum Strip Magnet Conductor

Aluminum strip magnet conductor can be designed into most electromagnetic devices when all of the parameters of the device as well as the characteristics of aluminum are taken into consideration.

Strip made of electrical conductor grade aluminum 1350 has a guaranteed conductivity from 61 to 62 percent IACS. 1350 aluminum strip conductors designed for equal direct current (DC) resistance compared to a copper conductor must, therefore, have a larger cross-section area.

This means that the aluminum strip conductor will require about 60 percent more space than is needed for an equivalent copper conductor. Therefore, space conservation must be employed in designs where dimensions are critical. Because of its geometric shape, the aluminum strip conductor will utilize more of the allocated coil space than the equivalent round wire. This is graphically shown in Fig. 14-4. It is noted that for the same coil "window" opening the utilization of space by the conductor is much greater in the foil or strip form than for the usual insulated round shape. This, in large part, is due to the elimination of need for the wire insulation.

In addition to better space utilization, strip conductor offers the following advantages:

1. More rigid construction results in greater strength. No side supports are necessary for the strip wound coil.
2. Better heat dissipation—each turn is exposed to the outside and in flat surface contact with insulation of the next turn.
3. Lower voltage stress between turns—turn voltage gradient is layer voltage gradient.
4. Easier winding—no traverse guiding necessary.
5. Less supplementary insulation necessary.
7. Better short-circuit performance in transformer since each turn is centered in the magnetic field.
**Winding Design Techniques With Strip Magnet Conductors**

Many techniques can be employed to adapt strip conductor to coils previously wound only with round insulated wire. Coils for field windings of rotating equipment, for example, previously considered only for winding with round wire because of shape, are now wound with strip conductor and used in many different types and sizes of motors and generators.

This ability to post-form coils after winding allows the designer more flexibility. Coils can be wound on a round mandrel then formed into rectangular shape. This is advantageous because round coils are more easily adapted to winding on automatic high speed machines than are rectangular coils.

The per unit cost of conductor increases as the size decreases. It is, therefore, advantageous to control the amount of smaller conductor used on a coil assembly. A transformer is an assembly where this design technique can be utilized. The smaller winding of the primary containing many turns can be located next to the core where the mean turn length will be minimized. The amount of smaller conductor is kept to a minimum and the larger conductor of the secondary, which is the lower cost, is placed to the outside of the coil.

Coils containing two or more windings that must be balanced in impedance can be wound bobar; that is, with the conductors of each winding physically paralleled and wound together with proper insulation between. The close coupling of the flat conductors results in the best possible balance in impedance between these windings.

The higher cost thin gauge conductors can sometimes be economically replaced by strip of heavier gauge and narrower width. This approach also decreases the amount of insulation required. The narrower coils can be wound and placed side by side on the core to utilize the available space. The cores can then be electrically paralleled with the same results as obtained with a coil of thinner, wider strip conductor.

These are but a few techniques the designer has at his disposal to arrive at the proper coil design.

**Determination of Foil Size and Coil Characteristics**

Direct current (dc) resistance of the aluminum strip magnet conductor coil can be determined by using the following formula:

$$R_w = \frac{t \times 12(MLT)N \times 10^{-6}}{A} \text{ ohms} \quad (\text{Eq. 14-1})$$

Where:

- $t$ = microhm-inches resistivity of 1350
- $t = 1.09483$ microhm-inches at $20^\circ C$
- $MLT$ = mean length turn in feet
- $N$ = number of turns
- $A = \text{cross sectional area of strip in square inches} = W \times t \text{ (width times thickness)}$

Then the winding resistance is:

*Based on aluminum at 62% conductivity

where: $A = \text{nominal cross-sectional area of the wire in square inches}$.

$$R_w = \frac{13.138(MLT)N \times 10^{-6}}{W \times t} \text{ ohms at } 20^\circ C \quad (\text{Eq. 14-2})$$

Ohms per 1000 feet is calculated as:

$$R_{1000} = \frac{13.138 \times 10^{-3}}{W \times t} \text{ ohms/1000 ft. at } 20^\circ C \quad (\text{Eq. 14-3})$$

Inductance values for strip magnet conductor coils can be determined approximately by using conventional formulae for round wire wound coils. Tests performed to date indicate that inductance values for coils of the same number of turns and of the same shape and size will be approximately equal regardless of conductor shape.

Bunet* gives formulae for round and rectangular shaped coils of round wire which are beyond the scope of this work. These formulae generally yield accuracies between -4% and +4.7% depending on the coil dimensions. Since they are for approximation of inductance, they suffice for engineering needs and can be used for strip wound coils as mentioned above.

If the round copper wire size used in a coil is known, the conversion to aluminum strip conductor for an approximate equivalent coil is simple. The cross sectional area of the round copper conductor is increased by 64% to obtain the required cross sectional area of aluminum for equal dc resistance in a coil having equal length. This area of aluminum conductor is then dimensioned to obtain the required thickness and width. Fig. 14-5 provides a ready means for determining strip dimensions and also the corresponding dc resistance per 1000 ft. at $20^\circ C$.

The following example illustrates the ease with which aluminum strip conductor can be sized for an equivalent round copper wire wound coil:

Fig. 14-5. Aluminum strip conductor application. (Notes and data on Fig. 14-5 may be found on page following.)
Strip Conductor Equivalents

(Notes and data on Fig. 14-5 preceding)

The computation chart is used for obtaining approximate data useful in coil design.

Since the electrical conductivity of 1350 aluminum in this chart is 61% of copper, approximately 64% more aluminum by volume is required. A useful rule of thumb is: for equal conductivity—use 2 wire sizes larger than round copper, and 3 wire sizes larger than square copper.

Example:

A small solenoid coil is wound with 100 turns of No. 19 AWG enameled round copper on a coil width of \( \frac{3}{4} \) inch. Aluminum Strip, electrically equivalent to No. 19 AWG copper, must have an area of .00167 sq. inches (approximately No. 17 AWG). From the chart a strip width of \( \frac{3}{4} \) inch requires a .0033 thickness. Slight adjustments may be necessary for choosing exact dimensions.

Resistance is determined by intersection of the .00167 area line and the appropriate resistance line. This resistance is found to be 7.8 ohms per 1000 ft. Weight calculated by formula 2 is found to be 2 lbs. per 1000 ft.

FORMULAS FOR STRIP WOUND COILS

1. Resitivity

\[ r = \frac{0.013118}{A} \]

(Example continued from page 14-7)

A coil is wound with 100 turns of No. 1/0 AWG* square copper wire (.1022 sq. in.) and is 3 inches wide. Based on an aluminum conductivity of 62 percent IACS, the equivalent aluminum strip conductor will have an area of .1648 square inch (.1022/.62). From the Fig. 14-5 computation chart, the intersection of the lines corresponding to a 3-inch width and a .1648 square inch area gives a thickness of .055 inch. The resistivity is found to be .08 ohms per 1000 feet by locating the intersection of the .1648 sq. in. area line and the resistivity line.

Tables 14-2, -3, -4 and -5 provide additional data and formulas which are useful in strip conductor wound coil design calculations.

Dielectric and Thermal Advantages of Strip Magnet Conductor

Since a strip wound coil consists of a number of turns of film-insulated aluminum strip or strip interleaved with thin layers of strip insulation, the number of layers is equal to the number of turns and the layer to layer voltage is equal to the turn to turn voltage. This eliminates the high layer to layer voltage common on copper magnet wire coils and the expensive layer insulation normally used. The result is a compact coil with no air voids and a minimum of insulation.

The system is flexible since many arrangements of strip width and thicknesses may be used. Two or more strips multiple wound may result in lower cost coils, since the lower cost of thicker strips and the elimination of almost 50% of the insulation may more than offset the slitting costs and the additional labor to handle two coils.

The excellent heat transfer characteristics of strip wound coils result in lower average operating temperatures and in much lower hot-spot temperatures. Fig. 14-6 showing temperatures vs. conductor location for an actual case amply demonstrates this principle. As noted, average operating temperature is reduced in this instance about 12°C and hot-spot temperatures are reduced approximately 40°C. These reductions may be significant when the choice of insulating materials is considered. Cooling ducts may be eliminated under certain conditions with significant cost savings.

Joining

Electrical connection of an aluminum strip wound coil to external circuits requires that a suitable lead be attached to the strip which can then be soldered or bolted into the external circuit. These leads usually are round copper wire or flat copper strip. Common methods of joining such leads to the aluminum strip and for making aluminum to aluminum splices are:

Coldwelding: Pressure welding at room temperature is an accepted method of joining aluminum strip conductor

\* See ASTM-B324 for additional information on rectangular and square wires of aluminum.
electromagnetic and other electrical applications of aluminum

Fig. 14-6. Heat transfer characteristics of aluminum strip conductor.

A (130)—Max. operating temperature—copper
B (96)—Normal operating temperature—copper
C (90)—Max. operating temperature—aluminum
D (34)—Normal operating temperature—aluminum

Mechanical Joints: Use of mechanical joints in aluminum and copper has been successful when joints have been properly designed. Riveted joints have been successfully used for years in the small strip conductor wound horn coil and the larger welder reactor coils. Mechanical connectors are available for joining solid or stranded wire leads to strip conductor.

Fold Out Parent Metal: The end of the strip may be slit or folded by various techniques and brought out at 90° to form a narrow laminated lead. A flexible lead can then be attached by welding, by mechanical connectors, or by bolted connections. In Fig. 14-7, C is a strip slit in four equal widths folded out individually—one on top of the other.

Shielded Inert Arc Welding: All types of inert gas shielded arc welding which do not require a flux are acceptable for joining aluminum to aluminum. Two methods are most commonly used:

1. A tungsten electrode with the filler rod being fed by hand as in gas welding. (TIG)

2. A consumable electrode of aluminum welding wire fed through the inert gas envelope. This is a particularly fast method and is used for automatic set-ups. The weld has 80-90% of the original strength of the parent metal. (MIG)

High Temperature Solder: Effective solder joints can be made without the use of corrosive fluxes. Abrasive means must be employed in pre-tinning the surfaces of the metals for subsequent soldering without fluxes.

Ultra-Sonic Welding: Lap joints may be made between aluminum to aluminum and to copper by a vibrating technique to result in a metallurgical bond without the application of heat.

Transition Pieces: An aluminum to copper transition piece (Fig. 14-3) may be used to make aluminum to aluminum connection at the strip and to make a copper connection to a lead or terminal. The transition pieces are usually made by cold or flash welding.

Strip Magnet Conductor Types

Magnet strip is available in gauges ranging from .001 inches to .0959 inches. It is supplied bare for use with interleaving materials, or coated with conventional film insulations and special high temperature types including anodized strip.

Magnet strip conductor from .008 inch and heavier can be supplied with a fully contoured round edge, both bare and insulated. Magnet strip conductor is supplied insu-
### TABLE 14-3

Comparative Cross Section Area—Equal Volume Conductance

<table>
<thead>
<tr>
<th>AWG WIRE SIZE</th>
<th>COPPER 100% IACS</th>
<th>ALUMINUM EQUIVALENT 1350-0</th>
<th>ALUMINUM EQUIVALENT 1235-0</th>
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<tr>
<td></td>
<td>SQ. IN.</td>
<td>62% IACS</td>
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<td>.000200</td>
<td>.000322</td>
<td>.000327</td>
</tr>
</tbody>
</table>

### TABLE 14-4

Useful Formulas for Aluminum Strip Wound Coils

<table>
<thead>
<tr>
<th>Area</th>
<th>A = W X T</th>
<th>Square Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Resistance @ 20° C</td>
<td>Ohms</td>
</tr>
<tr>
<td></td>
<td>R = .013136 L/1000A</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>M = 1.172 X L X A</td>
<td>Pounds</td>
</tr>
<tr>
<td>Length</td>
<td>L = N X MLT</td>
<td>Feet</td>
</tr>
<tr>
<td>Mean Length Turn</td>
<td>MLT = P + π D/12</td>
<td>Feet</td>
</tr>
<tr>
<td>Winding Depth</td>
<td>D = N(T + t) / .975</td>
<td>Inches</td>
</tr>
</tbody>
</table>

Where:
- W = Strip width in inches
- T = Strip thickness in inches
- t = Interleave thickness in inches
- N = Number of turns
- P = Perimeter of core insulation in feet

Some Basic Considerations Relating to Aluminum Magnetic Wire

When a current passes through a loop or turn of the electrical conductor, a magnetic field is set up within and around the turn. The magnetic field increases and decreases directly as the current varies. Adding turns also increases the magnetic field. The reverse of this process is that when a magnetic field varies within a turn or turns...
electromagnetic and other electrical applications of aluminum

Fig. 14-7. Various methods of applying terminals to aluminum strip conductor.

A. Mechanical joints. Use of mechanical joints in aluminum and copper has been successful when joints have been properly designed. Riveted joints have been successfully used for years in the small strip conductor wound horn coil and the larger welder reactor coils. Mechanical connectors are available for joining solid or stranded wire leads to strip conductor.

B. Coldwelding. Pressure welding at room temperature is an accepted method of joining aluminum strip conductor to aluminum or copper in production. Coldwelding anodized aluminum to anodized aluminum, bare aluminum or copper requires no wire brushing of the aluminum surface. Tests have proven that the joints formed by this method have high conductance and high strength. Commercial equipment is available for joining a wide range of thicknesses and widths of strip conductor.

C. Fold out parent metal. The end of the strip may be slit or folded by various techniques and brought out at 90° to form a narrow laminated lead. A flexible lead can then be attached by welding, by mechanical connectors, or by bolted connections. Shown is a strip slit in four equal widths folded out individually—one on top of the other.

of an electrical conductor, there is induced in the conductor an electromagnetic force which will cause current to flow if the turn is connected to a load. This action forms the basis of a fundamental law of electricity, the application of which underlies the design and operation of most electrical apparatus and circuitry.

Electrical energy may be transformed from one circuit to another with possible change of voltage and isolation of the two circuits by sharing of a magnetic field in which one component forms the magnetic field (must be alternating) and the other has induced in it the electromagnetic force from the changing magnetic field. This is known as mutual coupling.

A second method of transforming energy is by direct coupling—the sharing of a resistor, inductor or capacitor.

The magnitude of the induced emf (e) depends on two fundamental factors, as follows:

\[ e = N \frac{d\phi}{dt} \]  
(Eq. 14-4)

where: \( N \) = number of turns 
\( \frac{d\phi}{dt} \) = time rate of change of flux (the magnetic field)

and \( e = L \frac{di}{dt} \)  
(Eq. 14-5)

where: \( L \) = coefficient of self inductance 
\( \frac{di}{dt} \) = time rate of change of current

From (4) and (5) it is seen that:

\[ \phi = \frac{LI}{N} \]  
(Eq. 14-6)
### TABLE 14-5

Strip Conductor Alloys — Physical Constants at 20°C

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>Copper Electrolytic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1350—0</td>
<td>1235—0</td>
</tr>
<tr>
<td>Volume electrical conductivity minimum percent IACS</td>
<td>62</td>
<td>61</td>
</tr>
<tr>
<td>Density lb./in.³</td>
<td>0.09765</td>
<td>0.09765</td>
</tr>
<tr>
<td>Volume resistivity microhm — in.</td>
<td>1.09482</td>
<td>1.11277</td>
</tr>
<tr>
<td>Weight resistivity microhm — lb./ft.²</td>
<td>15.40</td>
<td>15.65</td>
</tr>
<tr>
<td>Temperature co-efficient of resistance ohm/°C</td>
<td>0.00410</td>
<td>0.00403</td>
</tr>
<tr>
<td>Specific heat cal/gram/°C</td>
<td>0.214</td>
<td>0.225</td>
</tr>
<tr>
<td>Co-efficient of thermal conductivity cal/sec/CM²/CM/°C</td>
<td>0.57</td>
<td>0.55</td>
</tr>
<tr>
<td>Co-efficient of linear expansion per °C</td>
<td>23.8 x 10⁻⁶</td>
<td>23.6 x 10⁻⁶</td>
</tr>
</tbody>
</table>

Where: \( \phi \) = flux or field  
\( I \) = current in conductor

For a coil with a magnetic core (iron) with permeability \( \mu \) and reluctance \( R \):

\[
\phi = \frac{N}{R} I \quad \text{(Eq. 14-7)}
\]

and

\[
R = \frac{1}{\mu A} \quad \text{(Eq. 14-8)}
\]

Therefore:

\[
\phi = \frac{N I}{\mu A} \quad \text{(Eq. 14-9)}
\]

Where: \( A \) = area of flux path in iron  
\( l \) = length of flux path in iron

To achieve a coil with high magnetic field capability and low cost, size, weight, and energy consumption has been the goal of designers since the time of Faraday who did fundamental work in the area of electromagnetic induction in the last century.

Electromagnetic coils consist of coils of many turns of magnet wire (insulated conductor) wound around soft iron cores whose ends are connected in loops, if design permits. Improvements over the years have been (1) lamination of the iron to reduce losses, (2) increasing the permeability of the iron, (3) reducing the thickness of the magnet wire insulation and layer insulation to permit more turns per unit space, (4) improving the thermal stability of the magnet wire insulation to allow more current to flow at higher temperatures, (5) use of rectangular wire and strip (interleaved) to gain in space factor, (6) improved thermal dissipation for cooler operation.

Other more recent advances in rapid-chilled iron with amorphous internal structure (glass-like) promise a drastic reduction in iron losses for next generation coils and transformers.