Aluminium foil for electrical windings

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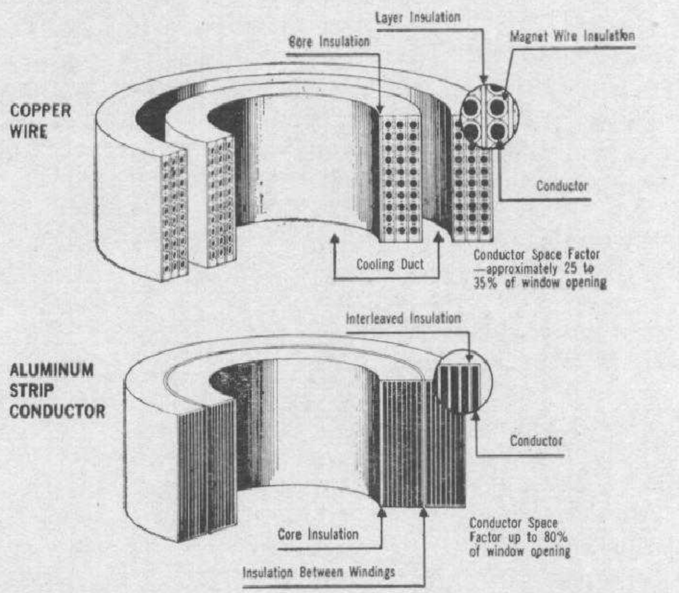
COMPARED to copper, aluminium is far more abundant. This is particularly true for India. The price of aluminium unlike that of copper has been quite stable for over a quarter century and for equal conductivity, the current price of aluminium is very considerably lower than that of copper. In view of its abundance coupled with versatile properties and relatively stable and competitive price, aluminium has rapidly established itself in various fields and has, in particular, replaced copper in many cases. Aluminium has firmly established itself as an electrical conductor. Today approximately 97% of high voltage transmission cables and about 75% of distribution cables are made of aluminium. During recent years aluminium has also made effective inroad into the bus bar field.

Efforts have more recently been made towards using aluminium foils and strips for electrical windings. The subject is no longer at experimental stage but is already in the sphere of standard production.

Basically, a strip wound electrical coil consists of a number of turns of aluminium strip, anodized, suitably coated or interleaved with layers of strip insulation.



1 *Comparison of space utilisation between copper wire and aluminium strip conductor*

Reasons for slow development

There are good reasons, of course, for the slow, and, as yet, rather limited acceptance of aluminium in electrical windings. For equal conductivity, aluminium conductor must have a much larger size than copper tending to increase the size of the winding. This is incompatible with the modern trend towards smaller and more compact electrical equipment, and has been an important consideration against the use of aluminium in electrical windings. Inherent problems of joining aluminium to itself and to copper, usually necessary at some point in electrical installations, further retarded the development of aluminium for such uses. The price advantage of aluminium mentioned earlier is much less significant in the case of conductors in finished form than for base metals.

The position has been even less favourable for aluminium in the early days because of the control of prices and distribution of aluminium conductors by copper interests. Finally, inertia, a factor usually associated with most new ventures, slowed down conversion to aluminium.

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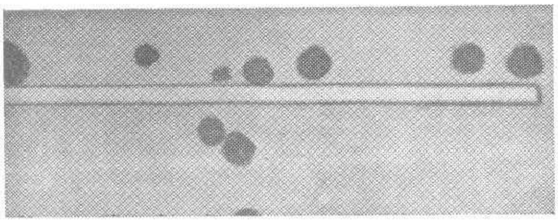
Size factor

The electrical conductivity of E. C. grade aluminium is 61% of that of copper, so that for equal conductivity, the cross section of aluminium conductor will have to be 1·64 times as large. For conventional winding, the larger conductor cross section would mean corresponding increase in the size of the magnetic circuit and case; this in turn will somewhat off-set the economic advantage of conductor costs alone.

The cross section of the conductor, however, is not the only determining factor for the overall size of the electro-magnetic system and the cost of the equipment. Compared to round copper wire, aluminium strip or foil conductor would give much better space utilisation. This is clearly illustrated in Fig. 1.[1]

Furthermore, the insulation system, including provisions for cooling, are important factors in determining the overall size of the equipment. Assuming that the number of layers in an aluminium strip wound conductor equal the number of turns of copper wire in an equivalent wire wound coil, the layer to layer voltage in the former would equal the turn to turn voltage in



2 *Cross section of film on ·075mm foil thickened towards the outer edge, magnification X 30. The film is 25μ thick at the edges, diminishing to 7μ at the centre*

the latter. As a result, the aluminium strip coil does not have the high layer to layer voltage and hence does not need expensive layer insulation common in copper wire coils. Insulation thicknesses and voids can be reduced in the case of aluminium strip wound coils and as a result even though conductor volume may be 60% greater than equivalent copper windings, in most cases aluminium strip can be wound in the same space required for the copper coils.

Heat transfer characteristics and operating temperatures

Heat transfer characteristics and permissible operating temperatures are further considerations which may affect the size of the conductor insulation system.

Aluminium strip has much better heat transfer characteristics compared to copper wire in electrical coil. The strip transfers heat from the centre to the outside edges at a much faster rate than layers made up of adjacent turns of insulated wire. Also, because of better heating and cooling characteristics, aluminium strip coils are capable of withstanding much bigger surges and safety factors may be greatly reduced. These circumstances are particularly important in determining the requirement of insulating material.

Aluminium can withstand considerably higher operating temperature than copper. The latter is susceptible to rapid oxidation and flaking at temperatures above 200°C. Aluminium, on the other hand, withstands temperature up to its melting point without flaking and without excessive oxidation. With anodised aluminium foil or strip the limitation of working temperature is determined by the melting point of the conductor itself, for the oxide film is stable up to much higher temperatures. This condition is unique ; in no other case is the melting point of the conductor lower than the permissible operating temperature of the insulation. With anodised aluminium foil windings continuous operation at 500°C has been reported.

In power engineering, where it is inadmissible to increase the load losses, the cross-section of aluminium conductor is to be based on equivalent I^2R losses and has to be 1·64 times that of copper as mentioned earlier. Where increased load losses are permissible, however, the cross-section of aluminium conductor can be reduced on the basis of equal temperature rise. On this basis, the cross-sectional area of aluminium needs to be only 1·28 times as large, because the specific heat of aluminium, ·230 Cal/gr/°C, is far greater than that of copper, ·095 Cal/gr/°C. The cross-section can indeed be reduced further on the basis of higher permissible operating temperatures. In the case of copper, current density of 1 000A/sq. in. is common. In the case of aluminium this figure need not be applicable and the current density may be calculated on the basis of permissible temperature rise.

If the current carrying capacity of aluminium can be utilised on the basis of equal temperature rise, if the higher operating temperature and better heat transfer characteristics of foil or strip winding are taken into account and if insulation volume is minimised by using very thin anodic film, the dimensions of an aluminium foil winding may actually be significantly smaller than the corresponding copper winding.

The higher operating temperature permissible with aluminium winding is also advantageous where ambient temperatures are high, e.g. in atomic energy reactors, missiles and supersonic aircraft as well as for normal use in many places in a country like ours.

Weight

An aluminium coil would usually weigh about half of an equivalent copper coil. This may be an important consideration, e.g. in aircraft and missile assemblies where weight is a vital factor. For the same reason, aluminium windings are conveniently used in lift magnets.

Insulation

The most significant development in recent years in the electrical coils technology has been in the field of insulation. There is today an extremely wide range of insulating materials available. The most important characteristic of an insulating material is of course its thermal endurance, i.e. the maximum temperature at which it can operate satisfactorily. Paper, for instance, is satisfactorily used at low operating temperatures, Epoxy Resins at somewhat higher and anodic films at considerably higher temperatures.

It is to be appreciated that other characteristics in addition to thermal endurance, namely, mechanical strength, abrasion resistance, resistance to moisture penetration and electrical strength are required in varying degrees in insulating materials for different applications.

Aluminium foil or strip wound with interlayer insulation consisting of paper or some kind of film such as Mylar, Nylon, etc. are in use. This type of coil, for equivalent load losses, requires larger volume compared to corresponding copper wires or strip wound coils, but may yet offer significant economic advantages. They are not capable, however, of high temperature performance, for the insulating material has relatively poor thermal rating.

Resin-coated foil windings can also be used. Somewhat higher temperatures, up to about 180°C may then be tolerated and space saving may be significant compared to windings with interlayer insulation. Using anodic film of several microns in thickness for insulation, the size of the aluminium foil winding even for equivalent load losses, need not be any greater than the corresponding copper wire or strip winding. Possibilities of using anodic films for insulation of aluminium conductors have long been recognised. Early developments were directed towards anodising of round sections. Technology of continuous anodising was developed and a satisfactory film could be obtained on straight conductors, but bending usually resulted in failure of anodic film. Attention was then diverted to foils and strips of aluminium having the same cross-sectional area as the round conductors. The bending problem was overcome but the ragged non-uniform edges were practically impossible to anodise satisfactorily.

Suitable chemical and mechanical treatments have since been developed to condition the edges and ensure a satisfactory and continuous anodic film all through.

The flexibility of the anodic film is of course dependent on the anodising process and on the thickness of the film. Highly flexible films are now possible to obtain. Anodised foil ·09 mm thick with 5 micron anodic film may be wound round 3 mm. mandrel without damage to the film.

Abrasion resistance of anodic film is also quite good both on the flat surface and on the edges.

Anodic films have good electric strength also. 5 micron thick anodic films produced by the common sulphuric acid process have shown breakdown figures of 200 volts min. It is possible, therefore, to design coils with interturn voltage up to 200V r.m.s. The film thickness may be increased particularly towards the edges to obtain higher electric strength. Figure 2[2] shows cross-section through an anodised film 7 micron thick at the centre and 25 micron thick at the edges with corresponding voltage breakdown figures of 342V. r.m.s. and 403V. r.m.s. respectively.

Coil winding

Coil winding with aluminium foil or strip is relatively simple. High speed semi-automatic winding equipments are available. Anodised, coated or interleaved foil or strip may be wound without difficulty and it should be possible to use electronic control device for extreme precision windings. Winding coils with strips is definitely faster and easier than that with round wire and the former lends itself more readily to automatic control.

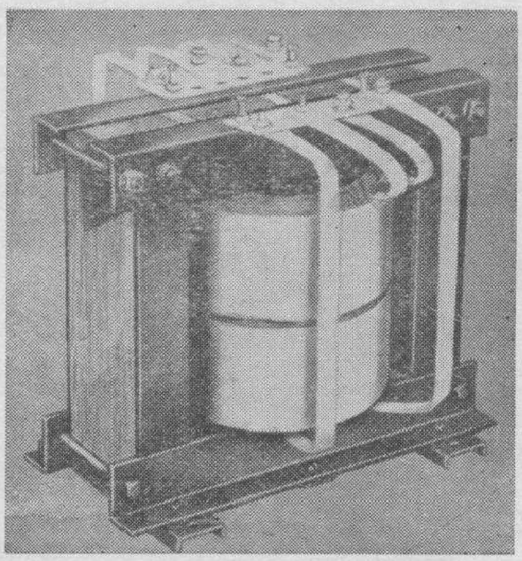
Aluminium strip or foil, most suitable for winding, is in hard or half-hard temper ; fully annealed material may tend to stretch and lose shape when handled and coiled. 99·0% and 99·5% aluminium min. purity are commonly used.

Jointing

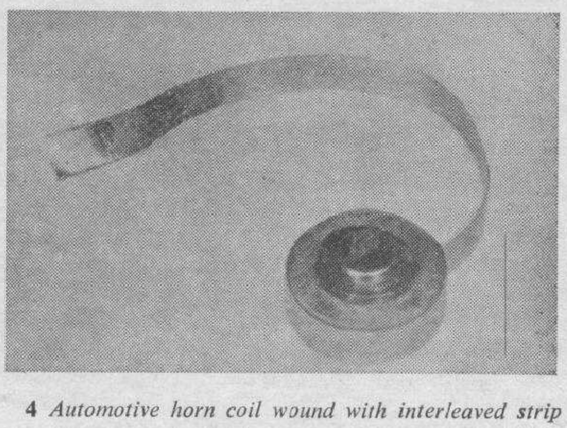
One of the reasons for the relatively slow development of aluminium as conductor is the inherent problem of joining aluminium metal to itself and to copper, which is often necessary at some point in the system. It is now appreciated, however, that these problems are no more serious than those normally encountered in any new development project. Suitable techniques have been developed and by judicious use of them it is possible to obtain high conductivity, high strength joints at economical costs.[3] Aluminium strip and foil windings with relatively large contact area available for jointing, renders the problem easier than with wire windings.

Shielded inert arc welding is useful for making aluminium to aluminium joints and is well established. Spot welding and ultrasonic welding have also been used successfully.

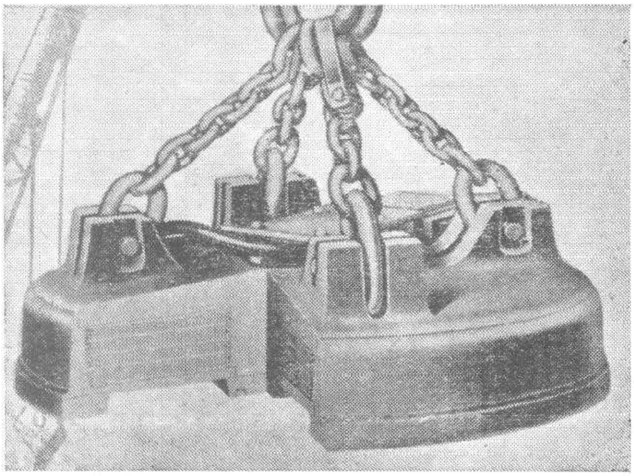
Cold welding or pressure welding at ordinary temperature has proved very useful for joining aluminium to aluminium or copper. In cold welding anodised aluminium to bare or anodised aluminium or copper no preparation of either surface is necessary. Joints formed by this method have high conductivity, high strength and are apparently unaffected by ageing or temperature cycling.



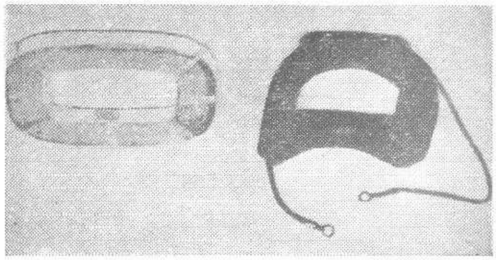
3 *10 kVA transformer wound with anodised strip*



4 *Automotive horn coil wound with interleaved strip*



5 *Lift magnet using anodised aluminium strip conductor*



6 *Automotive generator coil wound with aluminium foil interleaved with Mylar*

Mechanical joints in aluminium and copper have been successful provided adequate care is taken in designing the joints. Rivetted joints have been used successfully in small, strip wound horn coil as well as larger, welder reactor coils.

Soldering can also give satisfactory joints.[4] With bare aluminium, a special solder and flux may be used or alternatively, an ultrasonic soldering iron and solder without flux. For anodised aluminium, an ultrasonic activated solder bath has been used.

Present applications

Use of aluminium foil for electrical coils is now well established. It has been utilised in applications ranging from solenoids for heavy electro-mechanical equipment to field coils for travelling wave tubes and coils for television receivers. Anodised strip is being used for dry type and oil filled transformers, reactor coils, magnet coils, etc. Interleaved and coated aluminium foil and strip windings have proved particularly satisfactory for many automotive electrical applications such as field coils for generators and motor starter relay coils, voltage regulator and ignition coils and horn coils.

Figures 3 to 6 illustrate some of the typical uses of aluminium foil in electrical coils.

Figure 3 shows a 10 kVA 480/240 volt. transformer wound with anodised aluminium strip 2 mm × 84 mm. This coil was compared with an equivalent coil made with copper wire and wound into identical shell type core. Electrical characteristics were found to be practically identical. Space utilisation was about equal. The weight of the aluminium coil was only about 50% of that of the copper coil and the cost of the former was also about 60% of that of the latter. Heat run tests indicated favourable ultimate temperature rise of the aluminium winding as well as absence of any hot spots.

Figure 4[5] illustrates an automotive horn coil wound with interleaved aluminium foil.

Figure 5[6] illustrates another ideal application of anodised aluminium strip conductor, namely in lift magnets. With anodised aluminium strip, the space factor remains favourable, insulation and winding costs are reduced and the reduction in weight means greater pay loads with smaller cranes, leading to significant cost saving.

Figure 6[7] illustrates an automotive generator coil made with aluminium foil interleaved with Mylar. It is shown before forming as well as in the finished form, insulated with copper connectors. Extensive tests carried out on this type of coils indicate that aluminium wound coils are equal or superior to copper coils.

Conclusion

In conclusion, it is quite clear that aluminium foil and strip windings may be used quite satisfactorily in place of those with copper.

Aluminium is more readily and more abundantly available and is less expensive. Use of aluminium need not cause any significant increase in size. Joining methods are adequate. Higher operating temperatures may be effectively utilised. Reduced weight may be advantageous.

Because of the advantages noted above, aluminium strip and foil windings have been adopted for various applications.

References

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Discussions

Mr **Padmanabhan** (TISCO, Jamshedpur) : The author referred to anodised strips being used for electro-magnets. In case the aluminium anodising is scratched or broken at places, I would like to know if it would be possible to carry out repairs. Could we unwind the whole strip and use again the unaffected portions ?

Dr **B. N. Bose** (Author) : Anodised aluminium is a very hard, wear resistant and scratch resistant coating. There is no likelihood of any scratch occurring on the surface because the whole coil is actually given a thermostatic plastic resin coating which protects it just as in a sealed unit. If at all damages are caused there is little possibility of repairing and the whole unit has to be discarded.