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EXPERIENCE WITH ALUMINUM MAGNET COILS*

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Aluminum conductor has been used by various other groups in magnet construction but this has been the exception rather than the rule. At SLAC, after two years experience with the use of aluminum conductor for magnets, we are approaching the point where in large magnets, copper coils are becoming the exception. Our experience indicates that by using aluminum instead of copper for large magnets, we can make a saving of approximately 25% on the cost of these magnets. But to achieve these savings, full advantage must be taken of the characteristics of aluminum. It cannot be treated purely as a material substitute for copper. In these days of tight budgets, this saving is well worth considering.

There is no question that aluminum conductor has its drawbacks. The lower allowable current density for a given power dissipation increases the bulk of the magnet and is the limiting factor in the use of aluminum where high current densities are required (i.e., high gradient quadrupoles, inflector magnets, etc.). The corrosion properties of aluminum require close control of the cooling water purity. (Our results on corrosion have been exceptionally good, and are contrary to some previously accepted corrosion theories.) We have found that in the usual workhorse magnet (bending magnets, low gradient quadrupoles, spectrometer magnets, etc.), the low cost per pound of conductor or per unit of conductance, the ease of fabrication, and lack of shop-made joints within the coil, for aluminum conductor far outweigh the disadvantages mentioned above.

Hollow core aluminum E.C. grade conductor is extruded directly into its final configuration from large pre-heated billets or cylinders weighing up to several hundred pounds, and reeled onto large reels for ease of handling. In the so-called porthole extrusion process, the aluminum is first extruded into a number of ribbons or bars which are then recombined to produce the final shape. The entire process is completed in a die a few inches long. This procedure requires that four pressure welds be made (forming the square shape around a central mandrel) continuously for the length of the conductor. (Figure 1.) Additionally, to produce long lengths of conductor (up to several thousand feet) many billets are required, and these billet-to-billet interfaces are welded together under the pressure of the extrusion process and from the heat of the pre-heated billets within the die. Needless to say, the water-tight integrity of these long lengths of conductor was open to question.

There is another process for the production of lengths of aluminum extrusion where tubular billets are used. The die now forms the exterior of the conductor only. The center is formed by a mandrel extending through the center of the tubular billet. The process eliminates the continuous pressure welds produced by the porthole die process. It does not however, eliminate the press weld required to join billet-to-billet. According to aluminum fabricators, the die and mandrel process is more expensive and there is question as to the reliability of the billet-to-billet welds.

Metallurgical examination (1) made of the conductor indicated that the pressure welded continuous joints were metallurgical bonds. We had grain growth across the weld joint. The press weld joint joining billet-to-billet was smeared out for about a 10 ft. length of the extruded conductor. Microscopic examination indicated some oxide particles interspersed between grains of aluminum but that the joint was metallurgically sound.

All reels of conductor are leak tested (2) as they are received at SLAC. High pressure gas fittings are welded onto the exposed ends of the length of conductor on the reel. The reel is then encased in a large polyethylene bag. The interior of the conductor is pressurized with helium at 700 psi and held at this pressure for a period of 24 hours. Helium concentration within the bag is compared with the ambient concentration to determine the leak rate if any. To date we have tested about 30,000 ft. of aluminum conductor (approximately 1" sq.) without finding any indication of a leak.

This ability to procure single leak-proof lengths of conductor 5,000 to 6,000 ft. long, eliminates the need for splicing or joining the conductor within the coil. Elimination of the brazed or welded joints and required leak testing produces a substantial portion of the reduction in labor cost previously mentioned. The remainder of the reduction in labor cost can be attributed to the high workability of aluminum due to its relatively low strain hardening rate.

The yield strength of extruded aluminum conductor is listed at approximately the same as fully annealed copper (10,000 psi at .2% elongation). However, the rate of strain hardening of aluminum appears to be far lower than that of copper. Springback and keystoning in bending the aluminum conductor in a radius 1-1/2 times its thickness is negligible. This low strain hardening rate reduces the tension required for forming the conductor and the amount of cold working necessary (hammering, etc.) to form the conductor into the desired radius or shape. The reduced tension and keystoning allows pretaping the insulation on to conductor as it is wound onto the coil form. This is in contrast to the usual method used for copper conductor of forming the coils bare, spreading the formed coils, removing the keystoning sharp burrs, etc., from the conductor with files or routers and then hand taping the cleaned coil with insulating tape.

On comparable coils for a window frame magnet, labor time expended for the aluminum coil was about half that for the comparable copper coil. (Power dissipation and aperture size for both coils are equal.)

In addition to the large saving in labor, the difference in cost of materials is substantial. The cost of aluminum conductor per unit conductance is approximately 1/4 of the cost of copper. Aluminum has 60% the conductivity of copper, however, its specific weight is 1/3 as great, therefore, its conductance per unit

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weight is twice that for copper. The present price of aluminum conductor is approximately 60 cents per pound, versus copper at &1.00 to &1.20 per pound. So you get about 3-4 times the conductivity per dollar for aluminum, versus copper.

The fabrication process for an aluminum coil is as follows: the aluminum conductor is received from the vendor on a large reel (up to 6,000 ft. per reel). The conductor on the reel is leak checked as previously described. It is then placed on a de-reeling cradle and one end of the conductor is passed through a tension device consisting of two spring loaded wooden blocks and attached to the winding fixture. The conductor is cleaned with a suitable solvent and inspected for burrs and protrusions. It is then insulated with half lapped "B" staged epoxy fiberglass tape by a hand-held tape winding machine traveling on the conductor. On some coils a layer of mylar tape is half lapped onto the conductor and the "B" staged epoxy fiberglass tape is wound over this insulation in the same operation. In winding onto the coil form, a layer of sheet insulation (D. M. D.) is introduced between conductors at the high pressure points (bends) to reduce the possibility of cut through of the insulating tape.

For a one-off-magnet coil where the price of a potting fixture cannot be justified for the single coil needed, the following process is used to produce the coils with the mechanical rigidity required to withstand the magnetic and mechanical forces applied in operation. The pre-insulated conductor is wound on the coil form to produce a single layer of the coil. This layer is then coated with a very high-viscosity, long pot life epoxy resin. The high viscosity of the resin at room temperature does not allow the resin to flow at room temperature and interfere with subsequent winding. The long pot life is necessary so that we do not get polymerization of the resin prior to completion of the coil.

The now generously resin-coated layer of the coil is covered with a layer of insulating material (D. M. D.) that not only covers the epoxy resin and keeps it from interfering with the next layer, but also acts as layer-to-layer insulation as well. The next conductor layer is now wound directly on the previous layer and the epoxy insulating sheet procedure is repeated. This process is continued until the required number of layers is completed.

The wound coil is now removed from the winding form and given a layer of epoxy over which the ground insulation is applied. The ground insulation consists of sheet D. M. D. overwrapped with a half lap of "B" stage epoxy fiberglass tape. Pressure is applied to the coil by clamps and/or weights where dimensions have to be held. The resin is cured by passing steam through the coils.

As the temperature of the coils is raised the viscosity of the previously applied resin is reduced allowing it to flow throughout the coil binding the individual conductors into a solid mass when it polymerizes. After completion of the cure, the exterior of the coil is given several coats of epoxy paint as further protection against inadvertent wettings.

Where the cost can be justified as in making multiple coils for a series of magnets, the aluminum coils are vacuum impregnated by the same procedures applied to the usual copper coils. The epoxy formulation used in the coils are not cured for maximum physical properties. It is the belief of the author that radiation and/or high operating temperatures will first continue the cure increasing the physical properties of the epoxy before the well-known radiation degradation effects become predominant. The net effect should be an increase in the useful life of the epoxy.

Incidentally, the cure cycle for the resin (gel at 90^{o}C and cure at 130^{o}C) is in the recommended range for protective oxide formation (boehmite) (3). De-ionized water is circulated through the coils to obtain the 90^{o}C gel temperature. Steam generated from de-ionized water is used for the 130^{o}C temperature. Cure time is approximately 6 hours at 130^{o}C.

All fittings that are welded to the E.C. grade conductor are 6063 T6 aluminum. E.C. grade aluminum is so soft that it is impractical to machine. 6063 T6 was chosen because of its fair machine-ability, low alloy content, and general corrosion characteristics. Its low alloy content should reduce electrolysis with the E.C. grade conductor and makes for a greater compatibility in weld joints. All joints are made to the E.C. conductor by heliarc welding. Reliability of these joints is very high and the joints are easy to make.

No provisions are made to separate the water systems for copper and aluminum. The distribution system is stainless steel feeding both copper and aluminum coiled magnets. Water fittings to the aluminum coils are removed periodically and checked for corrosion.

The latest report available on corrosion of the aluminum conductor at SLAC indicates some minor corrosion after 15 months of operation on some of the fittings. I quote from the report:

"When received, some of the fittings had copper-colored deposits on the inside surface so several cross sections through the most heavily deposited areas were examined. The copper probably originated from the high purity water system. In normal water, only a few tenths of a part per million of copper can cause aluminum to corrode and it was feared that gross corrosion could be underway in the utility magnet coils made from E.C. grade aluminum ... In spite of the large amount of copper deposited on several of the 15 month aluminum fittings, only a minor amount of corrosion was observed. (Two small areas, maximum depth of corrosion approximately .003) ... Since these are the only areas of corrosion seen on some 16 samples of aluminum and stainless steel, I believe there are no serious corrosion problems to be concerned about. As a word of explanation, we have seen several instances of copper deposits on aluminum which have not corroded because of a prior film of copper oxide that first formed on the aluminum surface. I do not understand the protection mechanism offered by the copper oxide, but it seems to frustrate the copper-aluminum galvanic reaction."

As an indication of water quality, a typical analysis taken from two points on the water system is as follows:

Resistivity:	1.8 megohms cm.	PH: 6.7
	LCW1801 Pumps	LCW Patch Box C
Copper	0.06 ppm	0.1 ppm
Copper oxide	none	none
Iron	none	none
Iron oxide	none	none
Aluminum	none	trace
Aluminum oxide	none	none
Chrome	none	none
Nickel	none	none

Economically, there is a break point where the increase in the amount of iron required in the magnetic circuit due to the increased size of the aluminum coil negates all savings that can be made on the coil. This break point is a function of maximum flux density in the gap, width and height of the gap and configuration of the magnet. It is difficult to establish a clear break point but generally, if the area of the cross section of the aluminum coil exceeds the area of the gap, the cost differential will be in favor of a copper coil. There are exceptions to this rule of thumb: for instance, the fabrication cost differential for making pancake coils from aluminum instead of copper is relatively small if the coils are designed so that the copper conductor can be pretaped and conductor of the same configuration is used in each. The fabrication cost differential is substantial, however, if the aluminum conductor is extruded into a flat bar with coolant holes and the coil is ribbon wound with interleaved insulation. As per Fig. 2 each individual coil must be considered on its merits.

It is important that the coil designer and fabricator take full advantage of the characteristic of aluminum conductor instead of the thinking of it as purely a substitute for copper. If treated as copper, the majority of the cost savings indicated above will not be realized.

References

1. Private memorandum, G. P. Fritzke to author, April 18, 1967. Evaluation of diffusion joint in continuously extruded aluminum conductor.
2. Internal Engineering Note by author, February 8, 1967. Leak testing of long lengths of aluminum conductor.
3. Corrosion - National Association of Corrosion Engineers, Vol 18, April 1962. D. G. Altenpohl, "Use of Boehmite Films for Corrosion Protection of Aluminum."
4. Private memorandum, G. P. Fritzke to author, February 18, 1967. "Corrosion Investigation of Utility Magnet Fittings."

Summary. In the magnets where high current density within the coil area is not required, the use of extruded aluminum conductors can provide substantial savings in conductor and fabrication costs of the coils that more than offset the cost of additional iron required.

Solutions to problems unique to the use of aluminum conductors are described.

Two years experience with the use of water-cooled aluminum conductors in a mixed copper and stainless steel water distribution system shows minor discernable corrosion effects on the aluminum conductors and no corrosion on the copper or stainless steel.

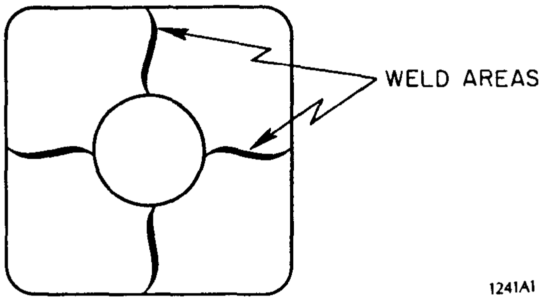

Fig. 1--Extruded square conductor indicating areas of continuous pressure welds

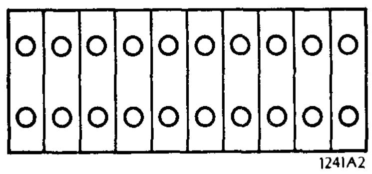

Fig. 2--Cross section of pancake coil using flat bar aluminum conductor