Aluminum in Superconducting Magnets

Robert J. Weggel
Magnet Optimization Research Engineering, LLC
January 28, 2012

For superconducting magnets a candidate material for some applications is aluminum, either ultrapure, as quench-stabilization matrix metal, and/or alloyed and cold-worked and heat treated for high strength, as reinforcement material. As reinforcement, aluminum is suitable only for magnets in which the stresses and strains are modest.

The strongest aluminum alloy commercially available, 7075-T6, has a strength at 4.2 K of 538-676 MPa[1] yield and 697-759 MPa ultimate. Nanostructure hierarchy can improve the ultimate strength to ~1.040 GPa[2]. A permissible-stress criterion of the lesser of ⅔ yield or ½ ultimate would permit loading nanostructure-hierarchy aluminum to 520 MPa. This is 37% shy of the 710 MPa allowable for 316LN stainless steel (the standard material used in the sheath of cable-in-conduit-conductors), for which the yield and ultimate strengths are[3] 1,065±15 MPa and 1,714±28 MPa. A further deficiency of aluminum that makes it completely unsuitable to strengthen magnets of wind-and-react Nb_3Sn is that aluminum permanently loses much of its strength upon exposure to the ~650°C reaction temperature for Nb_3Sn, a temperature so high as to risk melting the aluminum (m.p. = 660°C).

A limitation of aluminum for magnets of all types, not merely of the wind-and-react variety, is its low Young's modulus of 70 GPa, compared to 200 GPa for stainless steel. Whereas 316LN at its allowable stress limit of 710 MPa incurs a strain of only 0.710 GPa / 200 GPa = 0.355%, aluminum at its allowable limit incurs a strain of 0.52 / 70 = 0.74%—likely acceptable for NbTi, but for Nb_3Sn or high-temperature superconductors would require a winding geometry which guarantees that the strain in the superconductor is much less than that in the aluminum.

Aluminum is very good as a stabilizer. Its electrical conductivity can be much better than that of copper; that proposed for the COMET experiment has a residual resistivity ratio (RRR) of 500[4]; i.e., a residual electrical resistivity ρ_0 at 4 K of 300 nΩm / 500 = 0.6 nΩm. For copper co-processed with superconductor, it is difficult to achieve a RRR much better than ~100, for which $\rho_0 \approx 1.7$ nΩm, three times worse than aluminum. The superiority of aluminum over copper is even better in a magnetic field[5]. Aluminum also may be better than copper in a high-radiation environment. Irradiation of aluminum with 2.7×10^{20} n/m^2 increases its resistivity[6] by 0.064 nΩ m at 2.7×10^{20} n/m^2, a factor of 5.7/3.0, but cycling to room temperature restores 100% of the electrical conductivity. For copper the increase in resistivity is less—0.022 nΩ—but recovery is only 80-90% upon thermal cycling to room temperature.

[1] O N Senkov, et al., “Mechanical properties of commercial aluminum alloys at -253^{o}C (–423^{o}F),” NATO ARW, Kiev 7-13 Sept. 2003; Jeigh Shelley, Project Manager, Development of Super-high Strength Aluminum Alloys for Cryogenic Applications, AFRL Contract F04611-02-C-0014, Wright-Patterson Air Force Base.

[2] P V Liddicoa,t et al., “Nanostructural hierarchy increases the strength of aluminum alloy,” *Nature Communications*, MacMillan (2010).

[3] T Ogata, et al., “Results of VAMAS Activities on Pre-standardization of Mechanical Properties Evaluation at 4 K,”, Adv. in Cryo. Eng., **46A**, U. Balu Balachandran, et al., eds., pp. 431-434.

[4] M Yoshida, et al., “Superconducting Solenoid Magnets for the COMET Experiment,” IEEE Trans. Appl. Supercon., **21**, 1730 (2011).

[5] F R Fickett, “Magnetoresistivity of copper and aluminum at cryogenic temperatures,” BNL CONF-720908 (1972), http://lss.fnal.gov.conf/C720919/p539.pdf

[6] T Nakamototo, “Neutron Irradiation Measurements for Superconducting Magnet Materials at Low Temperature” (WASMSDO, CERN, Nov. 14, 2011), http://indico.cern.ch/contributionDisplay.py?contribId=31&sessionId=25&confId=113128