TITLE: **Developments in Materials for High-Field Magnets**

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SUBMITTED TO: **Thirteenth International Conference on Magnet Technology**

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Developments in Materials for High-Field Magnets

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Abstract—The results of the National High Magnetic Field Laboratory's program of characterization of materials and fabrication techniques used in the construction of high-field pulsed magnets are reported. High-field pulsed magnets require conductors with high mechanical strength (750 MPa or greater YS at 77 K) and high electrical conductivity (70% IACS or greater at RT). Electrical insulation and resin systems for vacuum impregnation with high compressive strength (500 MPa at 77 K) and moderate thermal conductivity (1W/mK at 77K) are also required. Developments and future plans for the characterization of new magnet material systems are discussed. Testing results are reported: Mechanical and fatigue testing, electrical conductivity testing and thermal expansion measurements of high strength, high conductivity conductors at cryogenic and room temperature, mechanical testing of a coil support material at cryogenic and room temperature, thermal expansion and thermal conductivity tests of an electrical insulating system at cryogenic temperatures.

I. INTRODUCTION

The National High Magnetic Field Laboratory is developing and building non-destructive pulsed magnets with higher fields and longer pulse duration than now currently available for its national user facility at Los Alamos. The successful design, analysis and fabrication of these magnets requires the understanding and optimum use of presently available materials.

Higher field (60 tesla and higher), long pulse (100 ms) magnets require the following 77 K characteristics of constituent materials: Conductors of high tensile strength (750 MPa), ductility (one to two % elongation and six % at room temperature), electrical conductivity of at least 70% IACS at room temperature with a resistance ratio of about four from 77 K to room temperature. The insulation system at 77 K should withstand a potential of 20 kV and an elongation of one to two %. The coil potting resin should, when combined with the insulation system and conductor produce a compressive strength of 500 MPa and develop a thermal conductivity near one W/m-K at 77 K.

The requirement to design, build and operate a dependable 60 T, large bore, long pulse magnet by early 1995 requires the use of commercially available materials in the magnet

design. A survey, combined with preliminary retesting of commercial materials with dependable sources of supply, resulted in the selection of the aluminum oxide dispersion strengthened coppers: GlidCop AL-15 and AL-60 (GlidCop is a registered trademark of SCM Metal Products, Inc.) for the conductors (C15715 and C15760). GlidCop has been characterized extensively at high temperatures, but its cryogenic performance has not been reported. Tapes of E-glass fabric and polyimide film combined with E-glass cloth were selected for the insulation system. CTD-101 (produced by Composite Technology Development, Inc., Boulder, CO), a cryogenic service rated epoxy resin system suitable for vacuum impregnation was selected. A nitrogen-alloyed manganese stainless steel (Fe-21Cr-6Ni-9Mn) was selected for the reinforcing shells. To prove these materials and give confidence to the magnet design and its analysis, a battery of tests were performed to obtain essential but unavailable material behavior information.

II. TESTING SPECIFICATIONS

Processing of the dispersion strengthened copper (i.e. GlidCop is outlined in Nadkarni, et. al., (1). The GlidCop AL-15 and GlidCop AL-60 were cold worked 90% and 70%, respectively. The nitrogen-alloyed manganese stainless steel was obtained from fully annealed bar stock. A four wire dc method was used to measure the resistance. The accuracy of the resistivity measurements is $\pm 1.0\%$ due to cross-sectional area and voltage tap separation measurement inaccuracies. Mechanical test samples were tested on a MTS 880 (MTS is a registered trademark of MTS Systems Corp.) at a strain rate of $1.67 \times 10^{-3} \text{ s}^{-1}$. An 11,000 kg load cell was used for the tests. All tests were accomplished in accordance with ASTM Standard E8-93. A 0.76 cm cryogenic extensometer was used for measuring the elongation for up to 15% total strain. The total elongation was also calculated by measuring the initial and final gauge lengths using a Mitutoyo microscope with a resolution of 0.25 mm.

Thermal expansion was measured using a three-terminal capacitance cell dilatometer with an accuracy of $\pm 2\%$.

A 100 kN capacity servo hydraulic test machine produced the sinusoidal tension/tension fatigue tests ($r=0.1$, $f=15 \text{ Hz}$.) in load control mode. Applied stress levels were monitored during fatigue testing with a digital oscilloscope.

Thermal conductivity was determined by measuring the temperature change across cooled samples carrying a known heat flux. Sample cooling was achieved using a Model 350 CIT Inc. helium refrigerator. Temperatures were measured using calibrated K-type thermocouples.

Manuscript received September 20, 1993. This work supported by National High Magnetic Field Laboratory and National Science Foundation, cooperative agreement No. DMR-9016241. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply endorsement, recommendation, or favoring by the United States Government or any agency thereof.

Material	Comments	Source	RT YS (MPa)	RT UTS (MPa)	RT EM (GPa)	RT %EL	77K YS (MPa)	77K UTS (MPa)	77K EM (GPa)	77K %EL	R R	RT-EC % IACS	Therm. Expan. 78K to RT (%)
GlidCop AL-15 f	6 mm dia. rod	S C M	506 (3)	537 (3)	112 (3)	12	626 (3)	665 (3)	119 (3)	12.8	4.61	93.4	0.3
GlidCop AL-60 Ω	6 mm dia. rod	S C M	570 (3)	620 (3)	118 (3)	9.2	745 (3)	856 (3)	143 (3)	16.6	3.98	79.5	0.299
Fe-21Cr-6Ni-9Mn ¥	76 mm dia. bar	Fry Std	466 (3)	754 (3)	176 (3)	-	1030 (3)	1516 (3)	192 (3)	-	-	-	-
				195K Fatigue Strength			77K Fatigue Strength						
				(MPa)			(MPa)						
GlidCop AL-15	10K cycles	S C M	585										
GlidCop AL-60	10K cycles	S C M	754				838						
E-glass/Epoxy	parallel to fiberglass tape layers												
Insulation Sample	normal to fiberglass tape layers												
E-glass/Epoxy/													
Polyimide Insul./Cu		(W/m-K)											
Therm. Cond. Sample		1.56											
KEY:													
RT=293K, YS=tensile yield strength at 0.2% offset, UTS=Ultimate tensile strength, EM=Elastic modulus (Young's modulus),													
%EL=per cent elongation at UTS, RR=ratio of electrical resistance at RT to the electrical resistance at 77K, RT-EC=electrical conductivity at RT,													
%IACS=electrical conductivity relative to IACS standard; 100% IACS=1.72 Microhm-cm at 293 K, (No.)=number of test samples if more than one,													
GlidCop AL-15=aluminum oxide dispersion strengthened copper (Copper No. C15715, low oxygen),													
GlidCop AL-25=aluminum oxide dispersion strengthened copper (Copper No. C15725, low oxygen),													
GlidCop AL-60=aluminum oxide dispersion strengthened copper (Copper No. C15760),													
f : GlidCop AL-15 was cold worked 90%, Ω : GlidCop AL-60 was cold worked 70%, ¥ : Fe-21Cr-6Ni-9Mn was in annealed condition,													
SCM=SCM Metal Products, Inc., Fry Std=Fry Steel Co., Santa Fe Springs, CA													

Table 1

III. DISCUSSION OF RESULTS IN TABLE 1

The results of these tests are shown in Table 1. Considerable effort has been made to characterize the aluminum oxide dispersion strengthened coppers: GlidCop AL-15, and AL-60. They were mechanically tested at RT and 77 K. Yield strength, ultimate tensile strength, elongation and Young's modulus were measured. As expected, the yield strength, elastic modulus, and ultimate tensile strength increased at cryogenic temperatures. The ductility also increased with a drop in test temperature due to an increase in strain hardening (2). Room temperature results compared well with those published by the Copper Development Association (3) and Metals Handbook (4). The thermal expansion of these coppers from 78 K to RT was measured. The total expansion of the GlidCop coppers from 78 K to RT is shown in Table 1, but continuous data for both total expansion and rate of expansion versus temperature was also obtained. The electrical conductivity at RT and 77 K was measured. Electrical conductivity and resistivity ratio decreased with an increase in alumina content due to an increase in scattering effects with a greater number of alumina reinforcement particles. Room temperature results compared well with those published in literature (3,4). Mechanical fatigue strength tests at cryogenic temperatures are underway; available data at 195 K and 77 K are listed.

The total thermal expansion (parallel and normal to the plane of the tape) of samples of the epoxy impregnated E-glass tape insulation system from 80 K to RT was measured and is shown in Table 1. Continuous measurements for both total expansion and rate of expansion were also obtained during these measurements.

The thermal conductivity of samples containing multiple copper/insulation interfaces and layers are being measured; available data at 100 K is listed.

The yield strength, ultimate tensile strength, and Young's modulus at 77 K and RT of the Fe-21Cr-6Ni-9Mn reinforcing shell material was also measured and is presented. This material was in the annealed condition. Room temperature results are comparable to those listed in literature with the exception of the modulus which was 10% lower (5).

IV. WORK IN PROGRESS

Mechanical fatigue strength tests (10,000 cycle strength) at temperatures of 77 K for GlidCop AL-15 and at temperatures of 140 K and 250 K for GlidCop AL-15 and AL-60 are continuing. The thermal conductivity measurements of the

samples containing multiple copper/insulation interfaces and layers continues. Thermal conductivity measurements are being made at temperatures of 77, 100, 150, 175 and 200 K.

CONCLUSION

Properties of GlidCop AL-15 and GlidCop AL-60 meet the specifications for the coil conductor of the 60 T magnet design. Glidcop AL-60 will be used for the more highly stressed coils and GlidCop AL-15 will be used in the coils with higher current densities or longer pulse duration. These materials are readily available commercially, unlike the Cu-Nb and Cu-Ag conductors and do not contain any toxic components like Be-Cu. Properties associated with the nitrogen-alloyed manganese stainless steel are sufficient to be used as coil support shells.

ACKNOWLEDGMENT

The authors acknowledge Robert Aikin, Sr. for extensive mechanical testing, Mike Hundley for making electrical resistivity measurements, David Mandrus for making thermal contraction measurements, Leonard Summers for assistance in making cryogenic fatigue strength measurements and Aditya Muktidoot, Halina Niculescu and Peter J. Gielisse for cryogenic thermal conductivity measurements.

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