Cryogenic Properties of Dispersion Strengthened Copper for High Magnetic Fields

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ABSTRACT

Cold deformed copper matrix composite conductors, developed for use in the 100 tesla multi-shot pulsed magnet at the National High Magnetic Field Laboratory (NHMFL) have been characterized. The conductors are alumina strengthened copper which is fabricated by cold drawing that introduces high dislocation densities and high internal stresses. The alumina particles and high density dislocations provide good high tensile strength and fatigue endurance. In tensile tests, the material exceeds the design criteria parameters. In the fatigue tests, in order to properly simulate the pulsed magnet operation, strain-controlled tests were more suitable than load controlled tests. For the dispersion strengthened coppers, the strengthening mechanism of the aluminum oxide provided better tensile and fatigue properties over conventional copper.

MATERIAL

The 100 tesla multi-shot pulsed magnet commissioned by the NHMFL at the Los Alamos National Laboratory (LANL) consists of an inner CuNb solenoid coil and a series of seven outsert coils. The conductor for coils 1 through 6 are composed of alumina dispersion-strengthened copper. This is a copper matrix composite with aluminum oxide ceramic particles Al_2O_3 as reinforcement component. Two different composites of alumina strengthened copper were used. The first is reinforced by 1.1 wt.% Al_2O_3 (UNS C15760) and is commonly referred to by the trademark name of GlidCop AL-60. The second is 0.5 wt% Al_2O_3 (UNS C15715) and uses the trademark name of GlidCop AL-15. Table 1 summarizes the outer coil set stress parameters for the 100 T multi-shot magnet.

TABLE 1. Outer coil parameters for 100 T multi-shot magnet

Coil No.	Material	Cross-section (mm)	Autofrettage Stress Range (MPa)		Nominal Stress Range (MPa)	
			Max	Min	Max	Min
1	GlidCop AL-60	5.2 x 7.2	711	-446	650	-426
2	GlidCop AL-60	5.2 x 7.2	712	-456	637	-437
3	GlidCop AL-60	5.5 x 10.5	668	-105	547	-105
4	GlidCop AL-60	5.5 x 10.5	668	-108	562	-108
5	GlidCop AL-15	6.7 x 11.0	432	-88	420	-92
6	GlidCop AL-15	6.7 x 11.0	409	-83	397	-70
7	C107	8.5 x 12.0	219	-54	211	-49

An initial autofrettage cycle was sometimes included during fatigue testing to induce compressive residual stresses in the sample to increase strength. It should be noted that the outermost coil no. 7 was manufactured from C107 oxygen free copper that is strengthened mainly from silver particles.

TEST PROCEDURES

Tensile specimen design and test procedures were conducted using the methods described in ASTM standard E 8 M. All tensile testing was performed using a 100 kN capacity servo-hydraulic Material Test System (MTS) machine equipped with a cryostat for 77 K testing. Testing was performed at a strain rate of 2×10^{-2} sec^{-1}. The modulus of elasticity, yield strength using the 0.2% offset method, ultimate tensile strength and ductility (elongation and reduction in area) are then calculated.

FIGURE 1. Tensile test setup

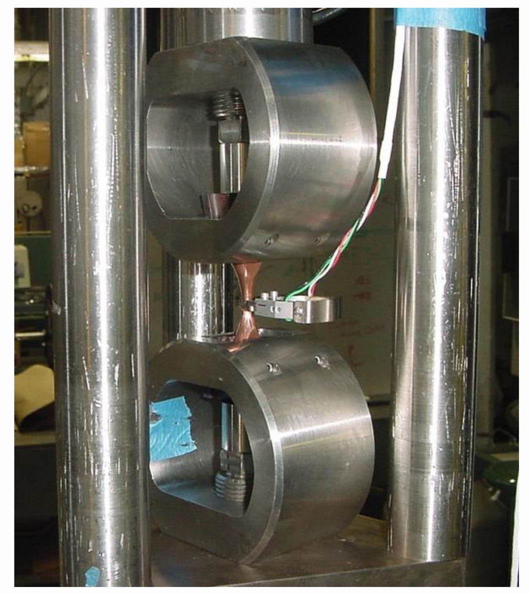

FIGURE 2. Fatigue test setup

Fatigue specimen design and test procedures were conducted according to the methods described in ASTM E466 and ASTM E606. A diametral extensometer is clipped to the hour glass specimen to record cross-sectional changes. In order to fully simulate the fatigue characteristics of the 100 T pulsed magnet, there are several variations from the standard procedure. The Lorentz forces generated in the magnet are reacted by the conductor, a fiber-reinforced composite insulation and a high strength metal shell which encapsulates the coil. The coils are designed such that the conductor operates in the elastic-plastic strain range while the metal shell operates in the elastic range. Because of this load sharing distribution the tests are strain controlled.

RESULTS AND DISCUSSION

A summary of the tensile tests for all coils is presented in Table 1. The alumina dispersion strengthened GlidCop room temperature samples compare favorably with manufacturers data. At 77 K, the GlidCop alloys are significantly stronger than the C107 used in coil 7 which has an ultimate tensile strength of 520 MPa. Since the GlidCop is strengthened by aluminum oxide precipitates, the dislocation cannot shear through the Al_2O_3 particles. For the GidCop AL-60 alloy, the higher strength is accompanied by lower ductility when compared to C107. The ductility for GlidCop AL-15 is significantly better than GlidCop AL-60.

TABLE 2. Summary of tensile test properties

Material	Coil No.	Temp (K)	Yield Strength (MPa)	Tensile Strength (MPa)	Elong. (%)	Reduction Area (%)
GC AL-60	1,2	295	557	590	6.5	22.7
		77	721	768	13.5	28.3
GC AL-60	3,4	295	570	615	6.6	21.6
		77	721	784	9.7	24.9
GC AL-15	5,6	295	469	518	15.3	39.1
		77	589	648	20.7	36.8
C107	7	295	413	422	13.2	69.9
		77	486	550	24.8	69.7

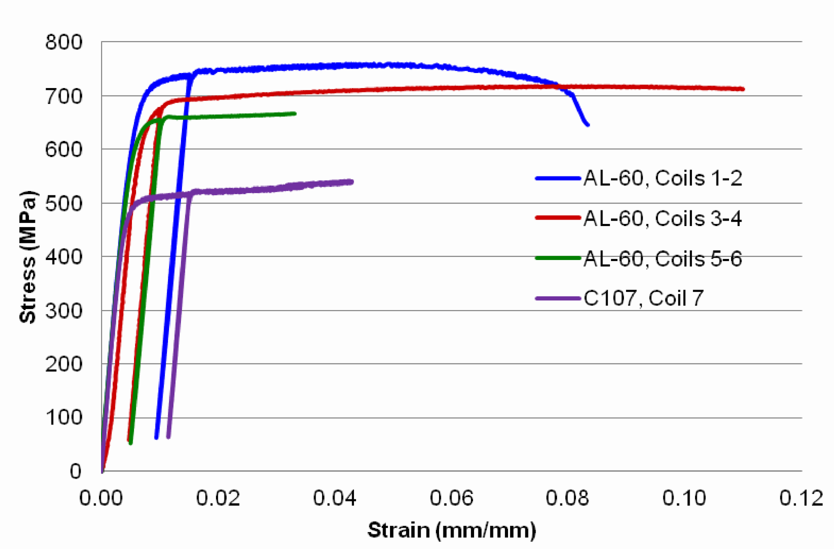

FIGURE 3. Stress-strains curves for GlidCop and C107.

Figure 3 shows typical engineering stress-strain curves for the different materials. An unload/reload cycle is performed at 1.5% strain to determine elastic modulus. It should also be noted that for the GlidCop AL-15 and C107 stress-strain curves, the extensomter slipped during testing resulting in the curve shown. Ductility (elongation and reduction-in-area at fracture) was measured post-test.

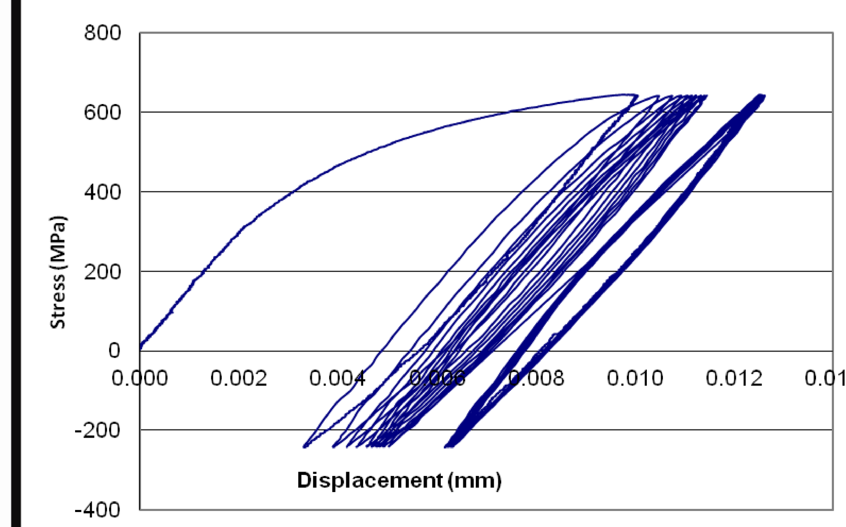

FIGURE 4. Initial cycles in load controlled mode.

The 100 T pulse magnet uses strong reinforcement materials with high strength and high elastic modulus that operate in the elastic range which results in displacement-controlled condition for conductors. Therefore, the conductors can be considered to operate close to displacement mode after a few cycles in stress-controlled mode. The initial stress-displacement curves are used to estimate the tensile and compressive strain used in displacement controlled test. As shown in Figure 4, the first 10 cycles of a GlidCop AL-60 sample in load control mode are shown.

In the strain-controlled cycling, total deformation is constrained by setting the tensile and compressive displacements. This ensures that the plastic deformation will not result in a continuous elongation of the material. As shown in Figure 5, the displacement restraints results in the stress being applied to the material decreasing as the fatigue cycles increase. It is observed that for the duration of the test, the absolute values of both the tensile stress and compressive stress are gradually reduced probably due to the fact that the plastic deformation portion in the stress –strain curves is reduced.

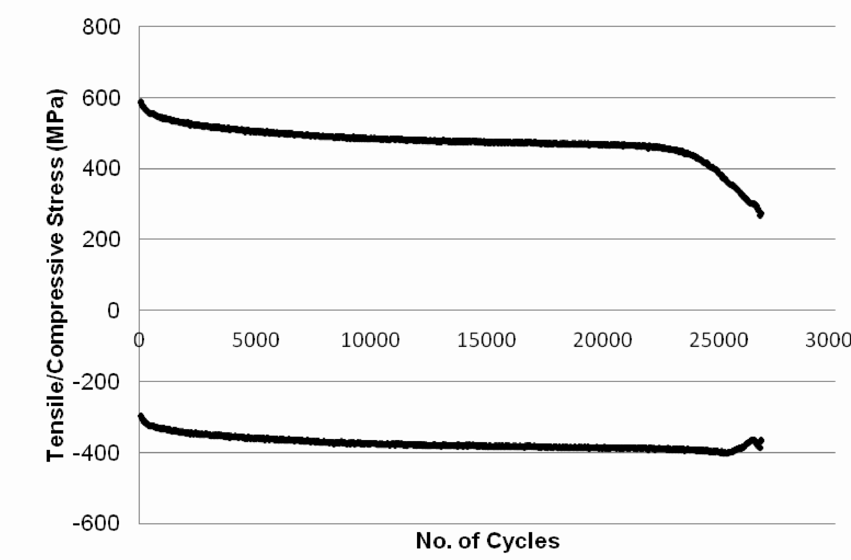

FIGURE 5. No. of Cycles vs. Stress, Strain control.

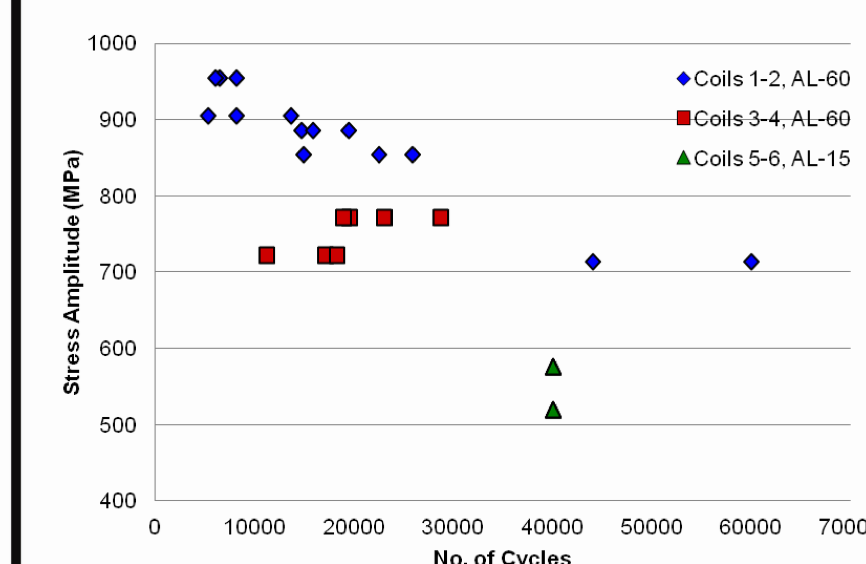

FIGURE 6. Stress amplitude vs. No. of cycles

The data is summarized in Figure 6 in a plot of the stress amplitude versus the number of cycles. It was observed that the cycle life was heavily dependent on the stress amplitudes of the cycle . It was also noted that compression load has smaller impact on the life of the conductors. The samples lasted at least 10 000 cycles with prescribed runout situations of 40-60K cycles.

CONCLUSION

The copper in GlidCop is strengthened by Al_2O_3 particles whereas Cu in C107 is strengthened by silver particles. Both types of materials were deformed to large strain to introduce deformation strengthening. After cold deformation, Al_2O_3 strengthened composites AL-15 and AL-60, have shown superior tensile strength to C107. Fatigue tests on the GlidCop materials has exhibited life of more than 10k for the prescribed stress amplitudes in the magnet design. Due to the plastic-elastic behavior of the GlidCop conductor and constraint effects of the reinforcement during operation, displacement controlled fatigue tests better models the coil interaction than load controlled tests.

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