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NIOBIUM-TIN MAGNET TECHNOLOGY DEVELOPMENT AT FERMILAB[*]

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Abstract

As a part of the Fermilab high field Nb_3Sn dipole development program, various issues of magnet technology are being investigated. In cable insulation development, S-2 fiber glass sleeve and a new ceramic insulation developed by Composite Technology Development Inc. (CTD) were studied as a possible candidates. For each type of insulation, Nb_3Sn ten-stack samples were reacted and then vacuum impregnated with epoxy. Measurements of modulus of elasticity and Poisson's ratio under compression were made at room temperature and at 4.2 K. For comparison, an epoxy impregnated NbTi composite was also tested.

1 INTRODUCTION

Fermilab, in collaboration with LBNL and KEK, is developing a high field Nb_3Sn dipole for use in the next generation Hadron Collider. The conceptual design for the first magnet, detailed in [1], is based on a 2-layer cosθ coil structure and cold iron yoke. As a part of this program, various issues of the magnet technology such as cable insulation, heat-treatment, epoxy impregnation and thermo-mechanical properties of the composite are being investigated. Due to limited space, this paper presents results only in the azimuthal direction. Readers are referred to [2] for more results.

2 SAMPLE PREPARATION

2.1 Cable Parameters

A summary of Nb_3Sn and NbTi cable parameters used in the present study are given on Table 1. The variation of Nb_3Sn cable mid-thickness with pressure before and after reaction is shown in Fig. 1. The cable mid-thickness increases with reaction and decreases with pressure [3]. On the other hand, the cable length contracted by about 4.5 µm/mm and the cable width increased from 14.232 mm to 14.669 mm due to reaction. Note that these measurements are taken at zero pressure.

2.2 Cable Insulation

The most common insulation material used for Nb_3Sn cables is S-2 fiber glass either in tape form or sleeve [4,5]. In the present work, we investigated S-2 fiber glass sleeve and a new ceramic insulation.

Table 1: Cable Parameters

	Nb_3Sn	NbTi
Number of Strands	28	38
Strand diameter	1.012 mm	0.808 mm
Cable Thickness	1.7852 mm	1.4573 mm
Cable Width	14.232 mm	15.3943 mm
Keystone angle	0.91 deg.	1.038 deg.

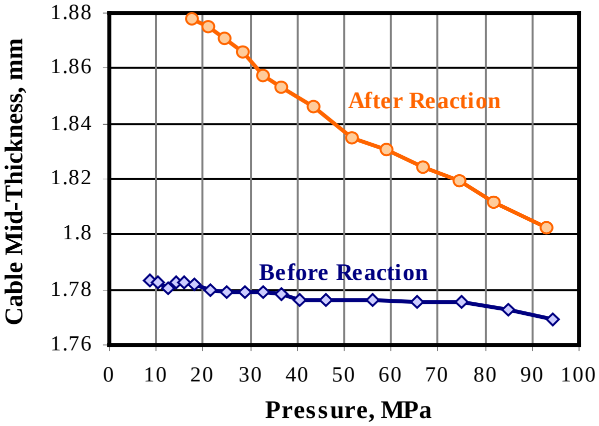

Figure 1: Variation of cable thickness with pressure.

The organic binder used on the S-2 fiber glass sleeve which provides protection/lubrication for the glass strands during processing left a carbon residue during reaction under argon atmosphere. This could create turn to turn shorts in the coil. So the sleeve was first heat-treated at 450 °C in air to remove the binder and a different binder was applied that would not leave much carbon residue during reaction [5,6].

Ceramic tape on the other hand does not have any organic sizing. The binder (CTD-1002x) which is applied to the tape is also inorganic and can be used to preform the coils in shape before reaction by curing at 120^0C for 30 min. Hence with the binder we can have a insulated and cured coil before reaction which helps to define the coil shape. This also makes the coils easier to handle. After reaction the ten-stack samples remain bonded together, however the binder became porous and formed crystals due to shrinkage. This is useful as it allows the epoxy to penetrate during impregnation.

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2.3 Epoxy Impregnation

Insulated ten-stack samples were first reacted and then vacuum impregnated with CTD-101K. Note that the samples were compressed with a pusher block during impregnation and the effect of this impregnation pressure on the mechanical behavior was also investigated. Fig. 2 shows an epoxy impregnated composite with direction convention used in this paper.

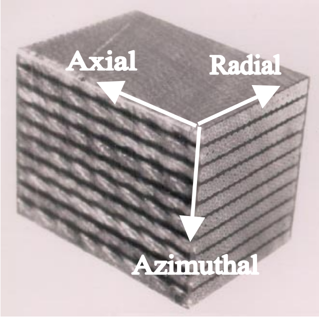

Figure 2: Epoxy impregnated composite.

3 MECHANICAL PROPERTIES

Strain gauges were mounted to measure strains both in the direction of load and transverse to the direction of the load. A calibrated load cell was used to record the force applied on the sample. Both monotonic and load-unload-reload tests were performed at 300 K and at 4.2 K and the test results are discussed below.

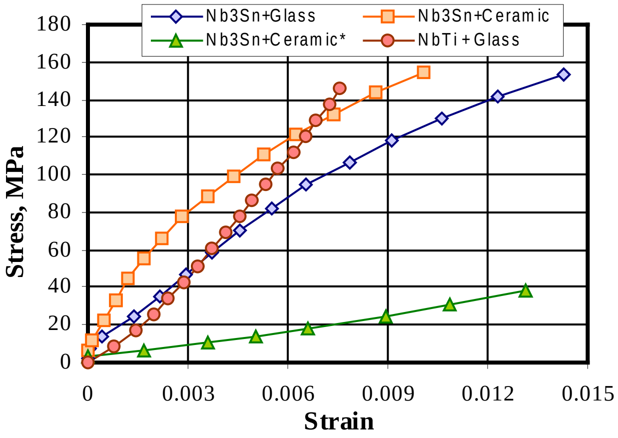

Figure 3: Mechanical behavior at room temperature. (*Nb_3Sn stack with ceramic insulation cured and reacted; but not impregnated).

3.1 Azimuthal Direction: Monotonic Loading

Fig. 3 shows the test results at room temperature. Note that the Nb_3Sn composite exhibits non-linear behavior in contrast to the linear behavior observed for NbTi composite. This behavior of Nb_3Sn composite was first thought to be due to low impregnation pressure (10 MPa) compared to NbTi composite (45 MPa). To test this hypothesis, another Nb_3Sn composite was fabricated at higher impregnation pressure (45 MPa) and tested. The results shown in Fig. 4 show that the mechanical response in azimuthal direction does not depend on impregnation pressure.

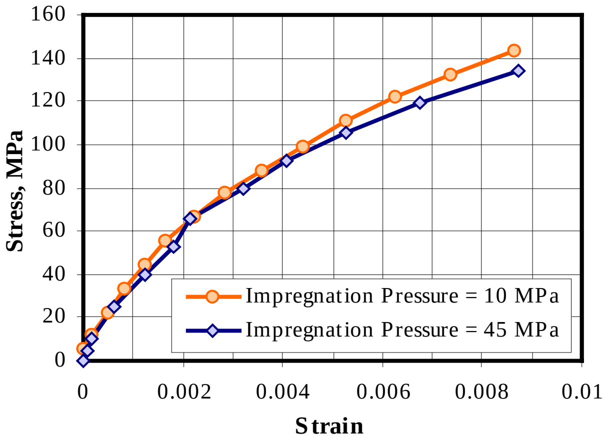

Figure 4: Effect of impregnation pressure.

The effect of temperature on the mechanical response of Nb_3Sn composite is shown in Fig. 5. There is significant increase in the modulus for Nb_3Sn composite with S-2 glass. However with ceramic insulation, the modulus did not change with temperature except that the composite behavior is more linear at 4.2K than at 300K. This behavior was very repeatable and even the load-unload-reload tests (see next section) show this behavior.

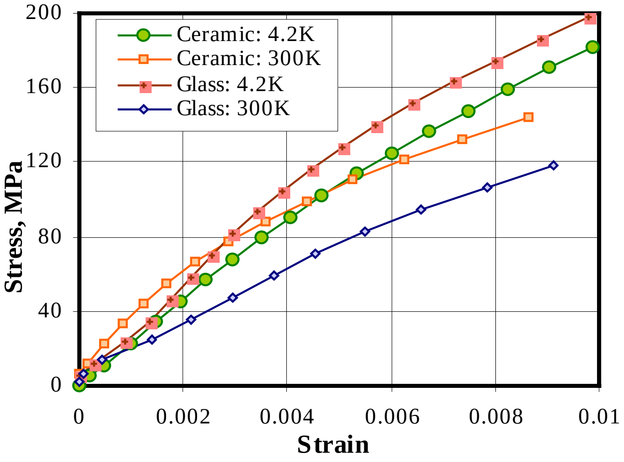

Figure 5: Effect of temperature.

3.2 Azimuthal Direction: Load-Unload-Reload

The coils in a magnet are subjected to loading, unloading and reloading repeatedly during assembly, cool-down and excitation. Hence it is very important to understand the mechanical behavior of the composite under these loading conditions. Fig. 6 shows load-unload-reload test results for Nb_3Sn composite with ceramic insulation both at 300K and at 4.2K. The following observations can be inferred from these results (i) the overall behavior of the composite under loading is similar to that under monotonic loading, (ii) there is no apparent change in modulus by decreasing temperature. Fig. 7 shows the behavior of the Nb_3Sn composite under cyclic loading after initial "massaging" to 100 MPa. The results show that we could massage the coils up to a peak stress before assembly, which would then result in a composite with higher modulus and a linear mechanical behavior. This massaging also results in a plastic deformation of 0.3% in the composite which should be taken into account while designing the magnet cros-section.

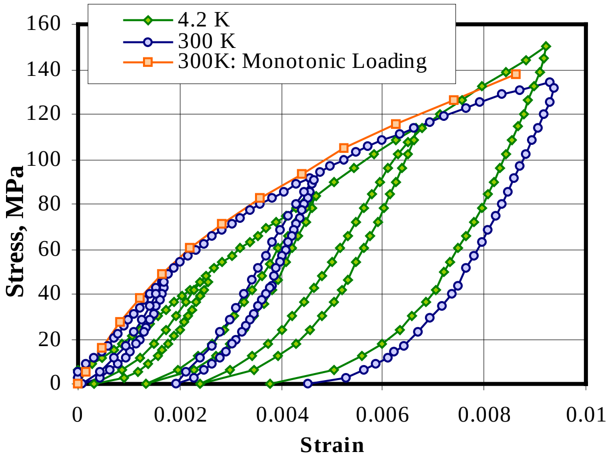

Figure 6: Load-Unload-Reload Tests.

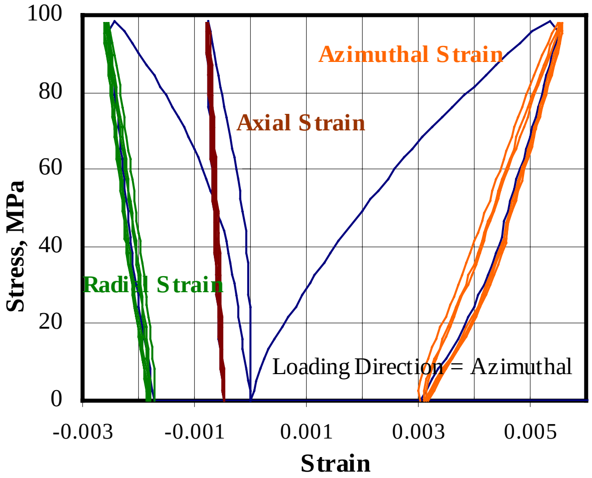

Figure 7: Cyclic loading tests up to a certain stress.

Fig. 7 also shows the Poisson's ratio measurements for the load-unload-reload tests. Note that the Poisson's ratio in the axial direction is higher than in radial direction. Also it remained constant in the axial direction from the first cycle to the second cycle at 0.14, however in the radial direction it decreased from 0.45 to 0.33.

Similar load-unload-reload experiments were conducted for the Nb_3Sn composite with S-2 glass insulation. The mechanical behavior was found to be similar to that with ceramic insulation.

4 SUMMARY

Table 2 summarizes the mechanical properties under monotonic loading for different composites tested. At room temperature, the behavior is nonlinear and hence two moduli are specified, one at low pressures and the other at higher pressures. Included in the table also are the data reported by LBNL[5,7] and University of Twente [4]. The moduli of the composite tested here are much lower than that reported by LBNL and higher than that measured at [4]. These differences in the data quoted here and else where in the literature are not understood yet.

Table 3 provides the data for Nb_3Sn composite after massaging to 100 MPa. The idea for the first short model dipole to be built at Fermilab, is to massage the coils to about 100MPa before assembly which would then increase the modulus to 38 GPa both at 300K and at 4.2K with linear mechanical behavior.

Table 2: Data under monotonic loading.

Composite	**E, GPa**		**Poisson's Ratio**
	300K	**4.2K**	
Nb_3Sn + S-2	17.5 6.5	26.0 14.0	ν_{21} = 0.16 ν_{23} = 0.46
Nb_3Sn + ceramic	27.0 10.0	22.0 14.0	ν_{21} = 0.14 ν_{23} = 0.45
NbTi + S-2	20.0	32.0	ν_{23} = 0.29
Nb_3Sn + S-2 [5]	35.0		
Nb_3Sn + S-2 [7]	44.0		
Nb_3Sn + S-2 [4]	2 to 5		

Table 3: Mechanical properties of the Nb_3Sn composite after massaging to 100 MPa.

Composite	**E, GPa**		**Poisson's Ratio**
	300 K	**4.2K**	
Nb_3Sn + S-2	39.0	40.0	ν_{21}= 0.15; ν_{23}= 0.34
Nb_3Sn+ ceramic	38.0	38.0	ν_{21}= 0.14; ν_{23}= 0.33

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