Tensile testing of superconducting wires

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The results of tensile tests on superconducting wires at room and liquid nitrogen temperatures are presented, and the apparatus and method used to obtain these results are described. The strain measurement at the start of the tests is prone to error due to wire flexibility and specimen curvature. This causes a translation error on the graphs that is approximately corrected for by utilising knowledge of the Young’s modulus determined from the test. The data from the tests of numerous specimens of the same wire can show significant scatter, but meaningful results are obtained by using statistical analysis techniques.

Keywords: Superconductivity; superconducting wires; mechanical properties; tensile test; tensile properties

Resultados de pruebas de tensión en cables superconductores a temperatura ambiente y a temperatura de nitrógeno líquido son mostrados. Las mediciones de deformación al comienzo de la prueba están propensas a error debido a la flexibilidad propia del cable y a su curvatura. Esto causa un error de traslación en los gráficos que se corrige al utilizar el módulo de elasticidad proveniente de las pruebas. La información obtenida en las pruebas de varios especímenes provenientes del mismo material mostró visibles irregularidades a priori pero después de ser analizadas con técnicas de análisis estadístico significantes resultados pudieron ser revelados.

Descriptores: Superconductividad; cables superconductores; propiedades mecánicas; pruebas de tensión; propiedades a la tensión

1. Introduction

The multi-filamentary composite wire that is used to make superconducting magnets can experience substantial levels of mechanical stress during the fabrication and operation of the magnet [1]. A major source of these stresses arises from the differences in thermal expansion coefficients between the different materials used in the magnet construction and within the wire itself. The coil of a magnet can experience undergo changes in temperature of $1000^\circ C$ as it is heat-treated at around $700^\circ C$ to form the Nb$_3$Sn superconducting compound and then cooled to the operating temperature of $4 \text{ K}$. Further stresses are produced as a result of the large magnetic forces that are generated when the magnet is energised. The stresses have a significant influence on the maximum superconducting current that the wire can carry [1-9] and, therefore, on the strength of the magnetic field that can be generated. Knowledge of these stresses is also important for design optimisation; for example, in minimising size and weight and therefore cost.

Despite this, there have been relatively few data published on the stress-strain behaviour of superconducting wires or the tensile testing methods [10, 11]. One reason for this is the difficulty in obtaining accurate results from tensile tests on thin wires (around 0.4 to 1.5 mm diameter), particularly at cryogenic temperatures. Another difficulty is that Nb$_3$Sn wires are extremely brittle and require very careful handling.

2. Tensile testing method

Figure 1 shows the tensile testing apparatus. The servo-hydraulic materials testing machine was fitted with a universal joint. The loadcell was placed between the universal joint and the test specimen. This ensured that only axial loads were transmitted through the loadcell. This was necessary because of the small cross-section of the test specimens. If the loadcell was not fitted in this way, any slight misalignment of the test specimen from the axis of the machine would have resulted in a bending moment being transferred to the loadcell, and significant error in the load reading would have been produced.

An extension rod was fitted directly under the loadcell to keep it away from the liquid nitrogen, as a change in the loadcell temperature would have affected the readings. The test specimens were attached to the grips and were then fitted in the machine. Pulley grips (as can be seen in Fig.1) were used because the test specimens were not brittle and there was no problem in wrapping them around the pulleys. By using pulley grips, which do not introduce significant stress concentration points, the ultimate tensile strength could be measured. The testing method has not yet been extended to the brittle Nb$_3$Sn superconducting wires, which require different grips.

Two extensometers were attached to the test specimens, as shown in Fig.1. They need to be small and lightweight, as are Epsilon Technology Corporation’s miniature extensome-
ters which were used for this work. By using two extensometers, two sets of strain data were obtained from each test. This enabled information to be gathered more quickly as well as providing a cross check on each extensometer.

To aid in the measurement of Young’s modulus for the wire, stress and strain were measured over several load cycles, extending the peak load each time. The first load cycle was taken to a point just above the yield stress.

3. Analysis of tensile test results

To assist in the determining of Young’s modulus, graphs of the slope of the stress-strain graphs were analysed to clearly identify regions where there was a linear relationship between stress and strain. The thick lines in Fig. 2 show the two stress-strain curves of an unloading cycle (one for each extensometer). The two thin lines show the differential or slope of those curves. It can be seen that, at the top end of the stress-strain curves, the corresponding slopes are approximately constant, indicating that the stress-strain curve is linear in this region. The slopes are both equal to 100 GPa, and thus Young’s modulus for this particular sample can be taken to be 100 GPa. However, the value obtained may vary between different loading and unloading cycles, and between different tests. By comparing the slopes of the initial parts of the various loading and unloading cycles, and taking an average of the results from several tests, it was normally possible to obtain a good measurement of the modulus.

It has been found that the slope of the initial part of the unloading cycles was often the most accurate measure of the modulus, because the strain measurements from the initial part of the loading cycles were prone to error. This was because the test specimens were not perfectly straight and were easily bent under the weight of the extensometers. This error was, however, corrected for by aligning the stress-strain curves to a line passing through the origin and having a slope equal to Young’s modulus. The strain values were simply shifted up or down to give the best alignment to the Young’s modulus line. To illustrate the technique, Fig. 3 shows a stress-stress curve with a particularly large degree of strain measurement error at low stress levels, before and after correction was applied. It is assumed that the start of the real stress-strain curve lies on the Young’s modulus line and that the corrected curve is accurate for stress levels above about 100 MPa.

In order to produce meaningful results, it is useful to do tensile tests on multiple test specimens and to employ statistical analysis techniques. Mean values and standard deviations were calculated for the various material properties that were measured: Young’s modulus, proof stress, ultimate tensile strength and elongation. The standard error of the mean (SEM) for each was then calculated using the following formula:

$$SEM = \frac{\sigma}{\sqrt{n}}$$  

(1)

where $\sigma$ is the standard deviation and $n$ is the number of samples.

A confidence interval for the mean was then calculated. This confidence interval can be explained as follows. If a very
large number of samples are taken from the population, there is a 95% probability that the mean of those samples would lie within the range given by the confidence interval.

95% Confidence Interval of the Mean = \( \bar{x} \pm 2 \text{SEM} \)  \( (2) \)

where \( \bar{x} \) is the mean.

In making comparisons between multiple populations (for example, different wire batches or designs) the confidence intervals of the means can be plotted as error bars on graphs. If there is an overlap of the error bars, then it cannot be said that there is a statistically significant difference between the populations (in this case, statistically significant means that there is approximately 99% confidence that there is a real difference). Figure 4 shows an example of this technique. The confidence intervals of the means of Young’s modulus (\( y \)-axis) are shown for five different wire types (\( x \)-axis). The wire types identified as 0 to 4 in the Fig. 4 correspond to the wires identified as A to E respectively in Table I. It can be seen that it is not possible to say with any confidence that there is any difference in Young’s modulus between the wire types, except between those identified as 1 and 2. When making a comparison between just two populations, however, a more precise calculation can be made. The difference between the two means is said to be statistically significant if it
is greater than 2 times the *standard error of difference* (in this case, statistically significant means that there is at least 95% confidence that there is a real difference). The *standard error of difference* (SED) is given by the equation:

\[
\text{SED} = \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}
\]

where \(\sigma_1\) and \(n_1\) are the standard deviation and the number of samples of the first population, and \(\sigma_2\) and \(n_2\) are those of the second.

### 4. Experimental results

A variety of superconducting wires were supplied by Oxford Instruments Superconductivity. They were all multi-filamentary composites wires with either round or rectangular cross-sections. The cross-sections range from 0.4 mm to 1.5 mm in diameter. These wires can be divided into two groups. In the first group, the filament material is niobium-titanium (Nb-Ti) whilst in the second it is a compound of niobium and tin, Nb\(_3\)Sn. To form the Nb\(_3\)Sn, the wire undergoes...
a heat-treatment, process at approximately 700°C. Prior to heat-treatment, the wire consists of niobium filaments, which are very ductile. During the heat-treatment, tin reacts with the niobium to form the very brittle Nb₃Sn compound. In this work, some results of the testing of niobium-titanium and un-reacted niobium-tin (i.e. prior to heat-treatment) wires are presented. Figure 5 shows a typical stress-strain curve that has been measured and Table I shows a summary of the results. The purpose of the table is to give an overview of the tensile properties of superconducting wire. Due to confidentiality, the exact composite structure of the wires cannot be given.

5. Conclusions

The method of tensile testing superconducting wires at room and liquid nitrogen temperatures has been described. Analysis techniques have been explained and the results of testing on a wide range of superconducting wires have been presented.