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The Measurement of Friction Coefficient Down to 1.8 K for LHC Magnets

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The Measurement of Friction Coefficient Down to 1.8 K for LHC Magnets

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The Large Hadron Collider (LHC) proposed for construction at CERN consists of a series of high field superconducting dipole magnets operating at 1.8 K. The mechanical structure of these magnets contains many components in close contact. A knowledge of the friction coefficient between these components is required. Indeed, during assembly and cool down of the magnets, prestresses must be transferred to the superconducting coils. During operation, frictional heating may provoke loss of superconductivity. A machine has been built at CERN to measure the coefficient of friction from room temperature down to 1.8 K. This paper describes the cryogenic tribometer and the results collected to date.

INTRODUCTION

CERN is currently conducting an active research and development programme to optimize the mechanical structure of the superconducting dipole magnets being designed for LHC. One of the most important considerations in this structure is the effect of friction between components. This is very important both during assembly and cool down of the magnets towards the operating temperature because the necessary prestresses required to support the superconducting coils have to be applied. Furthermore, during the magnet excitation the high induced Lorentz forces and associated deformations may lead to frictional heating and so provoke quenching or loss of superconductivity of the coils.

In order to investigate these effects, a cryogenic tribometer has been designed and built at CERN to measure the coefficient of dynamic friction from room temperature down to 1.8 K in superfluid helium. Indeed, no data are available at present for temperatures lower than 4.2 K. Moreover, the superfluidity of helium at 1.8 K may also have some influence on the tribological behaviour of constitutive materials.

DESCRIPTION OF THE CRYOGENIC TRIBOMETER

The tribometer is based on the reciprocating motion principle. It is illustrated in figure 1. A flat sample, the first material of the pair, slides between two fingers, the second material of the pair, on which a normal load is applied by means of two loaded springs. As most of the tests are made in cryogenic fluids, the whole measuring system is fitted in a glass cryostat properly insulated from the ambience. This cryostat is vacuum tight in order to enable the lowering of the temperature of the helium bath by pumping on it. A fundamental decision was made when starting the design of the tribometer in order to minimize all parasitic phenomena that might disturb the measurements: -all the required transducers must be fitted as close as possible to the tested samples - so as to avoid the inclusion of parasitic frictions in the measurements which are difficult to calibrate precisely if the transducers are installed outside the cryostat (e.g. friction in the bearings of the push/pull mechanism that transfers the reciprocating motion from the environment to the flat sample). This was made possible by using strain gauges especially designed and calibrated for cryogenic applications [1, 2].

The normal load applied by the springs is measured by 2 electrical resistance strain gauges glued on an aluminium structure which is deformed during the test. The frictional force is also measured by 2 gauges glued on a thin plate fixed on one side to the push/pull mechanism and on the other side to the flat specimen. The measurements are recorded by a Microcomputer connected to a UPM 100 measuring unit

(HBM- Germany). Compensating gauges give the value of the apparent strain and the required correction for the temperature effect. The apparent strain is the signal due to the thermal contraction.

The characteristics of the tribometer are:

- contact pressure : from 0 to 14 MPa,
- flat on flat contact area : 7,07 mm²,
- sliding velocity : from 0.1 to 2 cm/s,
- reciprocating stroke : 25 mm,
- operating temperatures : 293 K-ambient air, 77 K-liquid nitrogen, 4.2 K-liquid helium at 1 atm and 1.8 K in superfluid helium.

Calculation procedure for the coefficient of friction

The history of a friction test is well illustrated in figure 2 for the friction force transducer. The signals of both gauges (B1 and B2) are plotted versus time (in fact, as represented by number of measurements). Before making the flat sample move, measurements are taken during phase 1. These are the references that take into account the apparent strain. The motion then starts and the measurements continue (6 per second for each gauge). The friction force is obtained by dividing the signal by the slope of the calibration curve previously made by loading the structure with weights for the corresponding temperature:

$$F = \{ 1/2 \times (B1+B2)_{\text{cycle up}} - 1/2 \times (B1+B2)_{\text{phase 1}} \} / (\text{slope of calibration curve}) \quad (1)$$

Taking the arithmetic average of the signals cancels out the bending effect in the thin measuring plate. The calibration curve made at room temperature and at 77 K gives the response of the gauge in microstrain ($1 \mu\epsilon = 10^{-6} \text{ m/m}$) versus a known load in N.

The contact force is obtained in a similar manner, taking into account the apparent strain (A S) for each signal N1 and N2 and the slope of the calibration curve for the corresponding temperature.

$$N = 1/2 \times \left\{ \frac{N1 - A S (N1)}{\text{slope N1}} - \frac{N2 - A S (N2)}{\text{slope N2}} \right\} \quad (2)$$

The friction coefficient is then calculated using the results of equations (1) and (2).

$$\mu = F / (2 \times N) \quad (3)$$

The coefficient must be divided by 2 because there are 2 contact areas in the measuring system.

Errors taking into account the error on the correction for apparent strain, the error on the calibration curves and the use of the calibration at 77 K for lower temperatures are estimated to be at maximum 7 % of the calculated coefficient of friction.

RESULTS OF FIRST MEASUREMENTS

Stainless steel (304 L) on stainless steel (304 L): the coefficient of friction is almost constant from room temperature down to 1.8 K and approximately equal to 0.4. The evolution of the friction coefficient with time is roughly the same at all temperatures. It is illustrated in figure 3. Well known stick-slip phenomena for such metal on metal contact occur for all tests.

Stainless steel (304 L) finger on mild steel (AC 37) flat sample: the coefficient of friction decreases from room temperature down to 4.2 K and then increases at 1.8 K. It is given for each temperature in table 1. The behaviour of this pair of materials is the same at all temperatures. First, the coefficient of friction is low and stable because of the presence of oxide - mainly FeO that is ductile and lubricant - on the mild steel sample. The friction increases when the contact becomes metal on metal. This behaviour is illustrated in figure 4. When there is no oxide on the mild steel sample the coefficient of friction is high, around 0.6, and instability occurs.

Stainless steel (304 L) finger on vetronite, G10, flat sample: the sliding track of vetronite is machined. The coefficient of friction is given for each temperature in table 1. For each test, a higher coefficient is observed when starting the test. It then becomes more stable during the rest of the test. This

phenomenon disappears progressively with the number of cycles. This higher coefficient is probably due to a penetration of the finger in the flat sample, which requires a higher tangential force to initiate the motion. The evolution of the coefficient of friction with the number of cycles is given for all temperatures in figure 5. The results obtained at CERN are very close to those of Iwasa at the FBMNL (USA) [3] despite the fact that the tribometers do not work on the same principle: reciprocating motion at CERN and pin-on-disk at FBMNL with a 304 steel track and G10 fingers.

Aluminium finger on vetronite, G10, flat sample: the coefficient of friction is given for each temperature in table 1. The results obtained at CERN are also close to those of Kensley and Iwasa [4].

Table 1 Mean coefficient of friction

		Temperature:	300 K	77 K	4.2 K	1.8 K
Stainless steel / mild steel	CERN		0.57	0.52	0.5	0.61
Stainless steel / vetronite	CERN		0.23	0.46	0.11	0.36
Stainless steel / vetronite	FBMNL		0.32	0.51	0.21	-
Aluminium / vetronite	CERN		0.43	0.52	0.46	0.38
Aluminium / vetronite	FBMNL		0.47	0.60	0.51	-

Stainless steel (304 L) finger on PTFE coated stainless steel flat sample: in this test, the flat sample is coated with a 35 μm thick layer of PTFE (teflon). The mean coefficient of friction is about 0.08 at room temperature and 0.12 at 77 K in liquid nitrogen. These results are much lower than those of the 304 L / 304 L pair.

Stainless steel (304 L) on MoS_2 coated mild steel flat sample: in this test, the flat sample is coated with a thin layer of MoS_2 varnish applied by spraying. The mean coefficient of friction is about 0.06 at room temperature and 0.1 at 77 K in liquid nitrogen. These results are much lower than those of the 304 L / mild steel pair.

CONCLUSION

Despite the fact that the results when measuring coefficients of friction are very much dependent of the tribometer and a number of other parameters (e.g. applied load, shape of samples, roughness of samples, ...), we can conclude that the tribometer gives reliable measurements. This is well demonstrated in the comparisons with the available data in references [3] and [4].

Many other tests are needed in order to attempt to explain the different behaviour of the materials in liquid helium and in superfluid helium. Nevertheless, it can already be said that the dynamic friction coefficient is sometimes seen to increase or decrease between 4.2 K and 1.8 K, depending on the pair of materials. The tribometer is currently used to measure the tribological behaviour of superconducting magnet materials.

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Figure 1 Reciprocating motion principle for the cryogenic tribometer

Figure 2 History of a friction test with B_i in μe

Figure 3 μ at 1.8 K versus time- 304 L / 304 L pair

Figure 4 μ at 293 K- 304 L / AC37 pair

Figure 5 μ versus nb cycles- 304 L/vetronite G10