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LHC Note 253

829407

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Abstract

At each operation cycle of the LHC machine, the field of the superconducting dipoles will be raised from the injection level to the collision level and then decreased again. This will induce a stress cycle inside the structure. The collars will have to withstand several thousands of stress cycles during their life. In this paper a description of the test apparatus built to assess the resistance of different types of collars is given. We also present results of measurements and draw some preliminary conclusions regarding the influence of material properties, geometry and surface condition, on the endurance of the collars.

13th International Conference on Magnet Technology (MT13), Victoria, Canada
20-24 September 1993

Geneva, Switzerland
01/19/94

Measurement of the Resistance to Stress Cycling at 4.2 K of LHC Dipole Collars

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Abstract - At each operation cycle of the LHC machine, the field of the superconducting dipoles will be raised from the injection level to the collision level and then decreased again. This will induce a stress cycle inside the structure. The collars will have to withstand several thousands of stress cycles during their life. In this paper a description of the test apparatus built to assess the strength of different types of collars is given. We also present results of measurements and draw some preliminary conclusions regarding the influence of material properties, geometry and surface condition, on the endurance of the collars.

I. INTRODUCTION

During each cycle of operation of the LHC machine, the magnetic field will be raised from the injection level (0.58 T) to the collision level (8 + 10 T). This field cycle will cause an electromagnetic force cycle and, consequently, a stress cycle in the structure of the magnet.

Assuming for the machine a life of 20 years and an exploitation of 6 months per year with a rate of 2 cycles per day, each magnet will have to withstand about 7000 cycles.

The collars are fixed around the coils with keys or pins. Different locking systems and collar configurations have been designed for the models and prototypes built up to now.

The cycle of stresses could represent a danger for the collars since the stress concentration around the holes or the key slots is very important.

As an example we can refer to a two-in-one dipole with aluminium coupled collars 3 mm thick [1]. The average compression of the coils at 2 K can be 70 N/mm^2 for the inner coil and 45 N/mm^2 for the outer coil. In this case, the reaction force over 3 mm length of central pin is 22000 N. The reaction drops to 7700 N when a current of 15000 A is flowing in the coils [2]. It is therefore important to test the endurance of the collars and to set a criterion of comparison of different geometries and materials.

II. THE TEST DEVICE

The test apparatus is shown in Fig. 1. The sample is kept in liquid helium inside a cryostat. An air piston applies the cyclic force: the valves are driven by an electronic control system which also counts the number of cycles and controls the frequency.

The electronic control system and air piston were supplied by an industrial company. A displacement transducer monitors the test. If the deformation is greater than a threshold value (i.e. the sample is breaking), the transducer, via the control system, stops the machine and the helium feeding. The device is equipped with a data recording system and an automatic helium filler.

Fig. 1. The test apparatus

III. ALUMINIUM COLLARS

The MTA1 models [3] and the a number of prototypes were assembled using aluminium alloy twin collars (Fig. 2). The area around the central pin is the most highly stressed part of the collar.

Two different aluminium alloys (AA2014 and AA5083) were first tested using samples machined at CERN. Afterwards, we tested samples cut from collars produced by industry. These last were made of AA2014 and cut using the fine blanking technique.

For all of the three sample types, a roughness of class N7 ($R_a = 1.6 \mu m$) had been specified, however the samples produced by industry had a poorer surface quality around the pin hole than the others. This was due to some slight imperfections arising from the production technique. Moreover, everywhere in the collar laminations there were some small parallel grooves. Although these grooves were necessary for the cutting process to prevent the collars from bending, they can be a starting point for the crack.

Table I shows the results for the three sample types under the chosen loading. The maximum force of 34000 N corresponds to an average prestress of $90 N/mm^2$ for the inner coils and $74 N/mm^2$ for the outer ones, and the minimum force of 8600 N corresponds to a central field of 13 T. The electromagnetic forces considered here are about 50% higher than those in the prototypes. In case of lower field magnets (i.e. 9 T) the forces used in the tests are 2 times higher than the real ones

For the samples produced at CERN the average life of AA2014 and AA5083 is similar.

Unfortunately, the samples from industry show a much shorter life due to the poorer surface conditions.

Fig. 2. Aluminium alloy collars

Fig. 3. The forces loading the collars
 σ_i and σ_o are the average stress on the coils mid plane.
 $F_{mag}(t)$ is the electromagnetic force
 $F(t)$ is the reaction force of the pin

IV. WÖHLER DIAGRAM FOR AA2014 COLLARS MADE IN INDUSTRY

The Wöhler diagram is the standard way to compare fatigue data. In this diagram, the horizontal axis represents the logarithm of the number of cycles before breaking, and the vertical axis represents the logarithm of the amplitude of the stress cycles σ_a . For each diagram the mean stress value of the cycles is fixed. If we call σ_M the maximum stress of each cycle and σ_m the minimum stress, we have:

$$\sigma_a = \frac{\sigma_M - \sigma_m}{2} \quad (\text{variable}) \quad (1)$$

$$\sigma_{me} = \frac{\sigma_M + \sigma_m}{2} \quad (\text{constant}) \quad (2)$$

TABLE I
BEHAVIOUR OF THREE DIFFERENT KINDS OF SAMPLES AFTER CYCLING FROM $F_{MAX} = 34000 N$ TO $F_{MIN} = 8600 N$ AT $T = 4.2 K$

Sample type	Min. and Max. measured life (cycles)	Average life (cycles)
Al 5083 CERN	5091 8960	6750
Al 2014 CERN	5949 7637	6908
Al 2014 Industry	1845 2569	2172

To compare performances of collars of different shape, we will represent on the vertical axis the amplitude of the reaction force coming from the locking system, seen by a collar (Fig. 3). This force, at any time t , is defined as follows:

$$F(t) = [(\sigma_i + \sigma_o) \cdot W - F_{ymag}(t)] \cdot th \cdot n \cdot 2 \quad (3)$$

where:

σ_i and σ_o are the average stress in the inner and outer coil median plane at 2 K without current.

$F_{ymag}(t)$ is the electromagnetic force in vertical direction per unit of longitudinal length and per quadrant.

W is the width of the coils.

th is the collar thickness.

n is 1 in case of single separated collars, and 2 in case of twin collars.

The multiplication by two is due to the fact that only one out of two collars is carrying the force.

The Wöhler diagram, modified as explained, was determined for the Al-alloy industrial made collars fixing 18000 N as the mean value of the force ($\frac{F_{max} + F_{min}}{2}$). Fig. 4 shows

the curves for 4.2 K and for room temperature. The aluminium is increasing its resistance at low temperature. At 4.2 K the samples can withstand roughly double the number of cycles they can withstand at room temperature.

Figs 5, 6 and 7 are showing the fracture of some samples broken both at room and at low temperature. In each sample, several cracks start opening in the most highly stressed area

Fig. 4. Endurance of the 2014 real collars at $T = 300$ K and $T = 4.2$ K
 $F_a = \frac{F_{max} - F_{min}}{2}$

Fig. 5. Crack propagation at room temperature

around the pin hole. The propagation of the cracks, cycle after cycle, is clearly visible in Figs 5 and 6.

Once the resisting section of the sample is too small to withstand the force, the sample breaks with plastic deformation (Fig. 7).

At room temperature, the areas of the propagating cracks are larger than at low temperature.

In one sample made of aluminium 5083 machined at CERN and broken at 4.2 K it was not possible to find such areas.

In all the cases the propagation of the crack is very short and the critical section is reached very quickly. This means that the material is used very close to its limits.

Fig. 6. Crack propagation at 4.2 K

Fig. 7. Plastic deformation and breakage at 4.2 K

V. STAINLESS STEEL SEPARATED COLLARS

The CERN model MTB [4] had two stainless steel separated collars made of AISI 316 LN 10% hardened (Fig. 8). Each side of the collar must withstand a force varying from 9000 N to 4000 N. The upper value corresponds to an average compression of 75 N/mm^2 for the inner coil at 2 K without current and 55 N/mm^2 for the outer coil. The lower value corresponds to a field of 10 T.

Fig. 8. The stainless steel collars

A greater load is applied at room temperature once the magnet is assembled. This load of 11800 N then decreases during the cooling because of the differential contraction of coils and steel.

Samples representing the key slots were cut using the same wire machine, program and material of the real collars. The samples were pulled two times up to 11800 N at room temperature, then cooled and cycled from 9000 N to 4000 N at 4.2 K.

The pieces withstood without breaking 21000 cycles; that is three times their foreseen life. After 21000 cycles, the deformation of the key slots was measured. It was found to be about 0.01 mm. This is due to some plasticity at room temperature during the first cycle. From that point up to the cycle 21000 no extra deformation was added.

VI. CONCLUSIONS

For a good endurance of the collars, it is important to take a particular care of the surface quality of the pin holes or key slots. A more accurate way of production can make the collars survive even two or three times longer.

For the aluminium options, the force cycling is a problem which must be seriously taken into account when designing and producing the collars.

The endurance of the collars can be extrapolated from the curves in Fig. 4. In case of 10 T field, the industrially produced twin collars should withstand about 9000 cycles. This is barely sufficient. In case of 8.65 T field, the same collars should last about 12000 cycles; 70% more than the required minimum.

In case of steel collars the problem is less important and actually the design and material of the CERN model are matching the needs of resistance.

In the future, a systematic test of each design and material choice for the collars of any type of dipole and quadrupole for LHC should be carried on.

The different collar configurations will be compared plotting their test performances on the same diagram.

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