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BRITTLE BEHAVIOR OF SSC YOKES*

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ABSTRACT

In liquid helium at 4 K ultra--low carbon steel is known to be brittle. Fracture toughness and ultimate strength measured by the National Institute of Standards and Technology (NIST) are used here to examine the brittle behavior of the SSC yokes. The fracture toughness K_{Ic} of the material is used to estimate the maximum allowable length of pre--existing cracks. Tensile properties of the steel at 4 K are compared with maximum tensile stresses obtained from the ANSYS finite element analysis of the DSX201 cross--section.

INTRODUCTION

Brittle materials at low temperatures are usually not used as structural members in cryogenic structures. Since no other steel possesses the required ferromagnetic properties it is currently used in SSC magnets. Examination of existing magnets which have been built with this material have not shown evidence of brittle behavior. This work attempts to evaluate the safety margins with which the yokes are performing with respect to brittle behavior.

TEST RESULTS

Complete description of the tests appear in the report[1] by R.L. Tobler, L.M. Ma, R.P. Reed. The principal test material was a commercial ultra low carbon steel plate, 89 mm thick, with the following composition (mass percent): 0.007C--0.021Mn--0.012P--0.014S--0.006Si--0.052Al--0.003N. Compared to conventional mild carbon--steels, this steel has a lower C and Mn content which confers the desired ferromagnetic properties at cryogenic temperatures. The chemical composition of the yoke material has been altered since the NIST measurements were performed. The current yoke material has the following composition (mass percent)[2]: 0.005 C--0.5 Mn--0.012 P--0.02 S--0.005 Si--0.10 Al. Test results are thus only an indication of the current material behavior.

Tension tests

Results from tension test measurements are listed in Table 1.

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MASTER

Table 1. NIST tension tests

Specimen no	Temp. K	Yield Strength MPa (ksi)	Ultimate Strength MPa (ksi)	Elong. %	Red of Area %
1	295	137 (20)	267 (39)	49.4	89.4
2	295	137 (20)	269 (39)	47.9	89.4
average	295	137 (20)	268 (39)	48.7	89.4
3	4	700 (101)	753 (109)	1.4	0.5
4	4	709 (103)	735 (106)	1.9	0.5
average	4	705 (102)	744 (108)	1.7	0.5

Fracture toughness

Usually, test specimens are fatigued in tension and the fracture toughness K_{Ic} is then measured at the same temperature. (The definition of fracture toughness is recalled in the following.) The material is so brittle at 4 K that it either fails or never develops the fatigue crack required by the test procedure and thus will not fail. Since valid K_{Ic} data could not be measured due to difficulties encountered in fatigue-precracking, its estimated value is $15 MPa.m^{1/2}$.

PEAK STRESS IN THE DSX201 YOKE

To use the preceding data, estimates of peak tensile stresses in the SSC yokes are needed. The DSX201 cross-section was modeled using the ANSYS finite element analysis program and peak stresses calculated in the DSX201 yoke are presented for three cases. The cases analyzed depend on the type of collars used inside the yoke. There are two candidate steels for the collars.

The first collar steel (Nitronic 40) is a non-magnetic (Fe-21Cr-6Ni-9Mn) alloy with very low susceptibility and a thermal expansion which is larger than that of the yoke material.

The other material (Kawasaki 90) considered for the collars is a high manganese steel, with also a very low susceptibility and thermal expansion closer to iron than stainless steel.

A second type of Kawasaki collars is considered: it is called here anti-oval Kawasaki collar. The location of the keys holding the collars together is such that the final shape of the coil/collars assembly when cold and energized is closer to a circular shape than the elliptical shape that it would otherwise assume.

With Nitronic collars (Fig. 1), the peak stress in the yoke occurs during the assembly of the shell. We assumed an azimuthal shell stress of 207 MPa (30 ksi) after welding the shell. At this stage, the yoke midplane gap remains slightly open and therefore, the greatest amount of bending occurs at the pole of the yoke. This bending results in a tensile stress in the yoke at the pole. Also, where the yoke is in contact with the collars, a localized area of large radial compressive stress results in the yoke. While the magnet is cooled to 4 K, the yoke midplane gap closes, reducing the bending in the yoke and lowering the peak tensile stress. Also, yoke-collar contact occurs only at the pole, and radial pressure on the yoke is greatly reduced since the thermal contraction of the collars is much larger than that of the yoke. This then lowers the peak radial stress in the yoke. After magnet energization to 6500 A, the contact at the

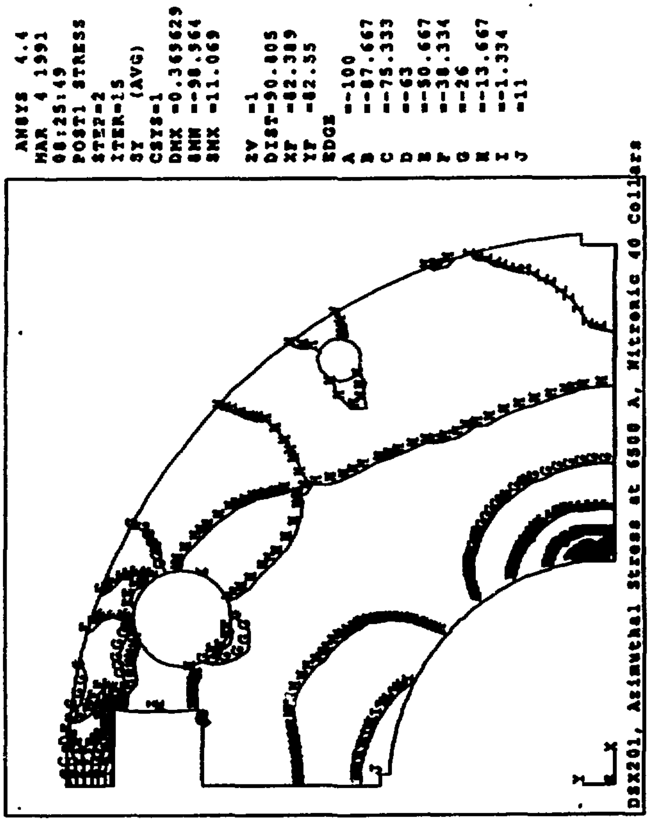


Figure 1.

DISCLAIMER

pole between the collars and the yoke disappears and is replaced by a contact at the midplane. Since the yoke midplane gap is closed at this point, the yoke acts as a rigid cylinder which offers more resistance to the bending action of the Lorentz forces. This contact at the midplane has a minimal effect on the bending of the yoke and does not greatly affect the peak stresses in the yoke. Therefore, the peak stress in the yoke with Nitronic collars occurs during welding of the shell where the von Mises stress is 80 MPa and the maximum tensile stress is 28 MPa. (By von Mises stress we mean the equivalent stress used in the Mises-Hencky yield criterion[3] which is an expression combining the principal stresses.) After cooldown of the magnet and at 6500 A, the maximum tensile stress for the yoke decreases substantially to 11 MPa and the peak von Mises stress is 100 MPa (the peak von Mises stress occurs in the region of highest azimuthal compression).

For Kawasaki steel collars (Fig. 2), the yoke has a slightly smaller thermal contraction than the collars. Therefore, after cooldown to 4 K, the yoke midplane gap remains open and the bending increases, causing a larger maximum tensile stress in the yoke without greatly affecting the contact stress between yoke and collar. After magnet energization, the yoke midplane gap still remains open and about 50% of the Lorentz forces are transmitted to the yoke near the horizontal midplane, increasing the bending in the yoke and resulting in larger tensile stresses. Therefore, the peak stress in the yoke with Kawasaki collars occurs after magnet energization. The peak von Mises stress is 122 MPa and the maximum tensile stress is 93 MPa.

If one assumes that the yoke remains closed with Kawasaki steel collars (with anti-oval Kawasaki steel collars) the peak von Mises stress is 95 MPa and the peak azimuthal tensile stress in the yoke is greatly reduced to about 36 MPa (Fig. 3).

Table 2 lists the maximum von Mises stresses and tensile stresses for each of the cases discussed above.

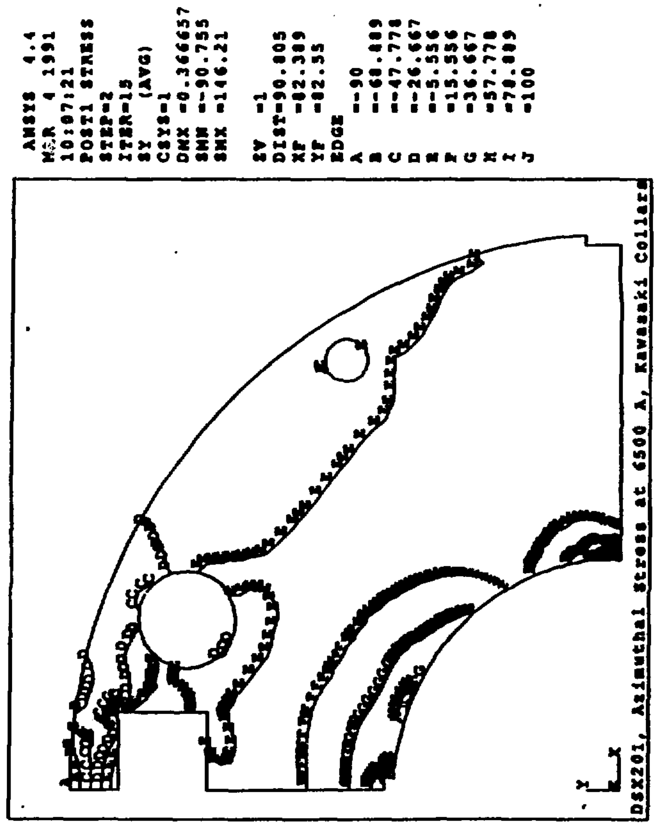
Figures 1 to 3 show the stress distribution in half a yoke only since symmetry with respect to the vertical axis is assumed. Peak tensile stresses occur at the pole because the yoke is bent due to Lorentz forces which act radially outwards and have largest components at the midplane.

CRITICAL PRE-EXISTING CRACKS LENGTH

Brittle fracture starts when there is a flaw or crack in the material which is subjected to tension. The stress field ahead of a sharp crack can be characterized by the parameter K_I called the stress intensity factor. The subscript I stands for mode I which is an opening mode as opposed to modes II and III for sliding and shearing. K_I is a function of the stress level σ and crack length a: $K_I = C\sigma\sqrt{a}$. (C is a constant which depends on the type of crack.) The critical stress intensity factor at which an unstable crack growth occurs is K_{Ic}. K_I is a measure of the stress intensity field ahead of a sharp crack in any material and K_{Ic} is a measure of the fracture toughness of a material.

Table 2. Maximum stresses

Case at 4 K 4 K	Max. von Mises Stress MPa (ksi)	Max. Tensile Stress MPa (ksi)
yoke/Nitronic collars	100 (14.5)	11 (1.6)
yoke/Kawasaki collars	122 (18)	93 (13.5)
yoke/Kawasaki anti-oval collars	95 (14)	36 (5)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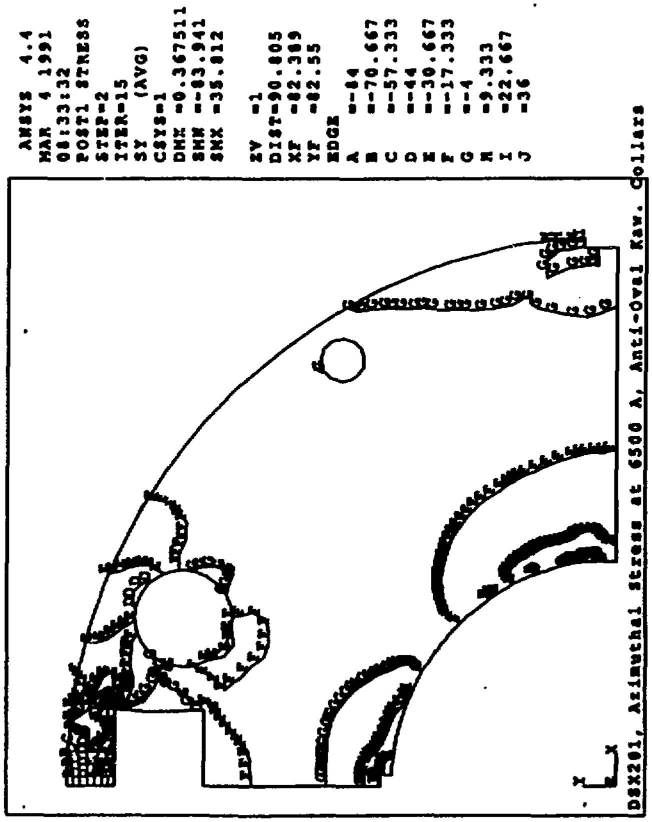
I =78.889
J =100
DSX201, Azimuthal Stress at 6500 A, Kawasaki Collars

Figure 2.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D =-44
E =-30.667
F =-17.333
G =-4
H =9.333
I =22.667
J =36
DSX201, Azimuthal Stress at 6500 A, Anti-Oval Kav. Collars

Figure 3.

There is a maximum permissible value for crack length above which the crack will propagate unstably. The fracture toughness K_{Ic} is used to determine this critical or maximum allowable length of pre-existing cracks for a given tensile stress σ_t using the following relation[4]:

$$a = \frac{1}{\pi}\left(\frac{K_{Ic}}{\sigma_t Y}\right)^2$$

where Y is a geometry-dependent parameter, ≈*1.12* for an edge crack. As the material composition has changed since the tests were performed, the available data are used only to estimate the critical crack length for the present material. For comparison purposes the two extreme cases of glass ($K_{Ic} = 0.7\ MPa\sqrt{m}^{1/2}$ according to R. Tobler) and Nitronic steel ($K_{Ic} = 180\ MPa\sqrt{m}^{1/2}$[5]) are also shown on Table 3.

An error analysis is performed to obtain the variance on a denoted ν_a. The variances $\nu_{K_{Ic}} = 1\ MPa\sqrt{m}^{1/2}$, $\nu_{\sigma_t} = 1\ MPa$, $\nu_Y = 0.01$ are used in the relation

$$\nu_a^2 = \left(\frac{\partial a}{\partial K_{Ic}}\right)^2 \nu_{K_{Ic}}^2 + \left(\frac{\partial a}{\partial \sigma_t}\right)^2 \nu_{\sigma_t}^2 + \left(\frac{\partial a}{\partial Y}\right)^2 \nu_Y^2$$

which reduces here to

$$\nu_a^2 = 2a\left(\nu_K^2/K + \nu_{\sigma_t}^2/\sigma_t + \nu_Y^2/Y\right)$$

The error analysis shows that the largest contribution in the above expression comes from the uncertainty on K_{Ic}. For the worst case the critical crack length is 7 mm plus or minus 1 mm for the yoke material. If the material were glass, the critical crack length would be 0.01 mm and if it were made of Nitronic steel it would be 950 mm for the same tensile stress. The magnitude of critical cracks, were there to be any on the surface, would be large enough to be detected by visual inspection.

BRITTLE FRACTURE FAILURE

The "maximum normal stress theory" is usually used to predict brittle fracture[3]. This stipulates that fracture in a brittle material will occur when the maximum principal stress at a point in tension is equal to the ultimate stress from a simple tensile stress. The ratio of the ultimate strength and maximum stresses from the ANSYS calculations is shown below as a safety factor.

Table 3. Critical crack length calculations

Case 4 K	Tensile Stress MPa	Crack/ Yoke mm	ν_a mm	Crack/ Glass mm	Crack/ Nitronic mm
yoke/Nitronic	11 (1.6 ksi)	470	8	1	7 x 10^4
yoke/Kawasaki	93 (13.5 ksi)	7	1	0.01	950
yoke/Kawasaki anti-oval	36 (5 ksi)	44	2	0.1	6 x 10^3

Table 4. Safety factor

Case	Safety Factor
yoke/Nitronic collars	67
yoke/Kawasaki collars	8
yoke/Kawasaki anti-oval collars	20

The lowest factor of 8 occurs when Kawasaki collars are used with the assumption that the midplane gap does not close. This number is comparable to the accepted safety factor of 10 used for the design of unprestressed glass.

CONCLUSIONS

Tests show that the carbon steel used in the SSC yoke is very brittle, however finite element analysis indicates that tensile stresses are very low. Fracture analysis shows that unstable crack propagation occurs if there are pre--existing cracks of at least 7 mm. Comparison between measured ultimate strength and computed tensile stresses result in safety factors which depend on the finite element model's assumptions with a minimum of 8.

ACKNOWLEDGEMENTS

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