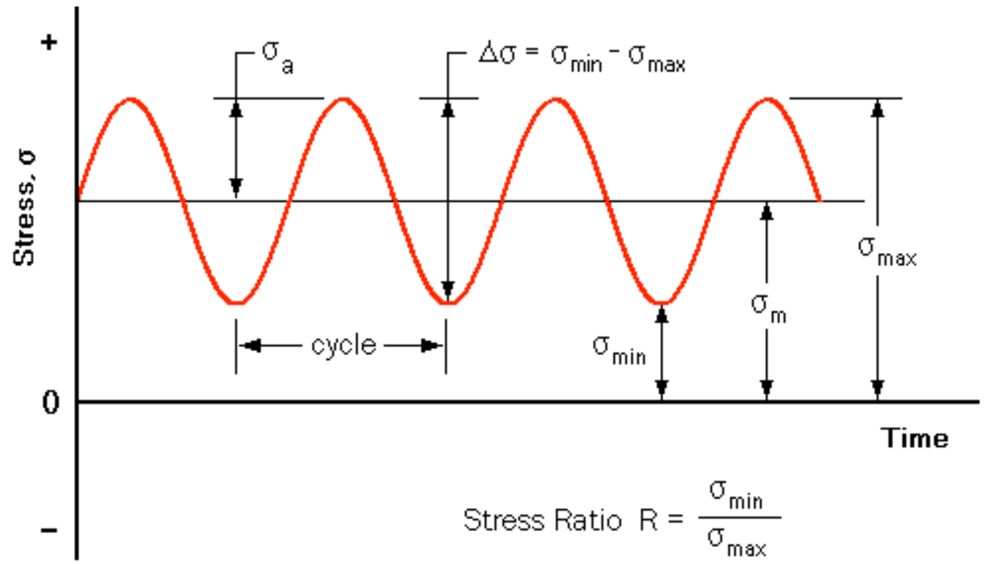
MECHANICAL PROPERTIES OF MODIFIED JK2LB FOR Nb3Sn CICC APPLICATIONS

R. P Walsh[1], V. J.Toplosky[1], K. Han[1]
N. N. Martovetsky[2], T. Mann[2], and J. R. Miller[2]

1. National High Magnetic Field Laboratory
2. US-ITER Project, Magnet Group



Magnet Science & Technology NHMFL

INTRODUCTION:

• Since the introduction of CICC magnets a variety of alloys have been proposed for fabricating the conduit. Some examples you may remember; 316, 316L, 316LN, A286, Incoloy 908, Haynes 242, JK2, JK2LB

• When Nb_3Sn is the conductor, the conduit alloy must retain good mechanical properties after exposure to the reaction heat treatment.

• An optimized version of JK2LB has been produced by JAEA to resist post-aging embrittlement and is presently being considered for use in ITER Central Solenoid (CS) Coils.

• Here we present data for modified JK2LB, before and after the exposure to the reaction heat treatment;

Tensile, Fracture Toughness, FCGR, and Axial fatigue (S-n)

MATERIAL INFORMATION

Alloy	C	Si	Mn	P	S	Cr	Ni	Mo	N	B	Fe
Specification	<0.03	<0.5	20.5-22.5	<0.015	<0.015	12.0-14.0	8.0-10.0	0.5-1.5	0.09-0.15	0.001-0.004	Bal
Present Conduit	0.025	0.41	21.42	n/a	0.002	11.93	8.43	0.78	0.119	0.0013	Bal
Billet A [3,6]	0.023	0.28	21.0	0.005	0.002	12.8	9.3	1.0	0.24	0.0017	Bal
Billet B [3]	0.032	0.35	20.9	0.008	0.003	12.68	9.25	0.98	0.20	0.0038	Bal
Hamada et al.[5]	0.013	0.26	21.8	0.007	0.002	12.8	9.25	0.98	0.12	0.0036	Bal

• Seamless CS conduit produced by JAEA and Kobe Steel Co.

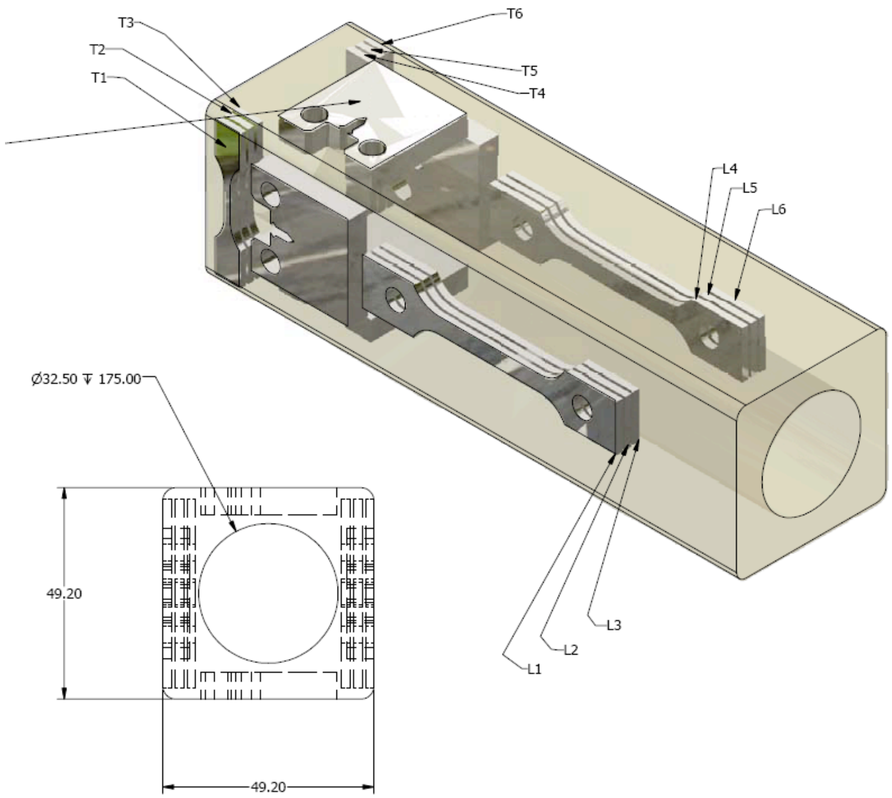
• Hot extruded to slightly oversized dimensions to facilitate cable insertion

• Final compaction performed cold, reduces the conduit's nominal dimensions, 2-2.5 mm

• Two 1m long sections of round-hole in square-tube conduit were received at NHMFL in the compacted state or As-Received (AR) state.

• The aged condition (AG) is accomplished by aging the conduit at 650C/200h in an Argon atmosphere.

•The AG condition has nominal grain size of approximately 100 μm.



295 K Tensile Properties

Specimen No.	Yield Strength (MPa)	Tensile Strength (MPa)	Elong. in 25 mm (%)	Red. Area (%)
AR-L1	438	627	51.4	74.2
AR-L2	420	601	62.2	73.9
AR-L3	432	595	65.1	76.8
AR-L4	416	599	59.3	75.7
AR-L5	430	608	54.0	77.7
AR-L6	562	642	36.8	69.8
AR Average	450	612	55	75
AR Stdev	55.6	18.6	10.2	2.8
AG1-L1	404	599	55.2	74.1
AG1-L2	388	605	52.4	72.1
AG1-L3	388	609	53.4	73.1
AG Average	393	604	54	73
AG Stdev	9.24	5.25	1.43	0.99

- The AG material has a 13% decrease in YS compared to AR material.
- The through thickness variation in YS isn't present in the aged material.
- Both of these factors indicate residual stress relief from the 650 C/200h heat treatment.

Summary of Tensile Properties

Temp	Spec. Orientat'n	Condit'n	Yield Strength (MPa)	Yield Std Dev (MPa)	Tensile Strength (MPa)	TS Std Dev (MPa)	Elong. in 25 mm (%)	Reduct'n of Area (%)	No of Tests
295	L	AR	450	56	612	19	55.0	75.0	6
295	L	AG	393	9	604	5	54.0	73.0	3
4	L	AG	1006	20	1414	22	46.0	39.0	9
4	T	AR	1015	77	1391	13	40.3*	44.9	3
4	T	AG	1063	3	1397	19	37.9*	37.5	3

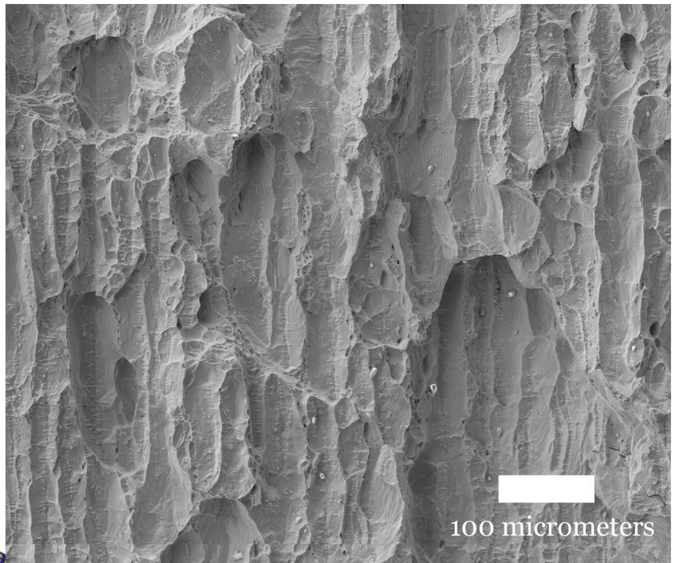
- The 4K Tensile results with respect to CS design are highlighted
- The AG material retains good ductility and acceptable Yield Strength
- These results are in good agreement with published results of the similar chemistry JK2LB (Hamada et.al. Adv in Cryo Engr. 2007)

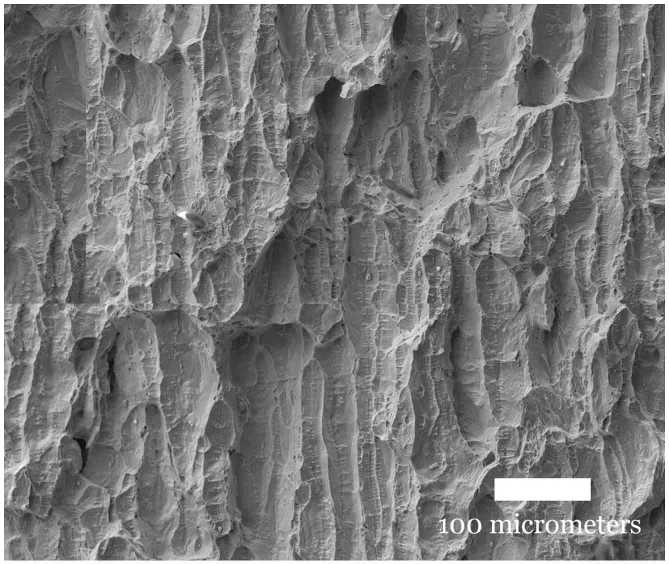
Summary of 4 K Fracture Toughness

Condition	Spec No. Orientation	Kic(J) MPa*m^0.5	Kic(J) Avg. MPa*m^0.5
As Received	LT-1	290	280
	LT-2	>270	
As Received	TL-1	157	154
	TL-2	152	
Aged	TL-1	161	167
	TL-2	174	

- The 4K Toughness results are acceptable with respect to CS design.
- The AG material exhibits a slight increase in toughness compared to AR.
- The 167 MPa*m$^{0.5}$ is somewhat lower than published results of > 200 MPa*m$^{0.5}$ for the similar chemistry JK2LB (Hamada et.al. Adv in Cryo Engr. 2007)

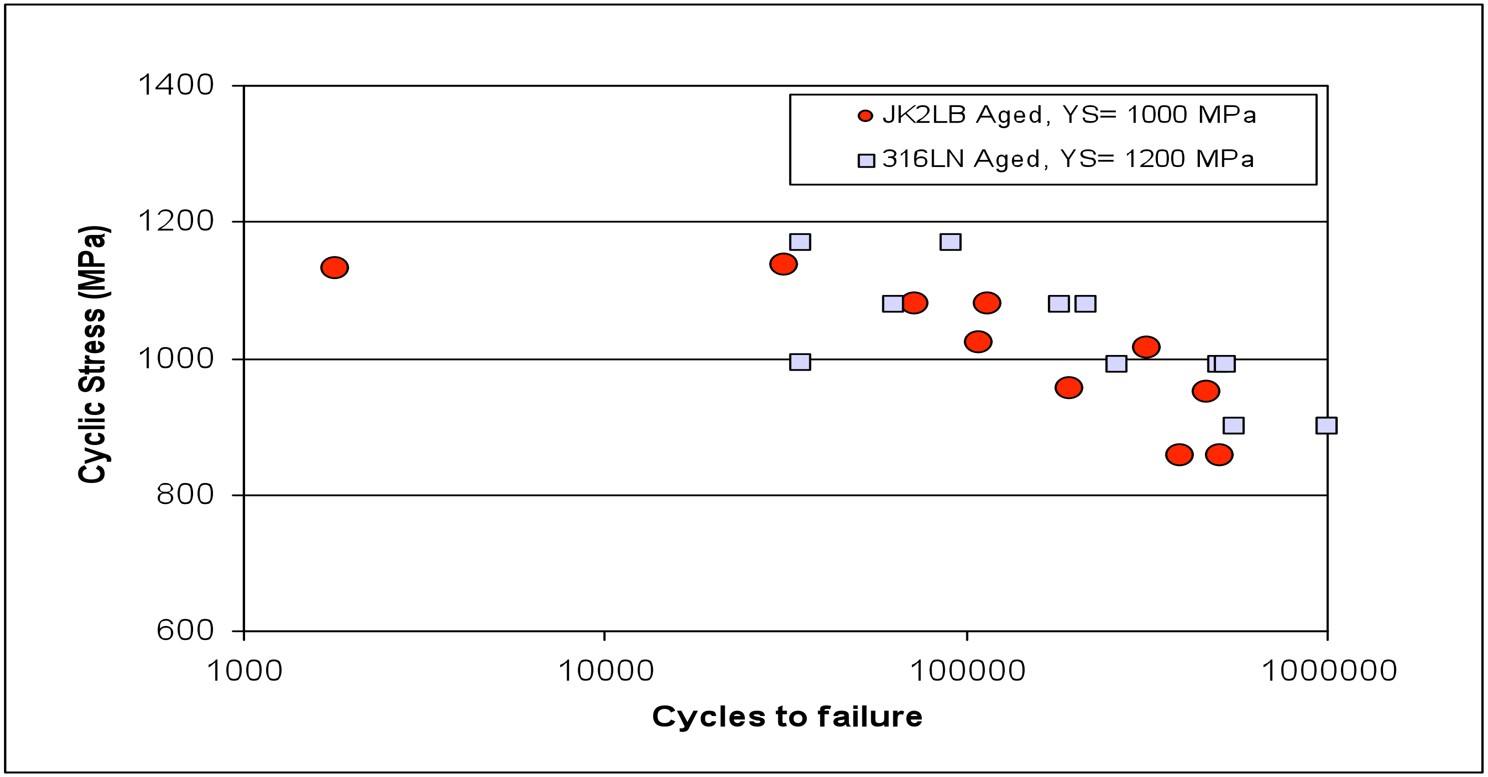
AR





AG

Summary of 4 K Fatigue Test

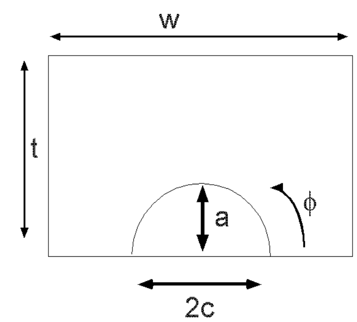


- The 4K S-n data for the Aged JK2LB is in relatively good agreement with data for Aged 316LN modified.
- The good agreement of the two data sets is interesting since they have significantly different yield strengths.
- There is limited 4 K fatigue data available in the literature for comparison and the data generated here and in [9] represent a significant addition.

Fracture Mechanics Fatigue Design – a more conservative design approach, acknowledges material imperfections can create localized stress intensity that may generate and drive fatigue cracks

- Assume a pre-existing flaw

Assume semi-elliptical flaw in infinite width plate



- Calculate a stress intensity factor (K).
- Evaluate the design life with respect to 316LN FCGR properties

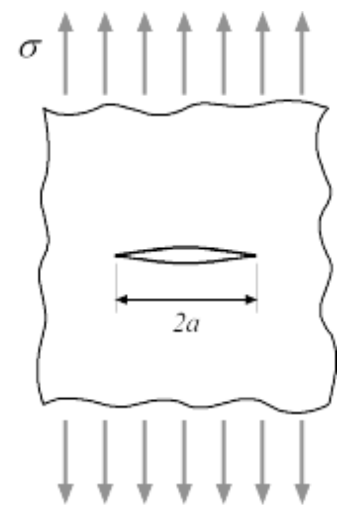
$K = \sigma ((\pi a)^{0.5})$ MPa*m^0.5

Modify eqn. for crack shape factor

$K = F \sigma ((\pi a/Q^{0.5})$ MPa*m^0.5

Insert cyclic stress range to calculate ΔK, the fatigue stress intensity range.

Example:
if Stress cycle = 0 to 368 MPa
and flaw size, a = 0.25 mm
Then;
$\Delta K = 9$ MPa*m^0.5



Fatigue Crack Growth Rate Testing: Performed over a range of applied stress intensity factors to determine the Stage II (Paris regime) FCGR parameters (ASTM E647 test procedures).

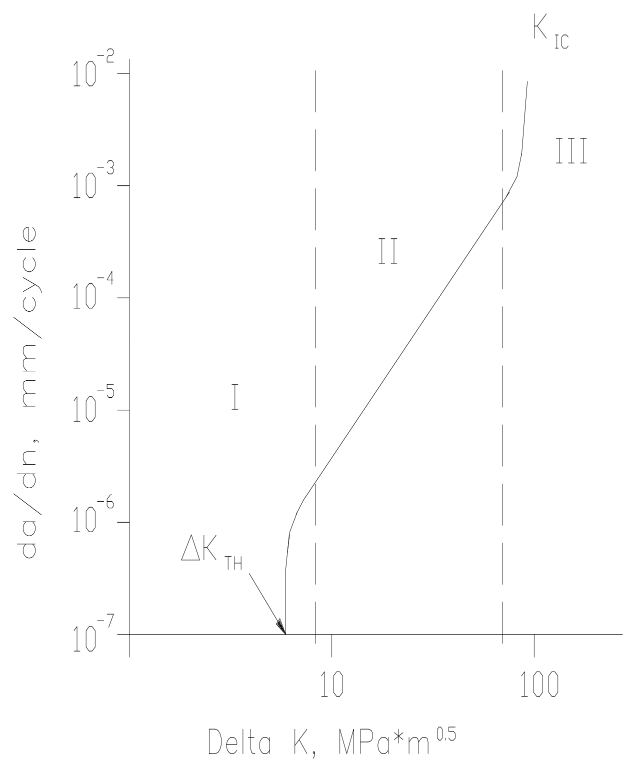
- Paris Law:
  $da/dn = C * \Delta K^m$

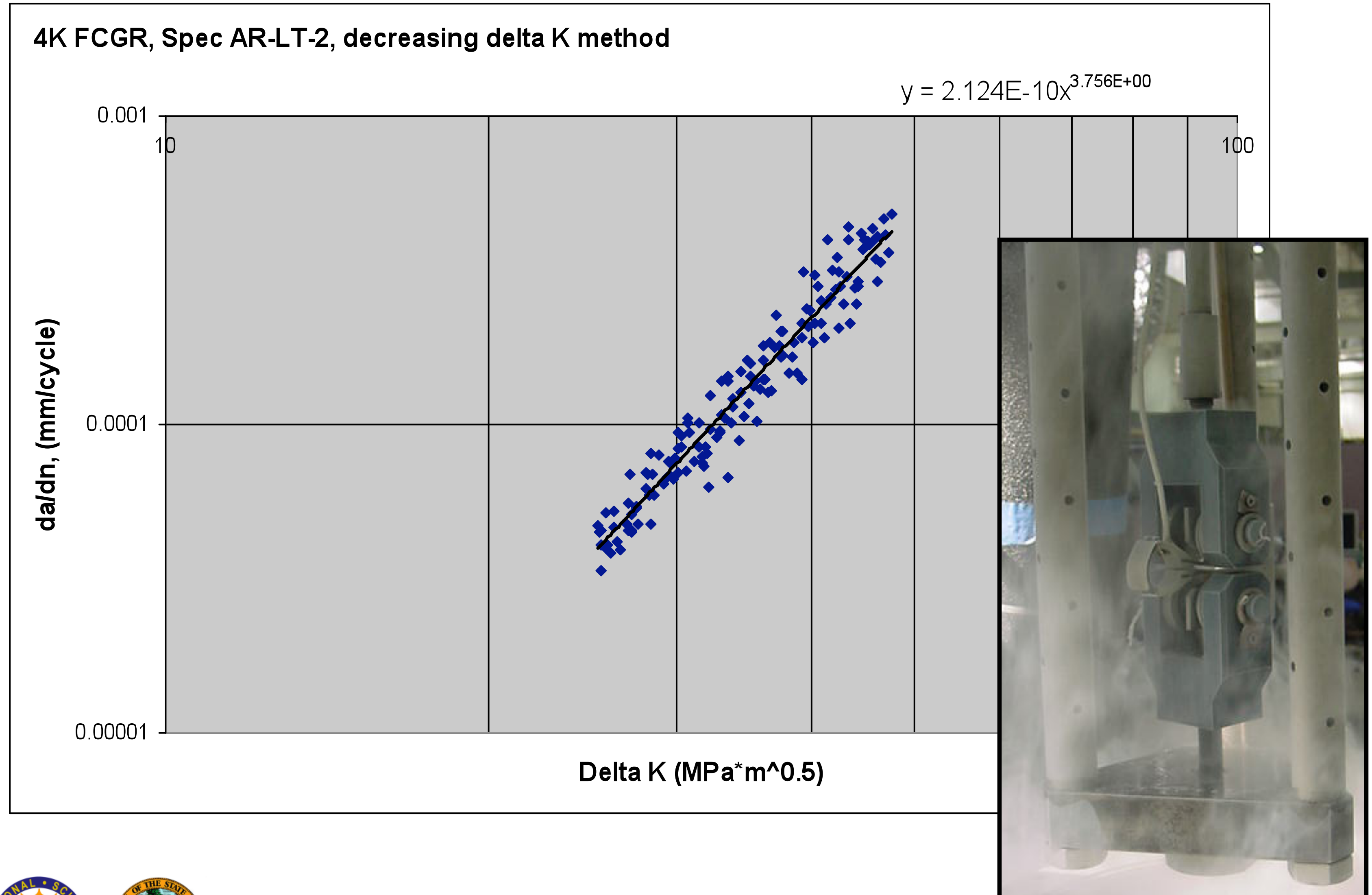
Where:

da/dn = crack growth rate (mm/cycle)

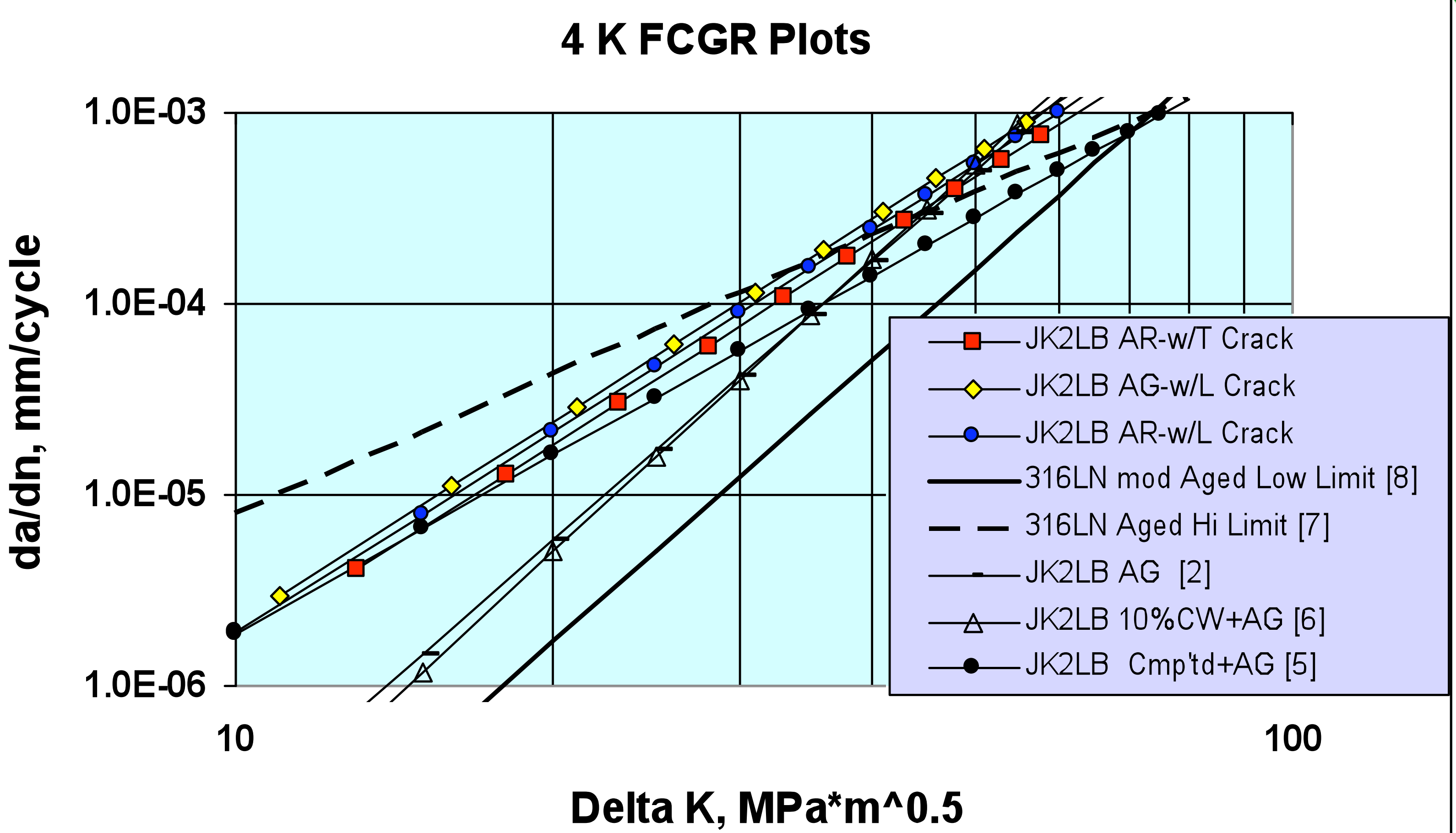
C and m = material constants

ΔK = stress intensity range





4K FCGR, Spec AR-LT-2, decreasing delta K method
y = 2.124E-10x^3.756E+00
0.001
0.0001
0.00001
10
100
da/dn, (mm/cycle)
Delta K (MPa*m^0.5)



The FCGR's are very consistent for the AR and AG conditions and there is little effect of crack orientation. For clarity, the results shown in the graph are calculated data based on the experimentally determined Paris parameters.

CONCLUSIONS :

• An optimized grade of JK2LB, with nitrogen content ~ 0.12 %, has undergone a comprehensive 4 K mechanical properties characterization to generate data for the ITER Central Solenoid design.

• The 4 K yield strength and fracture toughness exceed the ITER-CS coil requirements of yield strength >1000 MPa, and fracture toughness > 130 MPa*m^0.5 .

• Concerns about post-aged, low ductility and low fracture toughness, noticed in the prior higher nitrogen versions of the alloy, appear to be resolved in the optimized version as there was no post-aged degradation of fracture toughness or tensile elongation.

• The axial fatigue properties are plotted as an S-n curve that provides a limited database that should be bolstered before using for design.

• The FCGR measured here is higher than previously published for the higher N2 content JK2LB but in relatively good agreement with the similar chemistry version tested.