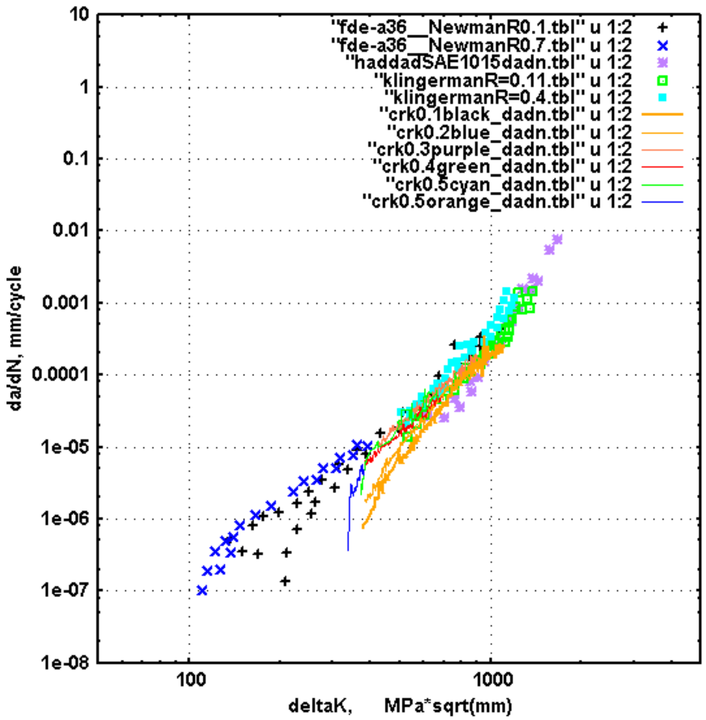
Univ. of Waterloo Crack Propagation da/dN Curve Collection for Steels

Presentation

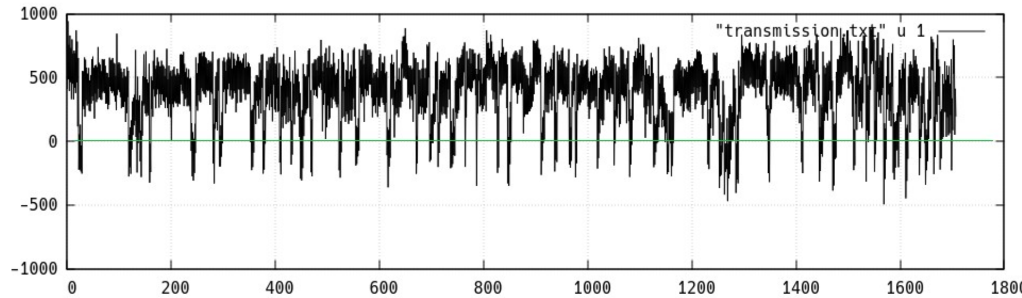
by
Al Conle and Carol Liang

Annotations have been added for Internet version.

Presented at F.D.E. Comm. of SAE Spring Meeting, April 15 2020



In 2018 we were developing some open-source crack propagation(FCP) models to add new capabilities. As a check the new models were used to simulate some existing center notched specimen test results



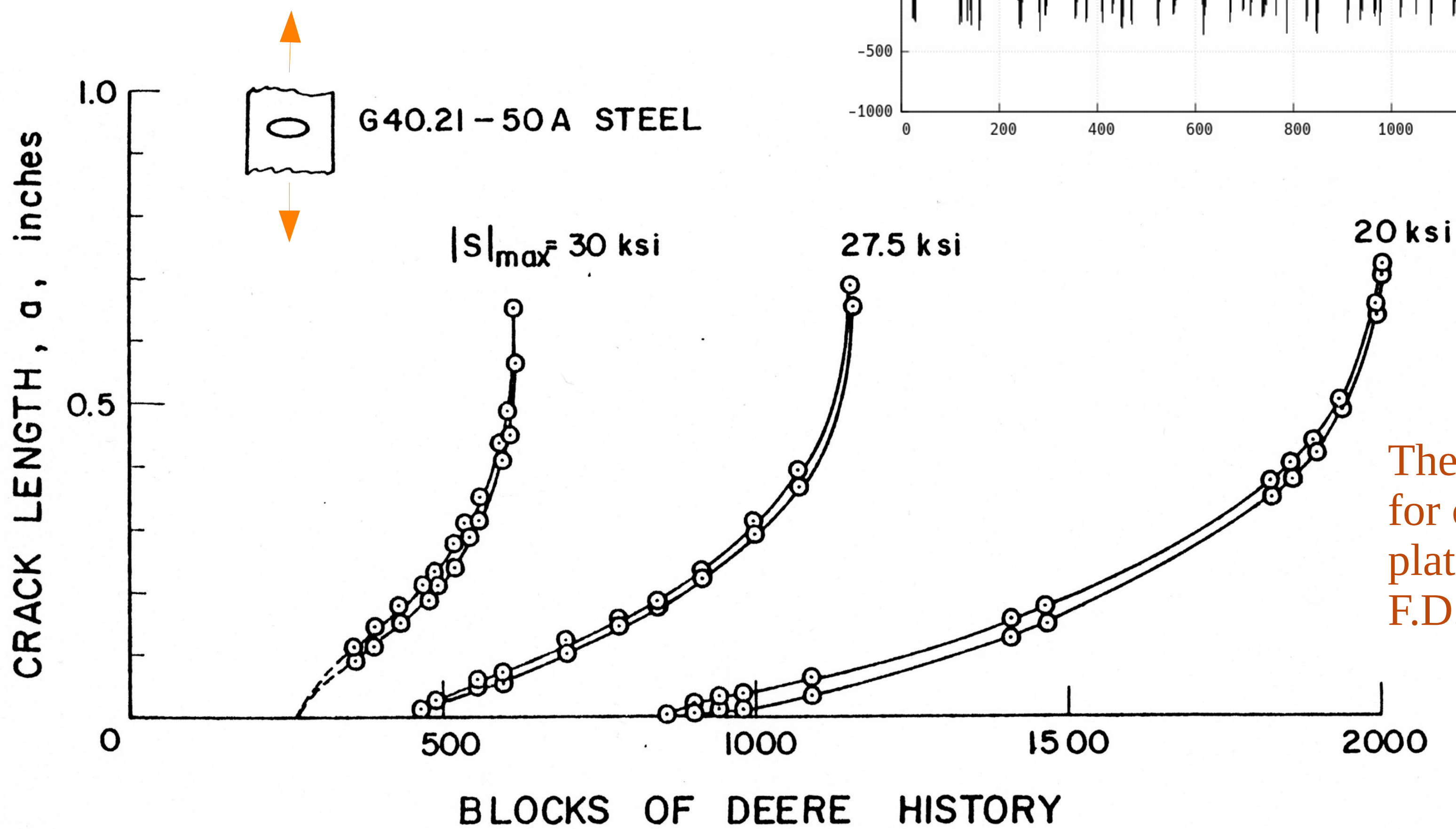
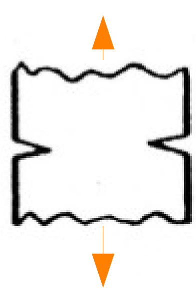


Fig. 56 Observed Crack Propagation Behaviour During Deere Loading History Fatigue (Central Notched Plate, K_t=4.6) F.A.Conle PhD thesis

The simulations were for center notched steel plates subjected to the F.D.&E

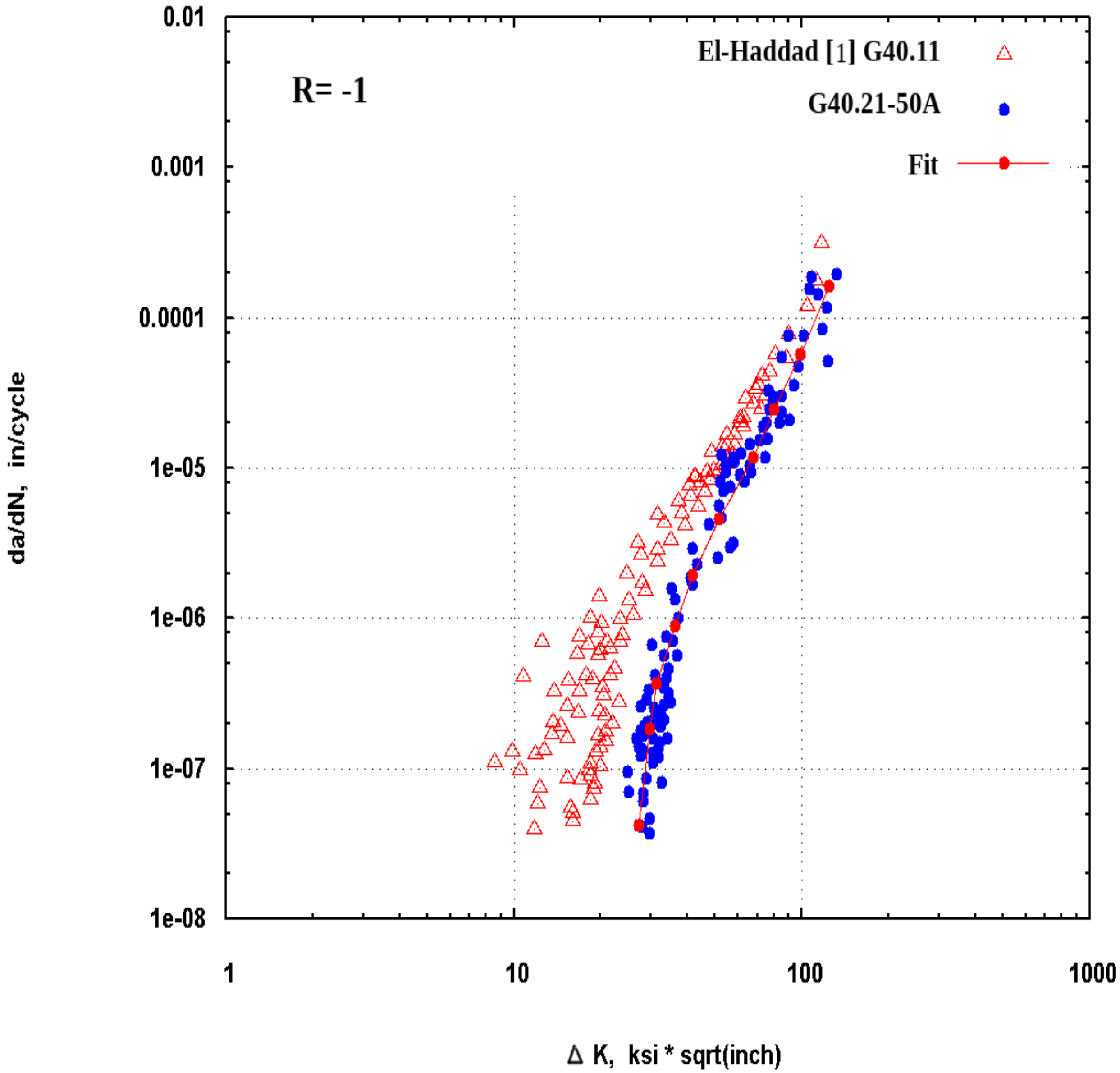
The da/dN curve was measured from a double notched plate specimen. (circa. 1978)



G40.21-50A STEEL

ΔS =40 ksi CA R= -1

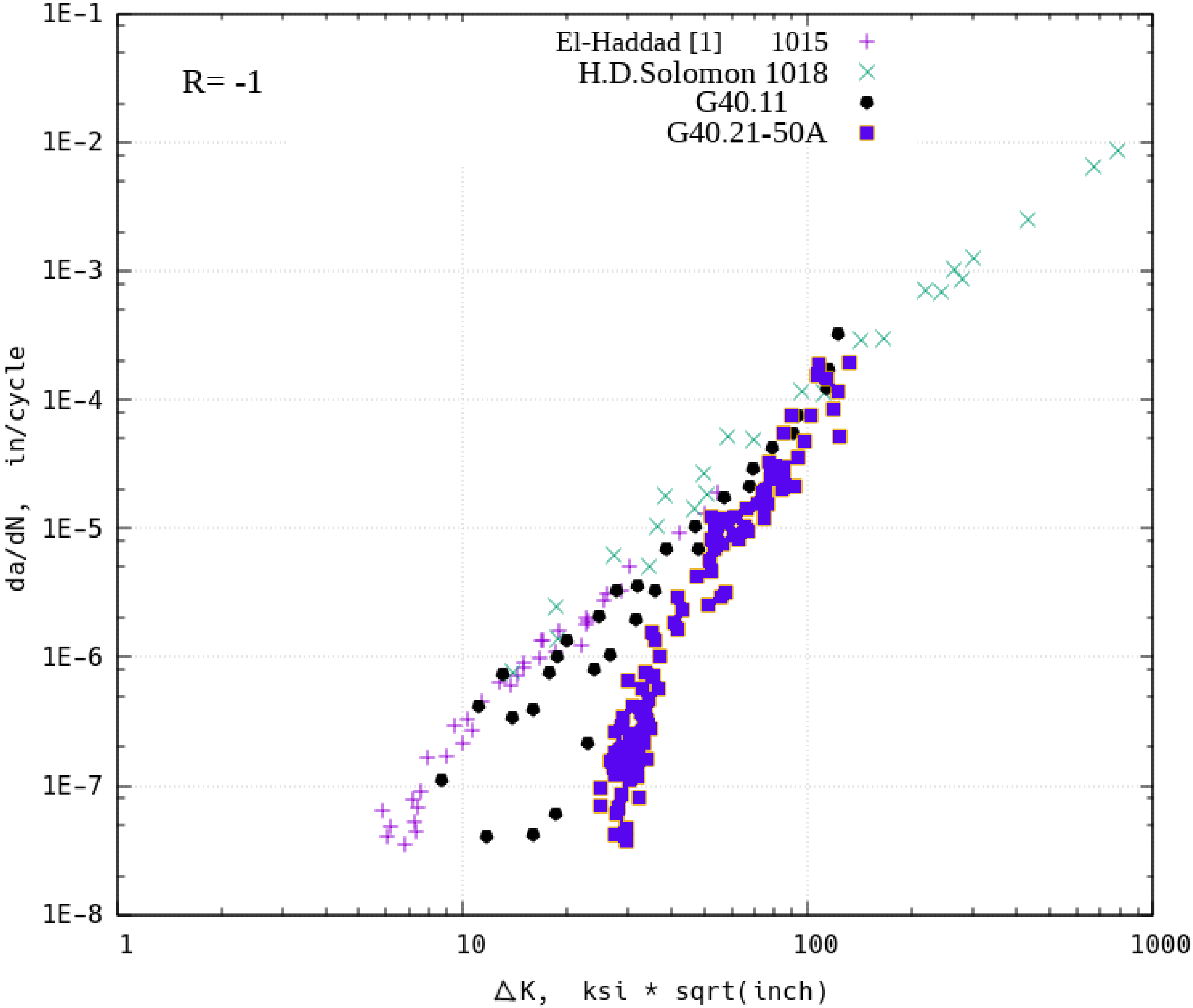
FCP test specimen



We decided to add in El-Haddad's older data set for a very similar material (shown in red)

The double edge notched data (shown in blue) did not coincide with the older data. Quite odd.

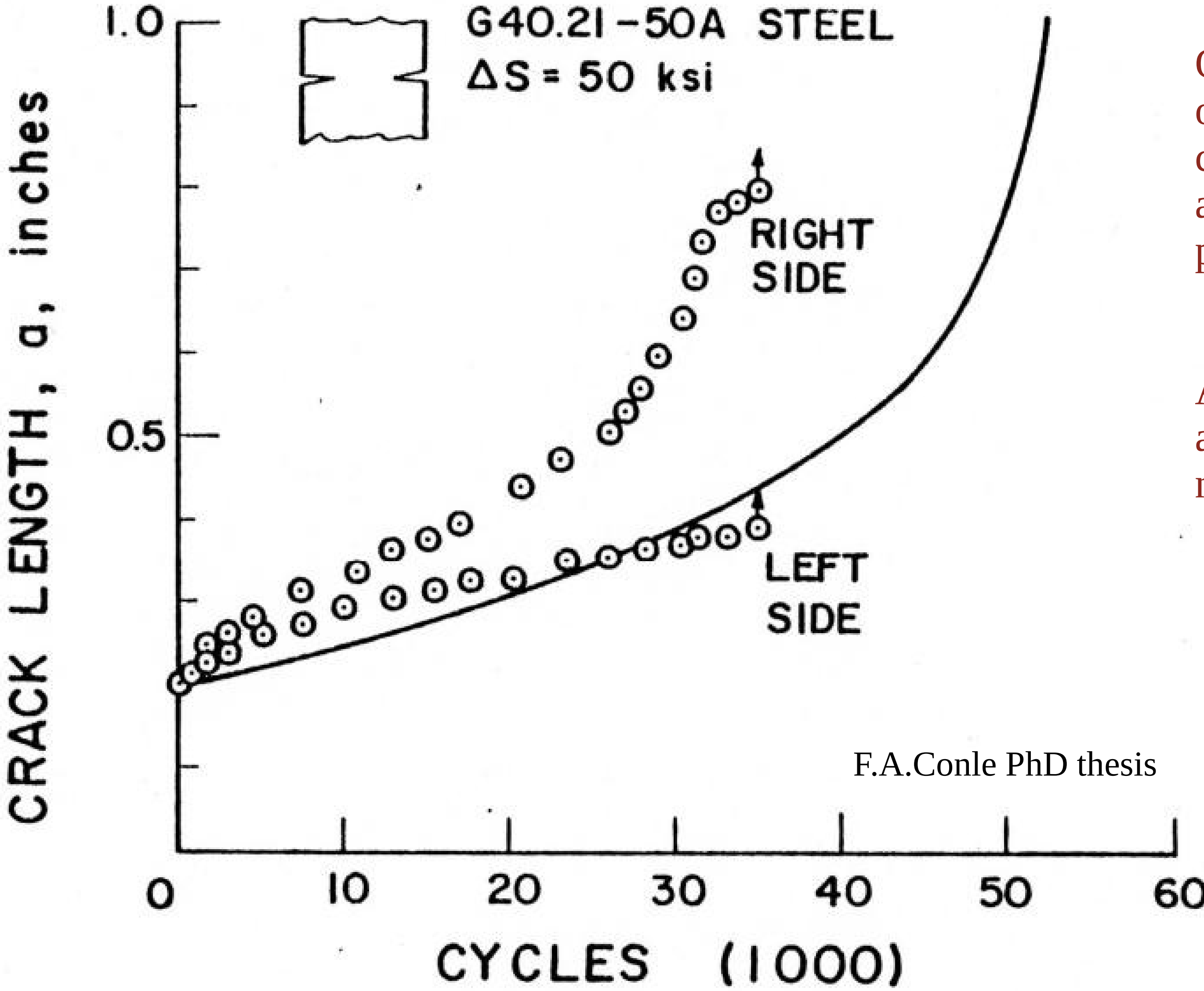
So as with any engineering problem faced with uncertainty:
Add more data. (next slide)



Adding R=-1 data from similar materials did not help validate the double sided notched plate data.

We decided that there was just something wrong with the double sided notched plate data. Cause unknown.

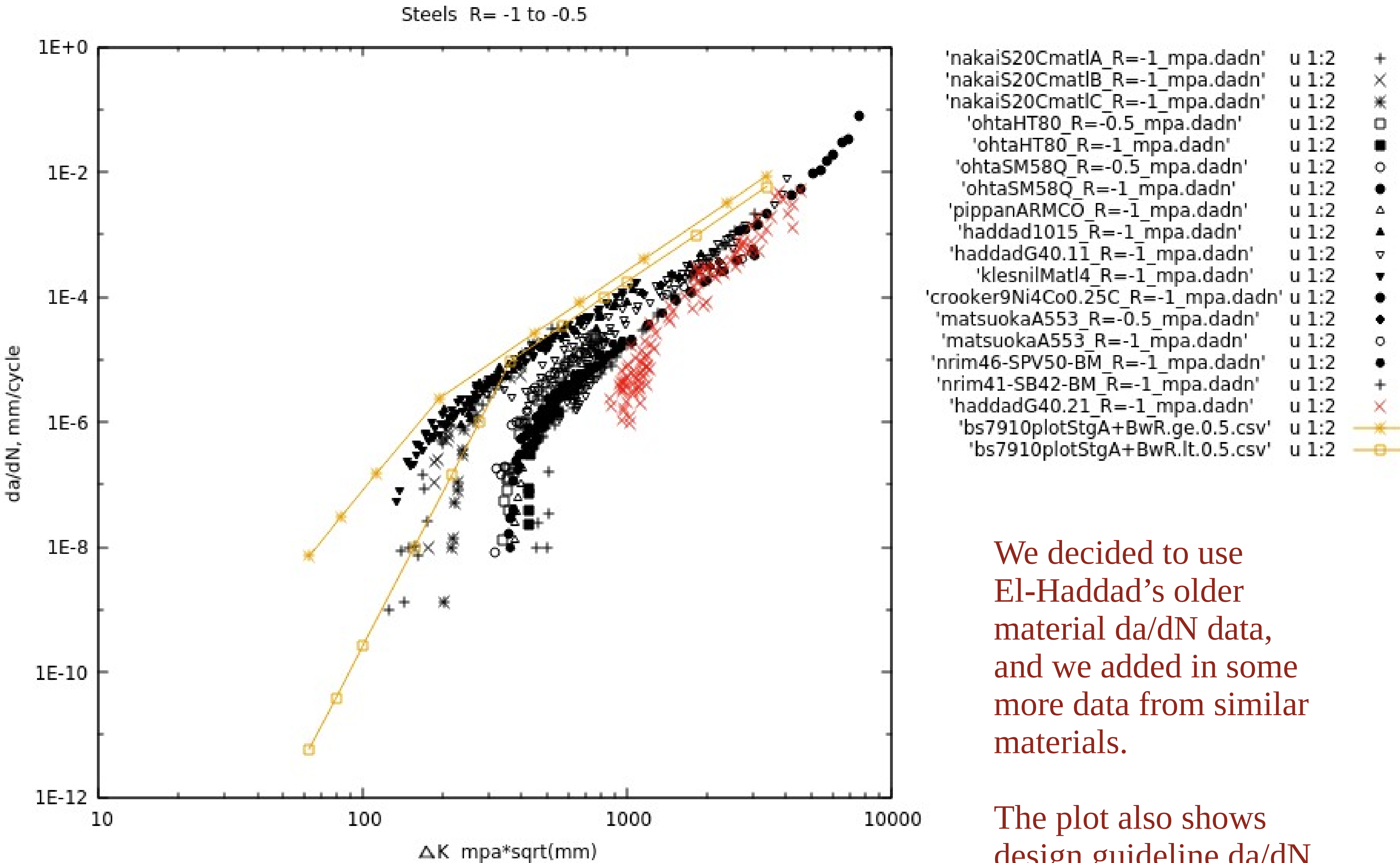
The red data from previous slide is outlined here with black points



F.A.Conle PhD thesis

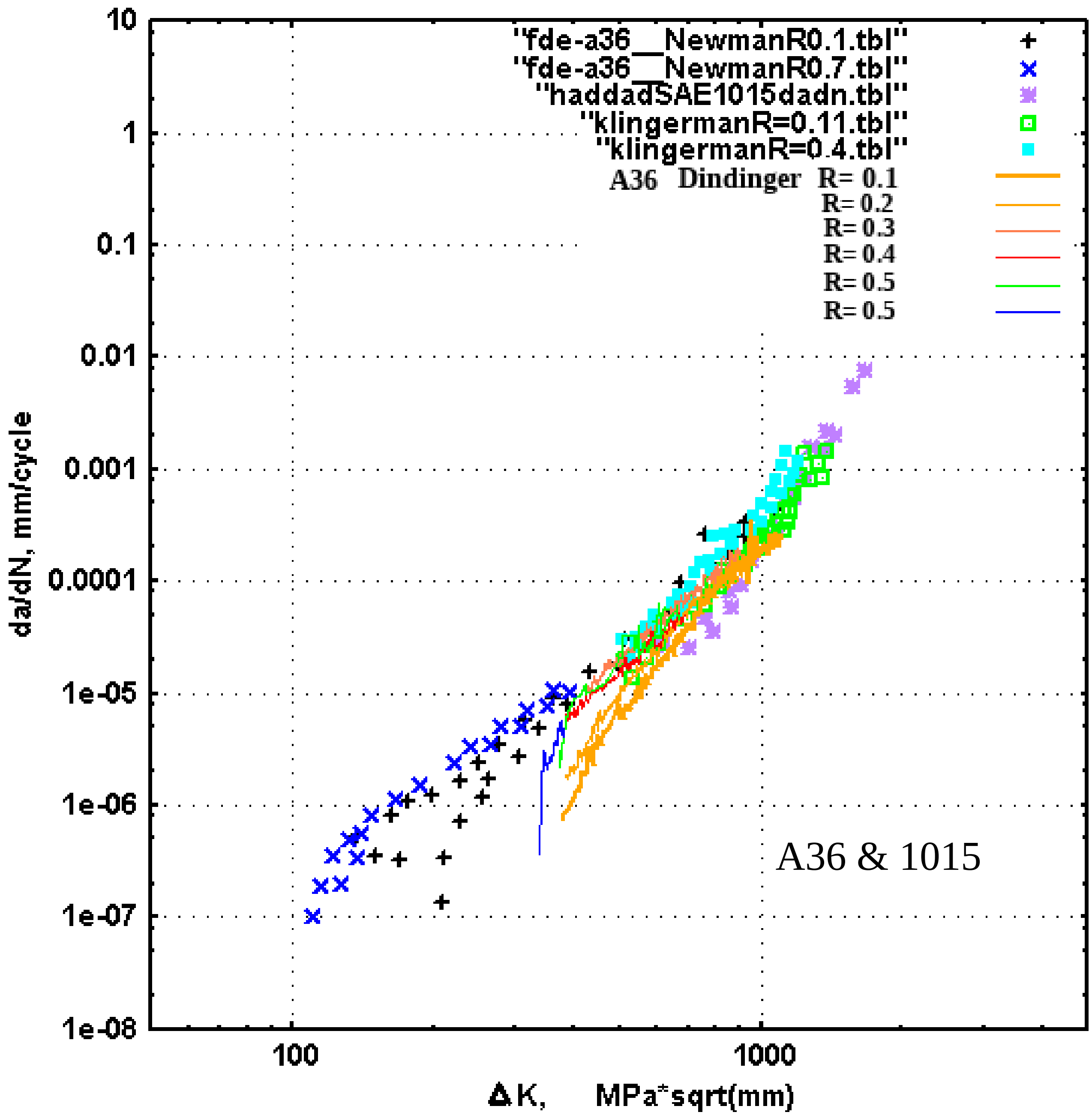
One possible cause is that one of the double sided cracks tends to “take over” and dominate the cracking process.

At this point we decided to abandon the double sided notched plate da/dN data.



We decided to use El-Haddad's older material da/dN data, and we added in some more data from similar materials.

The plot also shows design guideline da/dN lines from BS 7910 [2]

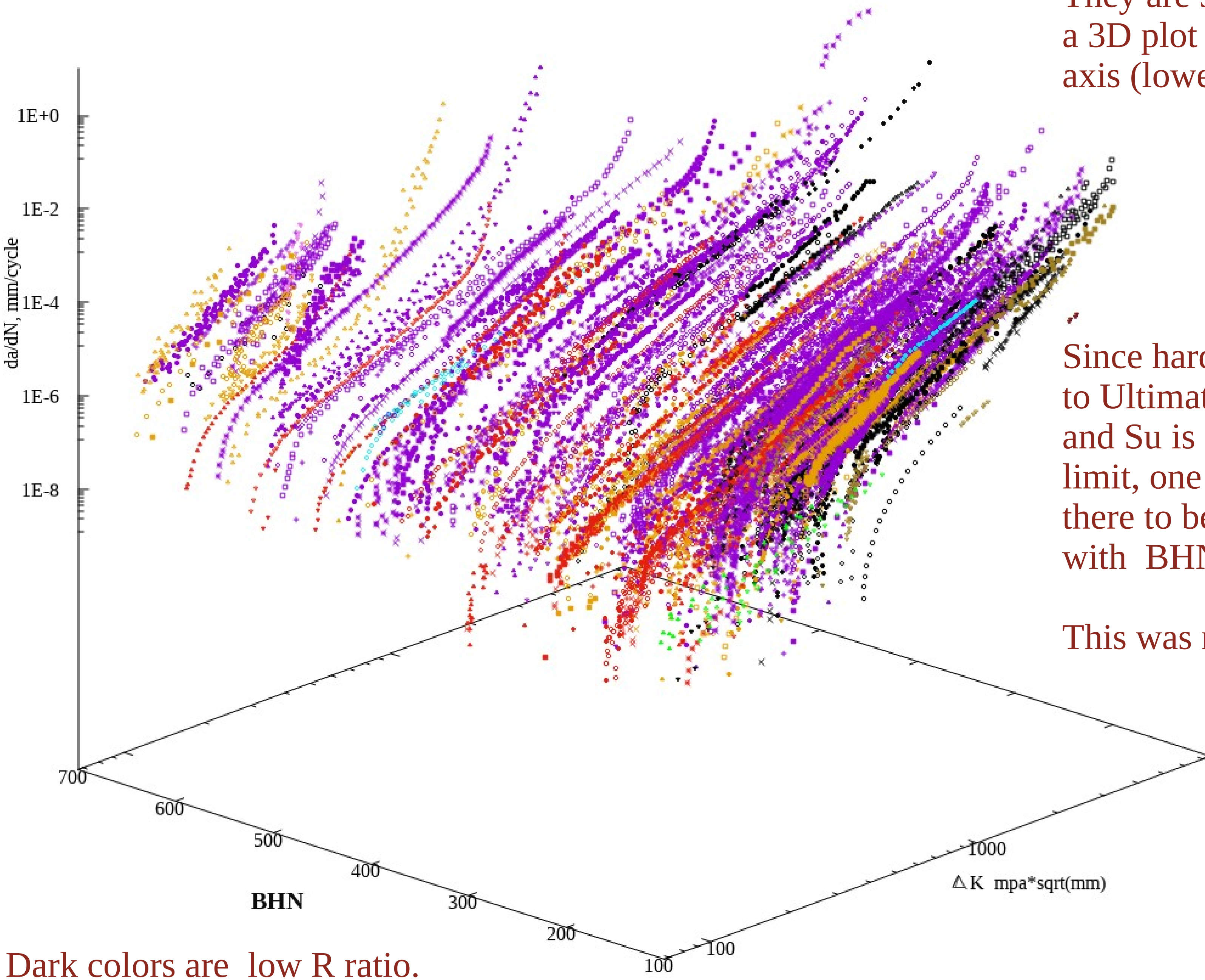


Also available were data sets for ASTM A36 steel, and SAE1015.

All this proved sufficient for our first set simulations, but there were other reseach objectives too, and as so often happens:
"one thing leads to another"

(next slide)

We now have about 450 sets of da/dN curves. They are shown here in a 3D plot where the 3rd axis (lower left) is hardness.

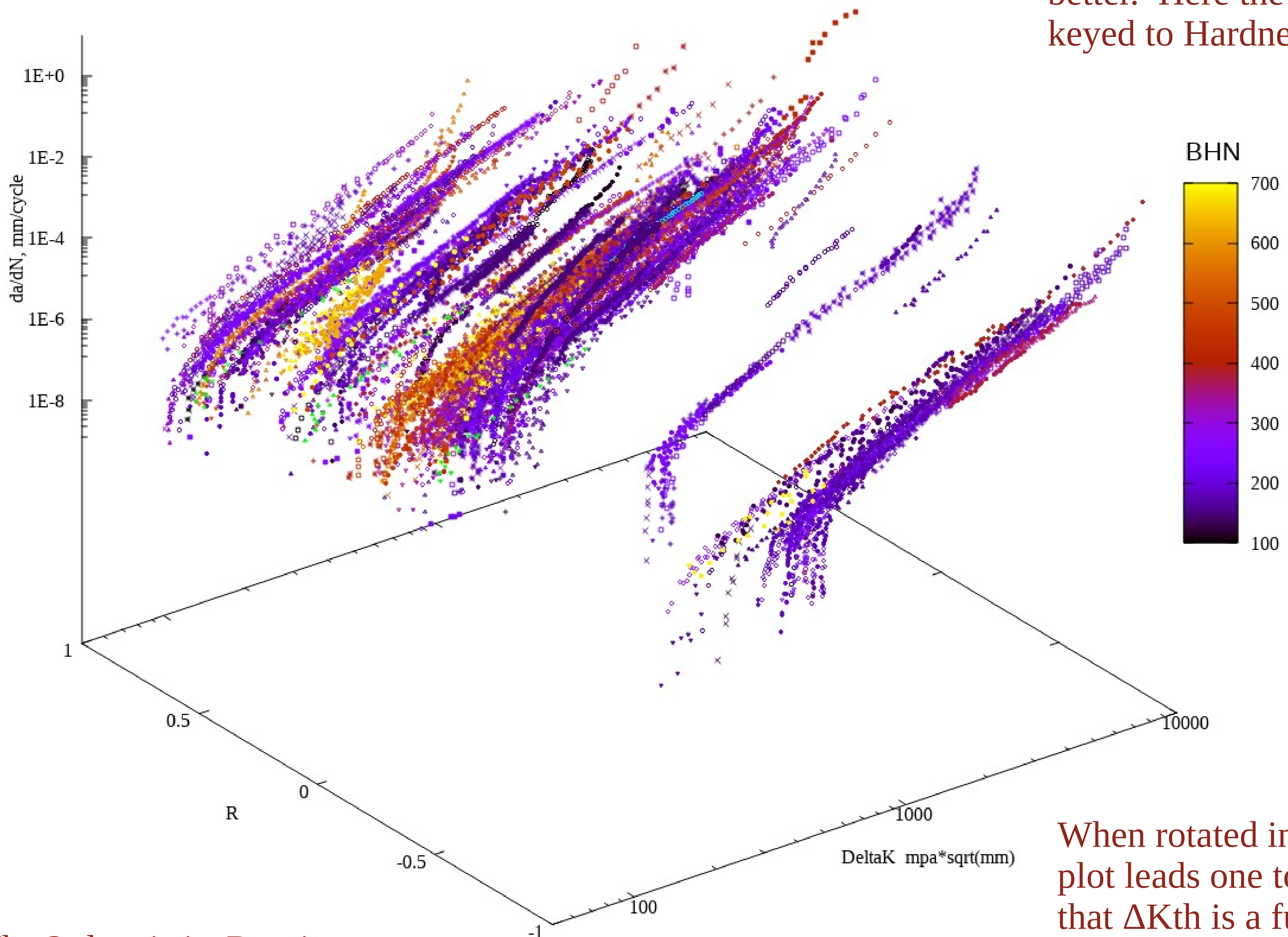


Since hardness is related to Ultimate Strength (Su) and Su is related to fatigue limit, one would expect there to be some correlation with BHN.

This was not the case.

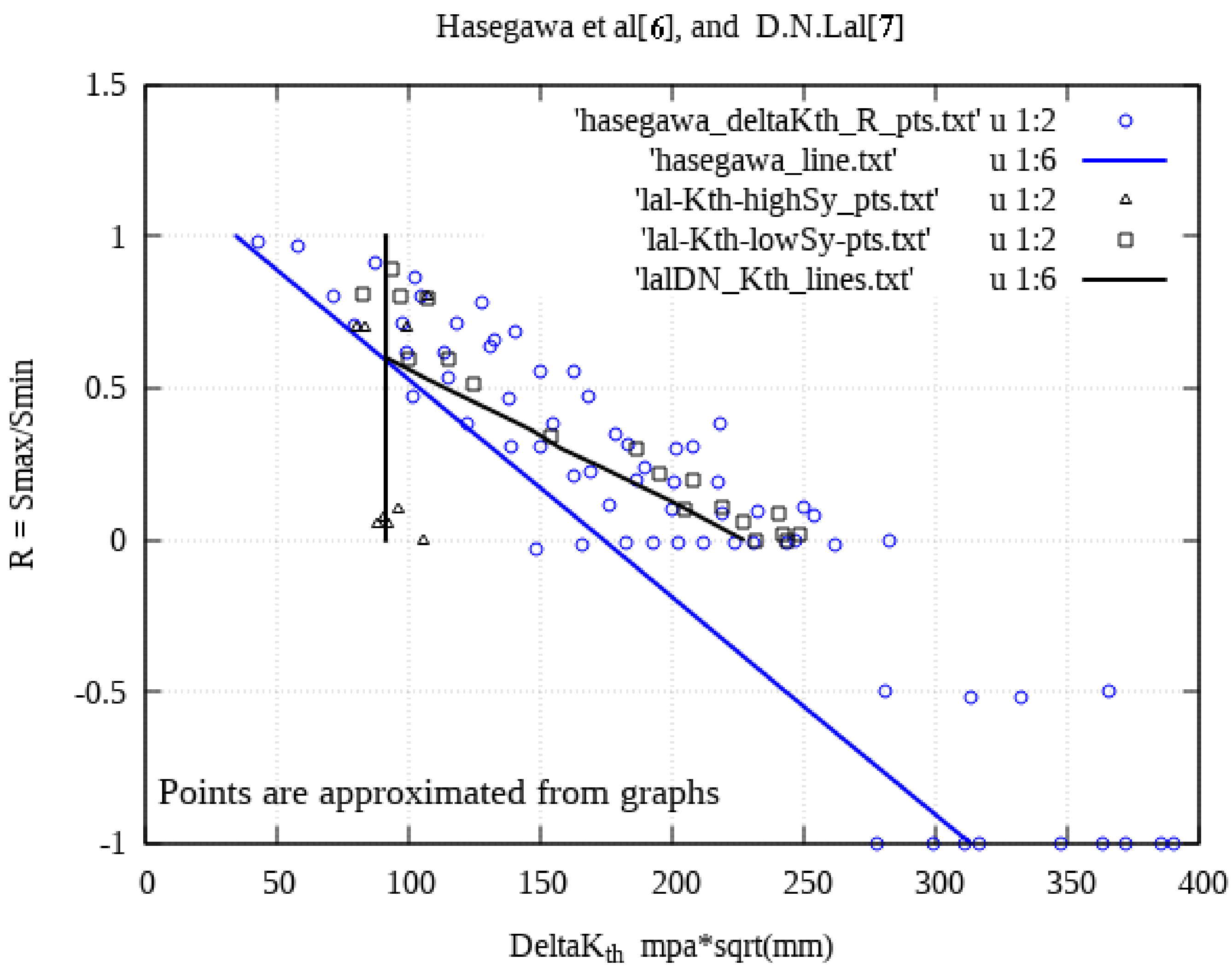
Dark colors are low R ratio. Light colors (red, gold, yellow are higher R ratio)

A sort by R ratio looks much better. Here the colors are keyed to Hardness



The 3rd axis is R ratio

When rotated in 3D this plot leads one to conclude that ΔKth is a function of R ratio.



Barsom, Lal, and recently Hasegawa have shown that ΔKth is a function of R ratio.

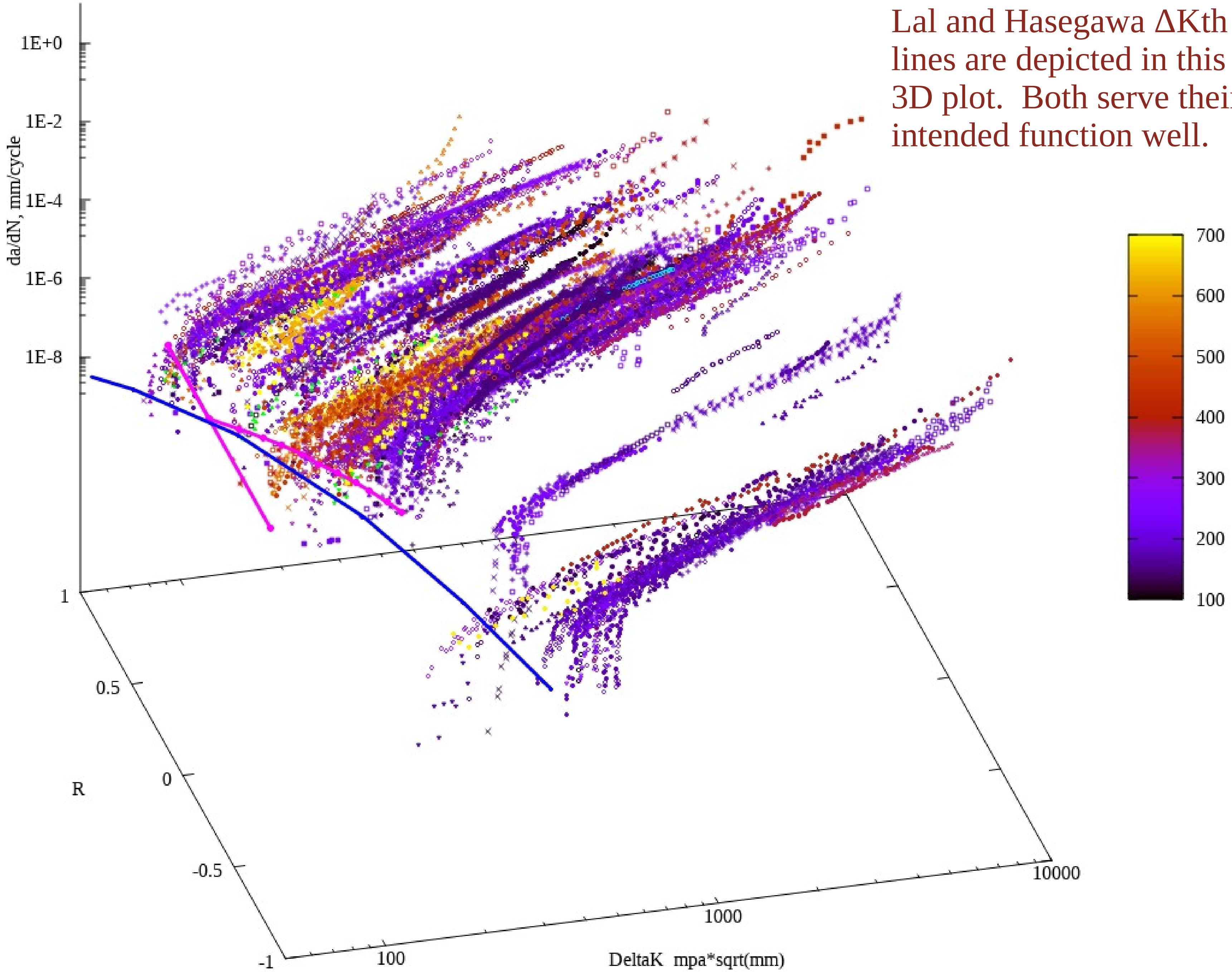
In this plot Lal's black diagonal line(and black points) are for lower strength steels. His vertical line (and points) are for high strength steels.

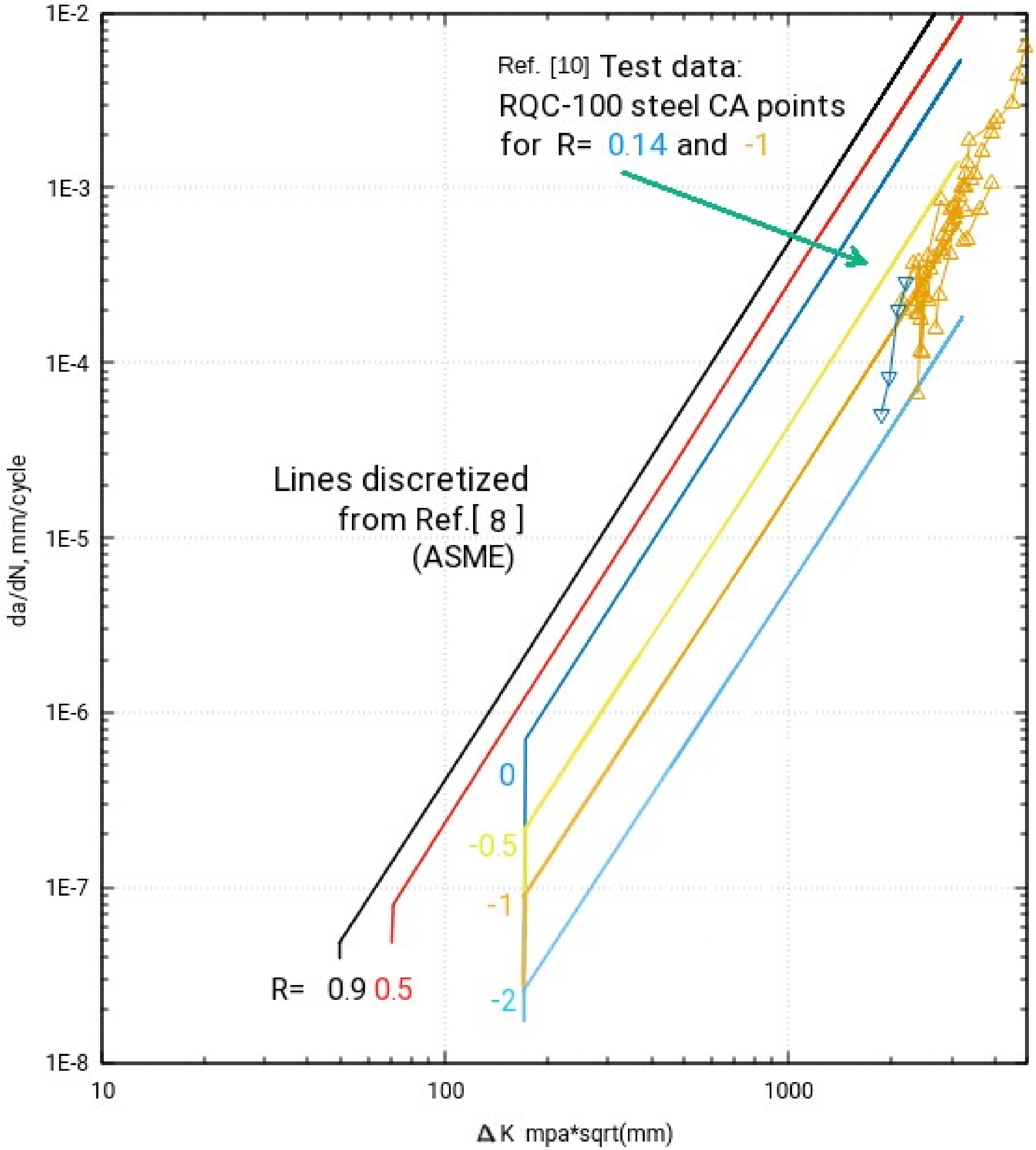
Hasegawa et al's points(blue) are for lower strength steels. His blue diagonal line is the lower limit of these points.

Both Lal and Hasegawa lines are plotted in the next slide.

Incidentally: K.Hasegawa serves on the ASME committee that defines the da/dN lines for pressure vessel steels. His papers are very informative and recommended references.

Lal and Hasegawa ΔKth lines are depicted in this 3D plot. Both serve their intended function well.





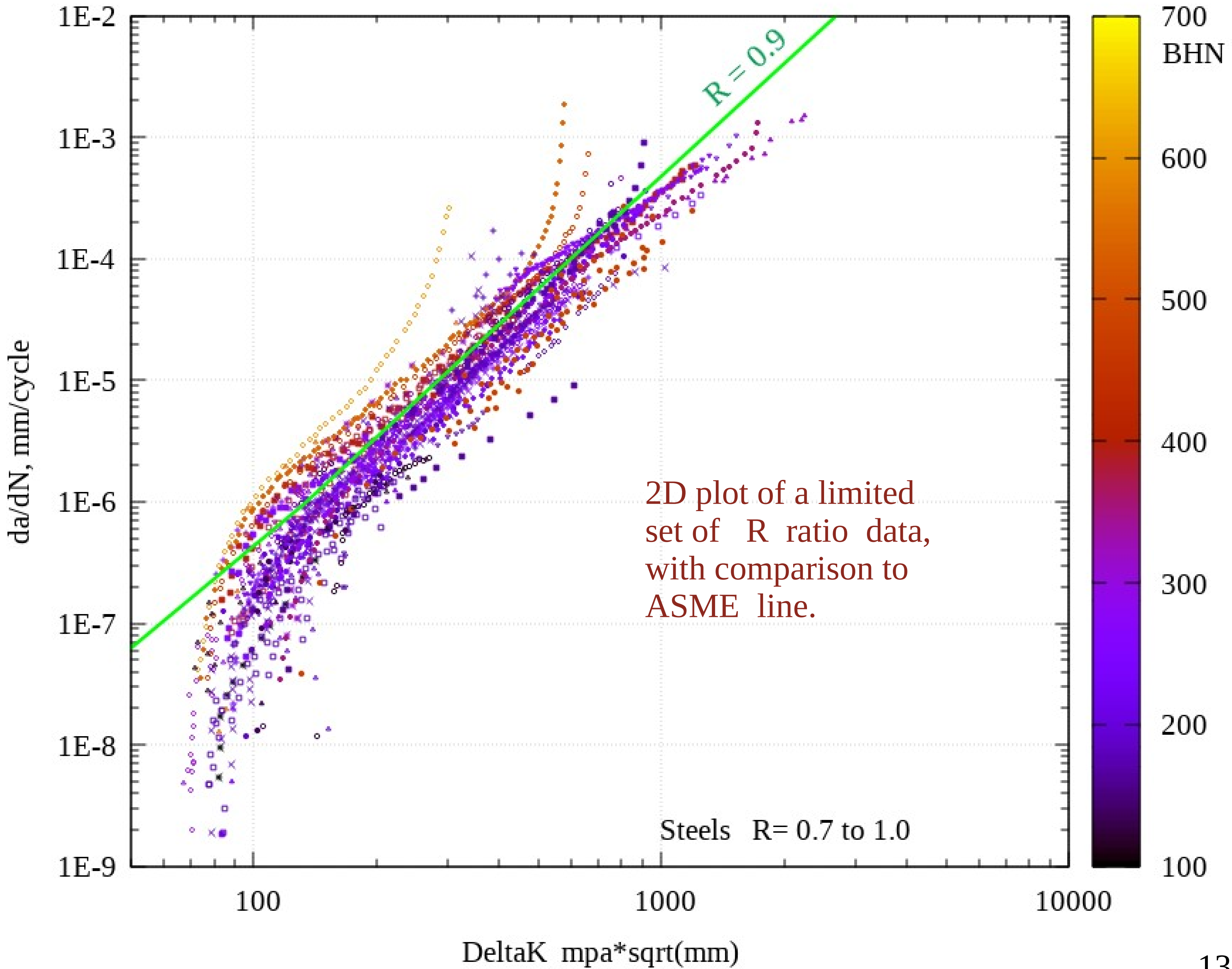
ASME specifies a set of functions to relate da/dN to ΔK. The lines in this plot are digitized from [8] and show typical lines one would need for FCP design or simulations

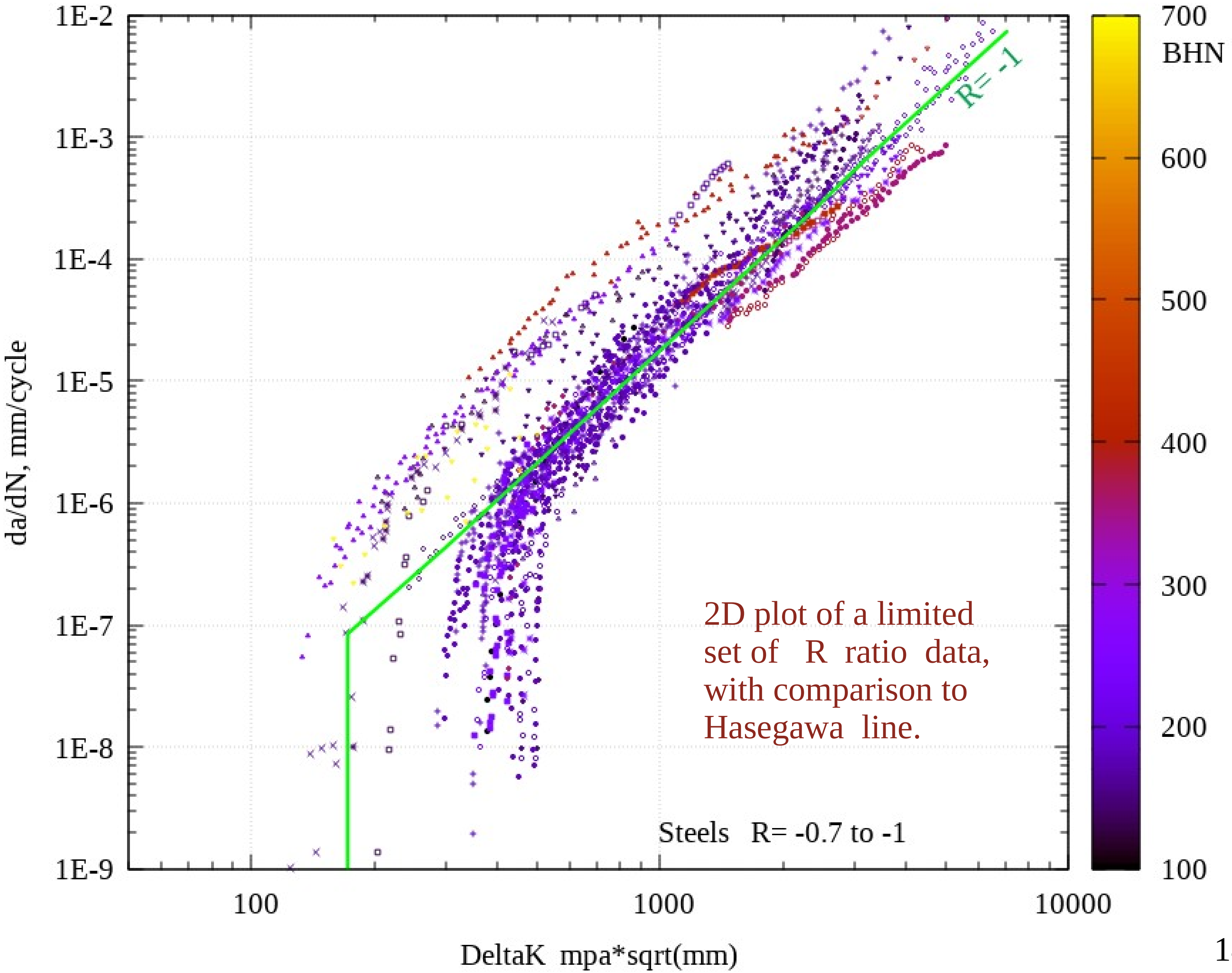
The data points at the top are from a 1972 F.D.&E. comm. Round Robin work. (see last slide).

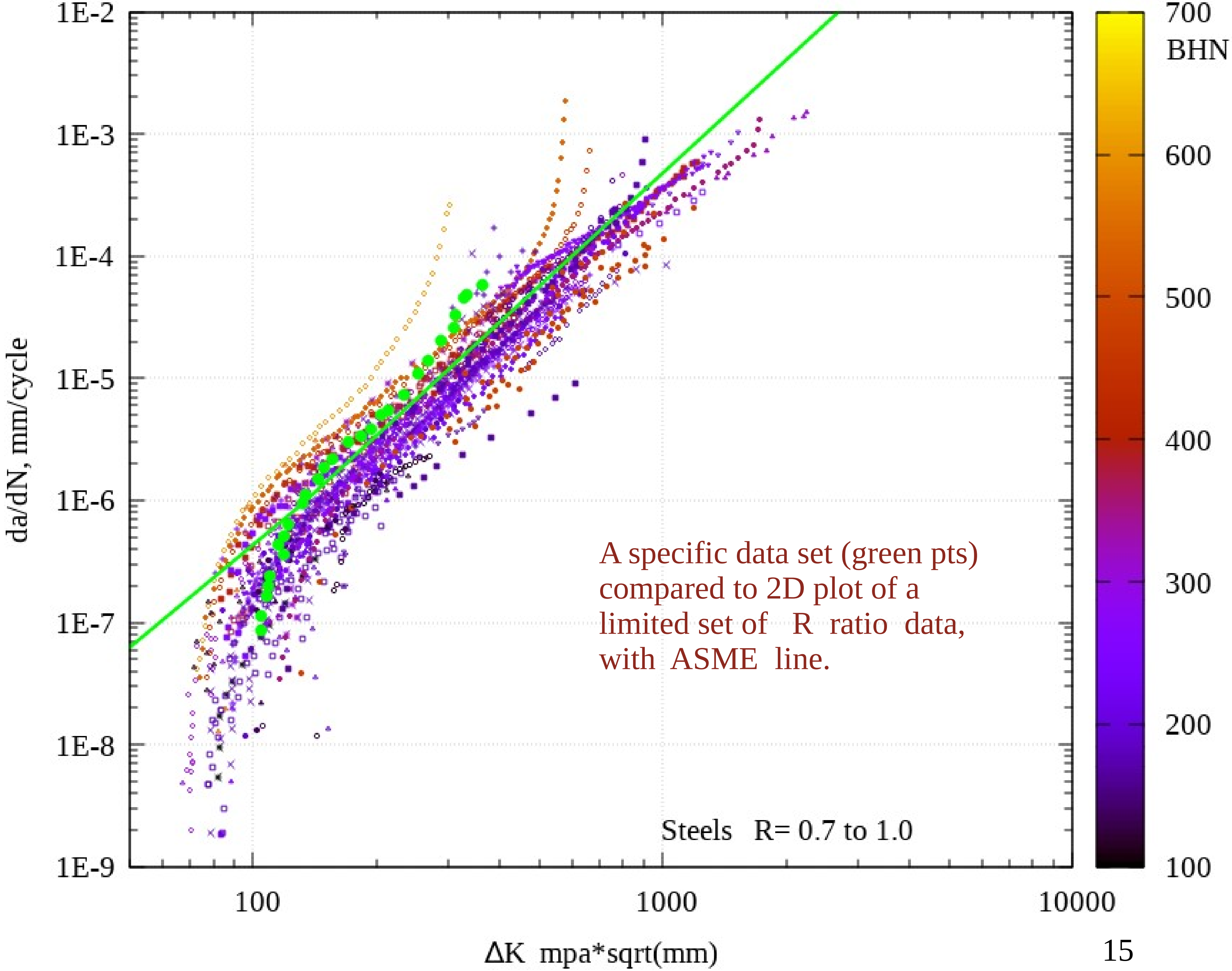
If the previous 3D plots can be described as the "forest" of da/dN curves, then when one is given a particular single set of da/dN data, one can compare this "tree" to the forest of lines.

Such a comparison is better displayed in a 2D plot however.

as in next slides


1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
da/dN, mm/cycle
100
1000
10000
DeltaK mpa*sqrt(mm)
R = 0.9
2D plot of a limited set of R ratio data, with comparison to ASME line.
Steels R= 0.7 to 1.0
700
BHN
600
500
400
300
200
100


1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
da/dN, mm/cycle
100
1000
10000
DeltaK mpa*sqrt(mm)
R= -1
2D plot of a limited set of R ratio data, with comparison to Hasegawa line.
Steels R= -0.7 to -1
700
BHN
600
500
400
300
200
100



1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
da/dN, mm/cycle
100
1000
10000
ΔK mpa*sqrt(mm)
700
BHN
600
500
400
300
200
100
A specific data set (green pts)
compared to 2D plot of a
limited set of R ratio data,
with ASME line.
Steels R= 0.7 to 1.0

Summary:

1. Having a data base for da/dN curves is useful when checking a new or old single data set.

2. Our data plots are similar to the ASME lines and to the thresholds proposed by Hasegawa et al.

3. We will place our data collection plots on the web with an option for a student, or any other researcher, to check a specific da/dn curve against the "Forest" of available da/dN curves.

References

1. M.H.El-Haddad, "A Study of the Growth of Short Fatigue Cracks Based on Fracture Mechanics, PhD Thesis, Dept. of Civil Engr., U. of Waterloo, Canada, Aug. 1978

2. BS7910-2005, "Guide to methods for assessing the acceptability of flaws in metallic structures," British Std.

3. P. Dindinger, Stork Inc, Oct 12, Presented at F.D.E. Milwaukee Meeting, 2013.

4. J.C.Newman Jr, B.M.Ziegler J.W.Shaw T.S.Cordes D.J.Lingenfelser, "Fatigue Crack Growth Rate Behavior of A36 Steel using ASTM Load-Reduction and Compression Precracking Test Methods," Paper ID JAI103966 J. of ASTM International, V9 N4 2012

5. D.J.Klingerman, K.H.Frank, J.W.Fisher, "Fatigue Crack Growth in A36 Steel", ONR, DoD, Lehigh Univ., Fritz Engr. Lab Rep. No. 358.31, May 1971

6. K.Hasegawa, B.Strnadel, S.Usami, V.Lacroix, "Fatigue Crack Growth Thresholds at Negative Stress Ratio for Ferritic Steels in ASME Code Section XI," J. of Pressure Vessel Tech., June 2019, V141 pg.031101-1

7. D.N.Lal, "The Combined Effects of Stress Ratio and Yield Strength on the LEFM Fatigue Threshold Condition," Fatigue Fract. Engr Maler. Sfrucr. V15 N12 pp.1199-1212, 1992

8. K.Hasegawa, Y.Yamaguchi, V.Mares, Yinsheng Li, "Fatigue Crack Growth Rates for Ferritic Steels Under Negative R Ratio,"Paper PVP2016-63872, Proc. ASME2016 Press.Vess.Piping Conf., PVP2016, Vancouver July17-21 2016

9. 2017 ASME Boiler and Pressure Vessel Code, Section XI Appendix A and C, American Soc. of Mech Engrs.

10. Tucker, L., S.Bussa, “The SAE Cumulative Fatigue Damage Test Program,” SAE paper 750038, Cong + Expon, Detroit, Feb.1975.

Sample Data file Format

```
 # S355JR steel plate   BaseMetal        f=30hz  R-0.1
# Equiv.: ASTM A572,  CDN 350W
# CT spec. 87.5x84x15mm W=70mm, crack length via optical micros.
# Chem.: Nominal BM:Max Values!  0.24C 1.50Mn .55Si .040P
# Chem.: .040S .012N .55Cu
# Ref.: M,Benedetti1 V.Fontanari  L.Battisti, "Structural health
# Ref.: monitoring of wind towers: residual fatigue life
# Ref.: estimation," Smart Materials and Structures, V22, N4 Mar.2013
# Paper also contains data for weld metal and for HAZ
# Observed: "Apparently, the cracks initiated in the HAZ spontaneously
# tend to propagate outside the HAZ towards the BM."

#Sy= 380 mpa
#Su= 560 = 81.2 ksi
#BHN= 169  converted from Su
#%Elongation= 30 %  total

## convert2MPa_mm  vers. 1.7 starts...
#OriginalName= benedetti-S355JR_BM_R=0.1raw
#Got Original #dadnunits= m
#Got Original #deltaKunits= mpa_m
## 1 ksi*sqrt(inch) = 34.7485  Mpa*sqrt(mm)
## 1 ksi*sqrt(inch) = 1.0989   MPa*sqrt(m)
## 1 MPa*sqrt(m)  =   31.6228  N/(mm**(3/2) )
## 1 MPa*sqrt(mm) =         1  N/(mm**(3/2) )
## 1 MN*m**(-3/2) =   31.6228  Mpa*sqrt(mm)
## 1 kg*(mm^(-3/2)  =  9.80665 MPa*sqrt(mm)
#All inputs converted to    MPa*sqrt(mm)   and  mm/cycle
#Note that this is same as  N/(mm**(3/2))  and  mm/cycle
#deltaKunits=  mpa_mm
#dadnUnits= mm

## MPa*sqrt(mm) mm/Cycle    BHN  Su  Sy  R  Hz
 324.  0.3027E-06 169 560 380 0.1 30
 325.  0.1114E-05 169 560 380 0.1 30
 327.  0.1485E-05 169 560 380 0.1 30
 329.  0.1349E-05 169 560 380 0.1 30
 331.  0.1703E-05 169 560 380 0.1 30
 348.  0.4791E-05 169 560 380 0.1 30
 377.  0.5723E-05 169 560 380 0.1 30
 423.  0.7981E-05 169 560 380 0.1 30
 451.  0.1002E-04 169 560 380 0.1 30
 499.  0.1829E-04 169 560 380 0.1 30
 593.  0.3463E-04 169 560 380 0.1 30
 666.  0.7937E-04 169 560 380 0.1 30
 763.  0.1067E-03 169 560 380 0.1 30
 894.  0.2086E-03 169 560 380 0.1 30
1019.  0.3086E-03 169 560 380 0.1 30
1318.  0.5949E-03 169 560 380 0.1 30
1620.  0.8260E-03 169 560 380 0.1 30
```

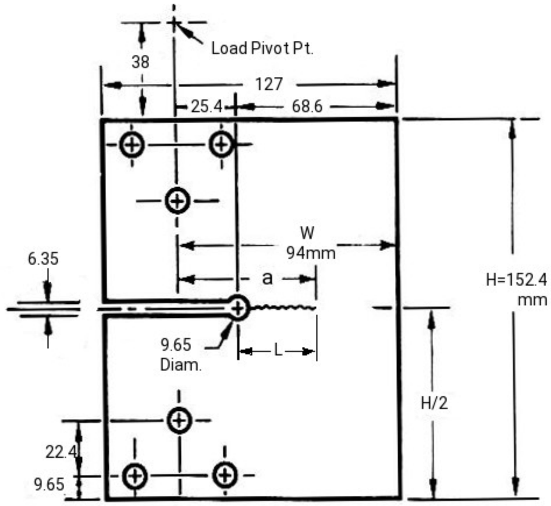
Sample Gnuplot Script

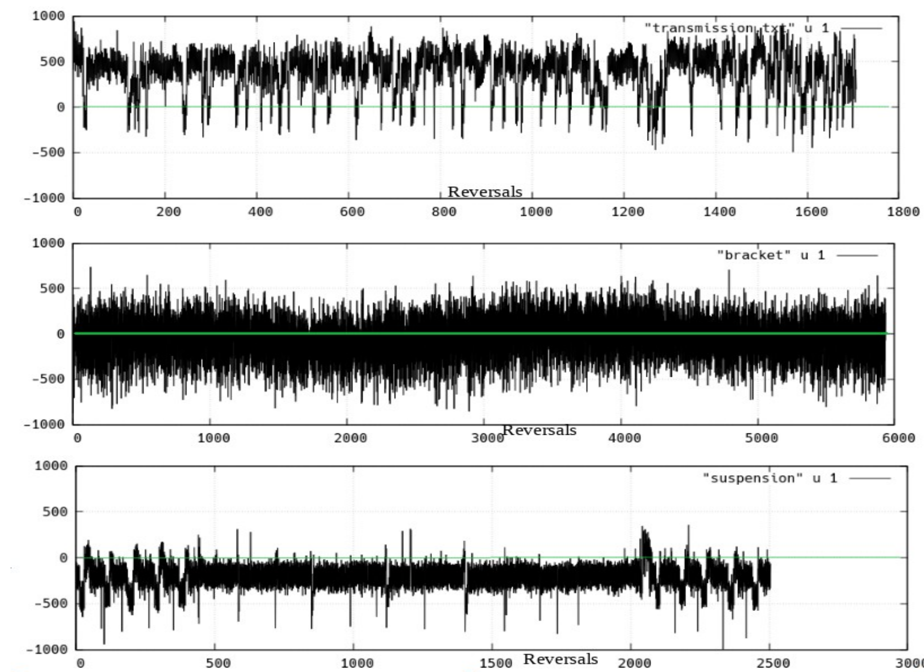
```
 set term qt enhanced font "liberation serif,12" size 1200,900
set logscale x
set logscale z
set key outside
set xrange [50:10000]
set yrange [-1:1.0]
set zrange [*:*]
set format z '%.0tE%+T'
set xlabel "{/Symbol D}K  mpa*sqrt(mm)"
set ylabel "R"
set zlabel "da/dN, mm/cycle" rotate by 90
unset key
set pointsize 0.6
set colorbox default
set cbrange [100:700]

set palette   #This will reset to default

 set view 64, 322, 1, 1.4
 splot 'barsom12Ni_R=0.1_mpa.dadn'       u 1:6:2:3 w p lc palette , \
 'barsom12Ni_R=0.2_mpa.dadn'             u 1:6:2:3 w p lc palette , \
...etc
```

SAE Technical Paper link: 2020-01-0191





https://fde.uwaterloo.ca/Fde/Loads/Keyhole/keyhole.html
https://fde.uwaterloo.ca/Fde/Loads/Keyhole/keyholeSpec.Histories.pdf