Simulating Crack Aspect Ratio Control

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Using BAMpF, AFGROW and NASGRO

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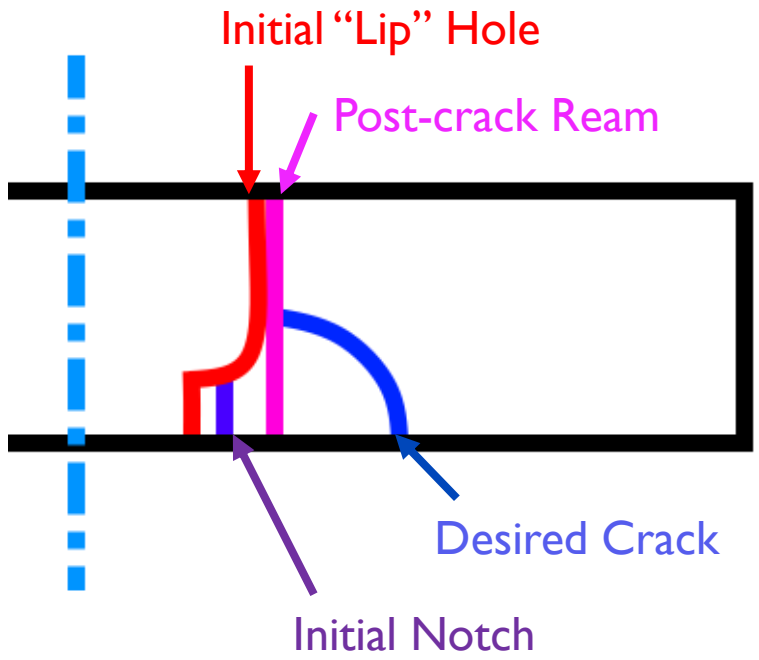
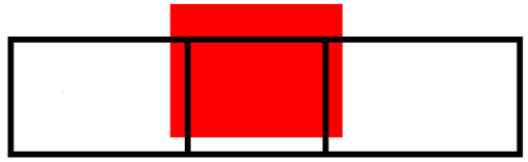
Objective

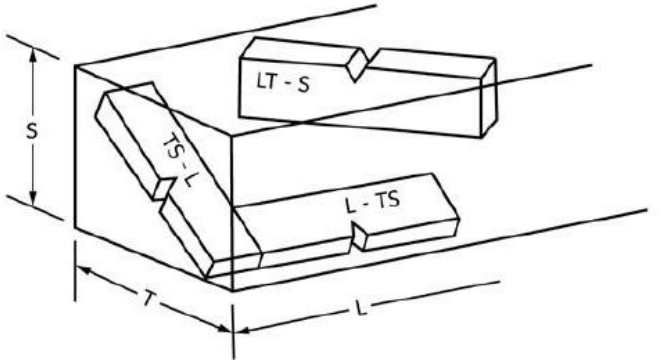
- Goal is to grow a crack with a longer ‘c’ tip than ‘a’ tip.
  - end product is NDI coupons for a through-bushing inspection experiment
  - we want to grow a longer ‘c’ tip; this is because the end goal is a crack with the same ‘a’ and ‘c’ length, and no notch.
    - A notch would affect the NDI experiment.
    - To grow a crack, there is a notch in a ‘lip’ in the hole; the hole will be reamed to remove the notch, but that will shorten the ‘c’ tip more than the ‘a’ tip. So we need to start with an extra long ‘c’ tip.
- Problem is that ‘a’ tips tend to grow faster than ‘c’ tips near holes since the ‘c’ tip grows away from the stress concentration factor at the hole and the ‘a’ tip doesn't.



Tools

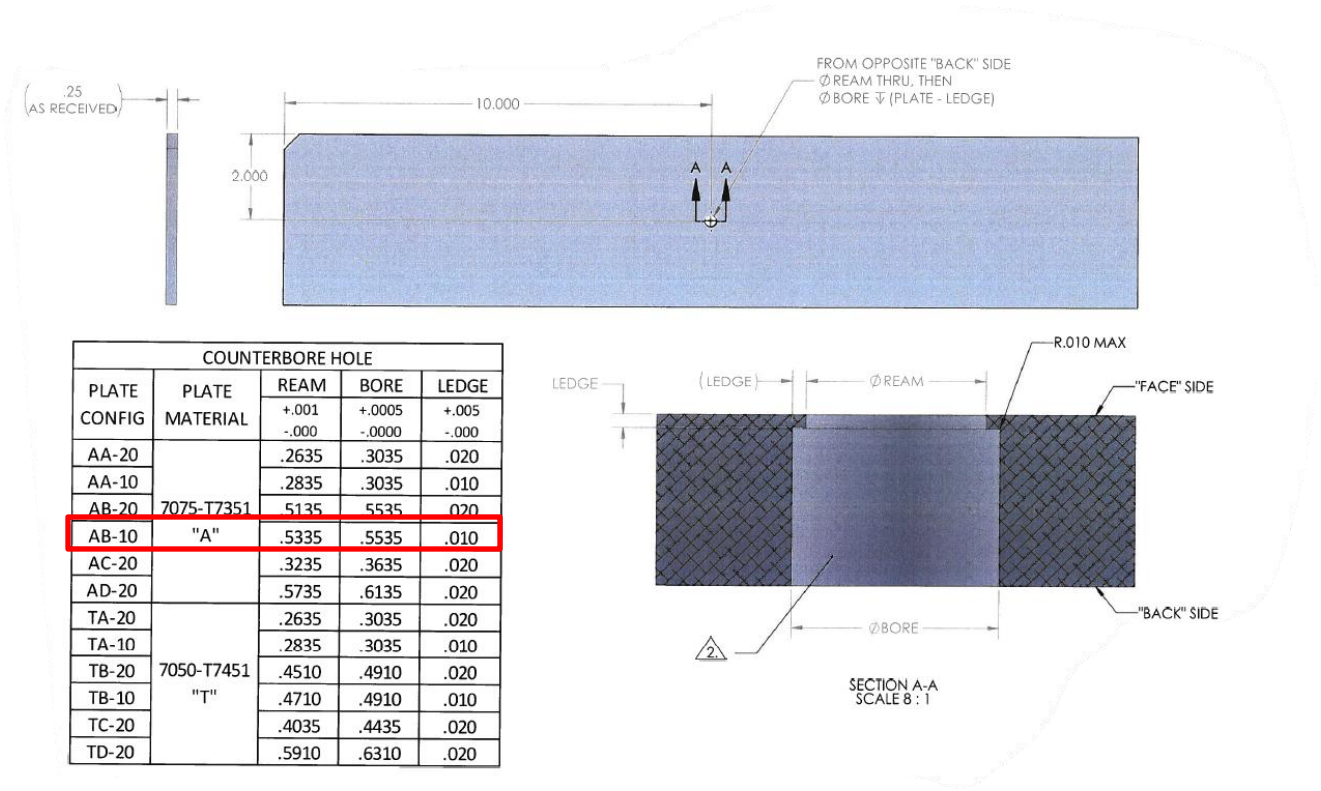
- Lip on the coupon
  - And the radius between the lip and the bore of the hole.
  - ‘a’ tip grows more slowly when traversing the radius.
- Pin in the hole
  - Interference fit pins and pushings have been shown to reduce crack growth rate, and anecdotally have been observed by testing group to affect the crack aspect ratio.
  - This is the main tool used.
- Material orientation
  - Take advantage of more rapid crack growth rate in the L-S direction than the L-T direction.
  - Problem with that is the L-S direction is usually very short, it’s the material thickness direction, and the coupons are 4 inches wide.
- Altering the load level
  - this interacts with the material orientation; the biggest difference between ‘a’ and ‘c’ tip growth rates is below 4 ksi root inch, which in this case corresponds to about 6 ksi loading, decreasing to around 3 ksi by the time the crack reaches the desired size.
  - Anecdotally, Materials Testing group thinks this has some affect on the aspect ratio.
- Bending moment
  - Most obvious choice.
  - NDI section didn’t want to do this for some reason. Not investigated further.





Load Level

- First step was to look at the effect of altering the load level
  - 3 BAMpF models
    - 12, 15 and 20 ksi
    - 0.010" lip in the bore and 0.006" straight flaw
    - 7075-T7351 material (isotropic)
    - 7 points on crack front
  - No pin, bending or anything else. Just uniaxial loading



COUNTERBORE HOLE				
PLATE CONFIG	PLATE MATERIAL	REAM +.001 -.000	BORE +.0005 -.0000	LEDGE +.005 -.000
AA-20	7075-T7351 "A"	.2635	.3035	.020
AA-10		.2835	.3035	.010
AB-20		.5135	.5535	.020
AB-10		.5335	.5535	.010
AC-20		.3235	.3635	.020
AD-20		.5735	.6135	.020
TA-20	7050-T7451 "T"	.2635	.3035	.020
TA-10		.2835	.3035	.010
TB-20		.4510	.4910	.020
TB-10		.4710	.4910	.010
TC-20		.4035	.4435	.020
TD-20		.5910	.6310	.020

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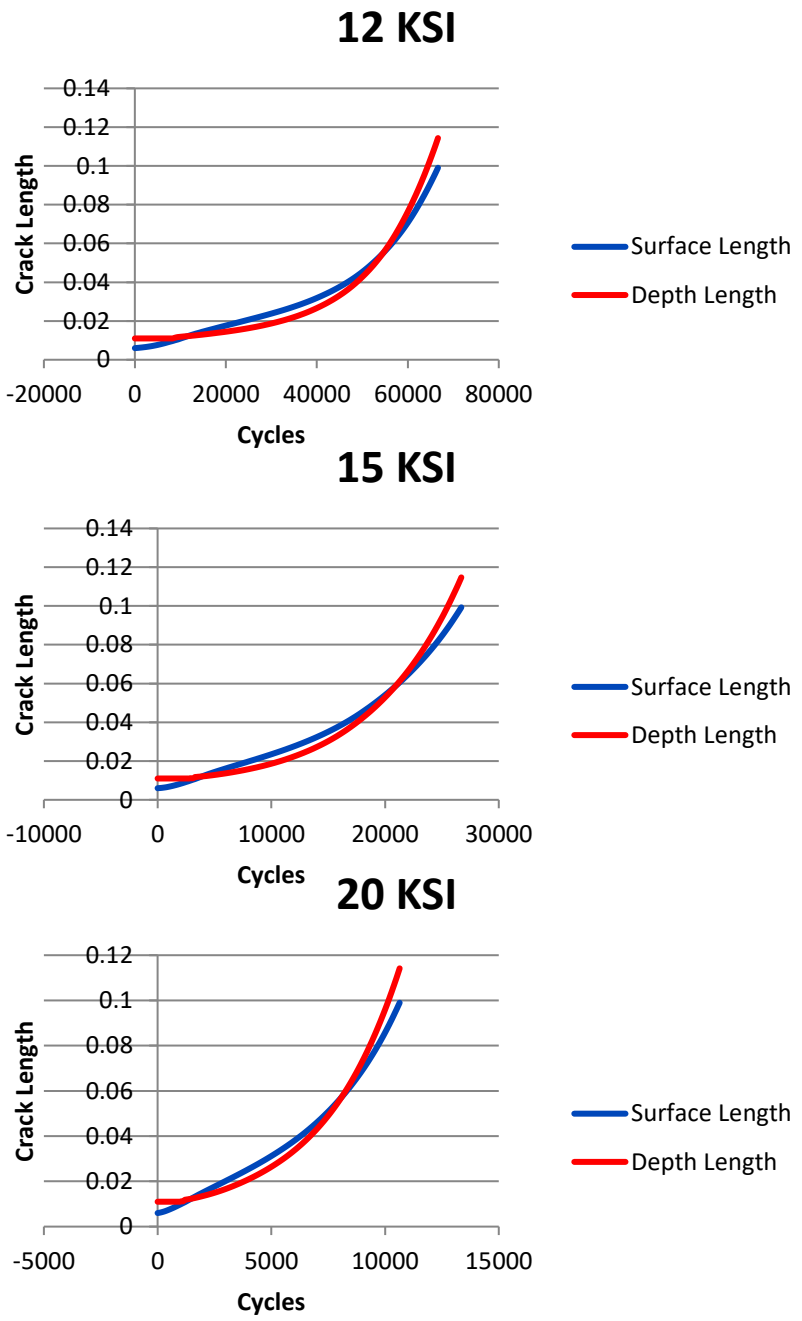
Load Level - Results

- Results were all pretty much the same
  - a/c briefly dipped below 1 before 'a' eventually overtook 'c'.
    - Unless you subtract the length of the lip, in which case 'a' never overtakes 'c'.
- Growth rate in the 'a' direction *is* inhibited for some time after exiting the lip.
- Also created a model with a single 1.5 magnitude overload cycle (22.5 ksi for the 15 ksi load level) every 1000 cycles.
  - Not shown here
  - Did not grow past first overload.
  - The change in crack growth rate after the first overload cycle is obvious
  - No conclusions about what this would do to the aspect ratio, if anything.



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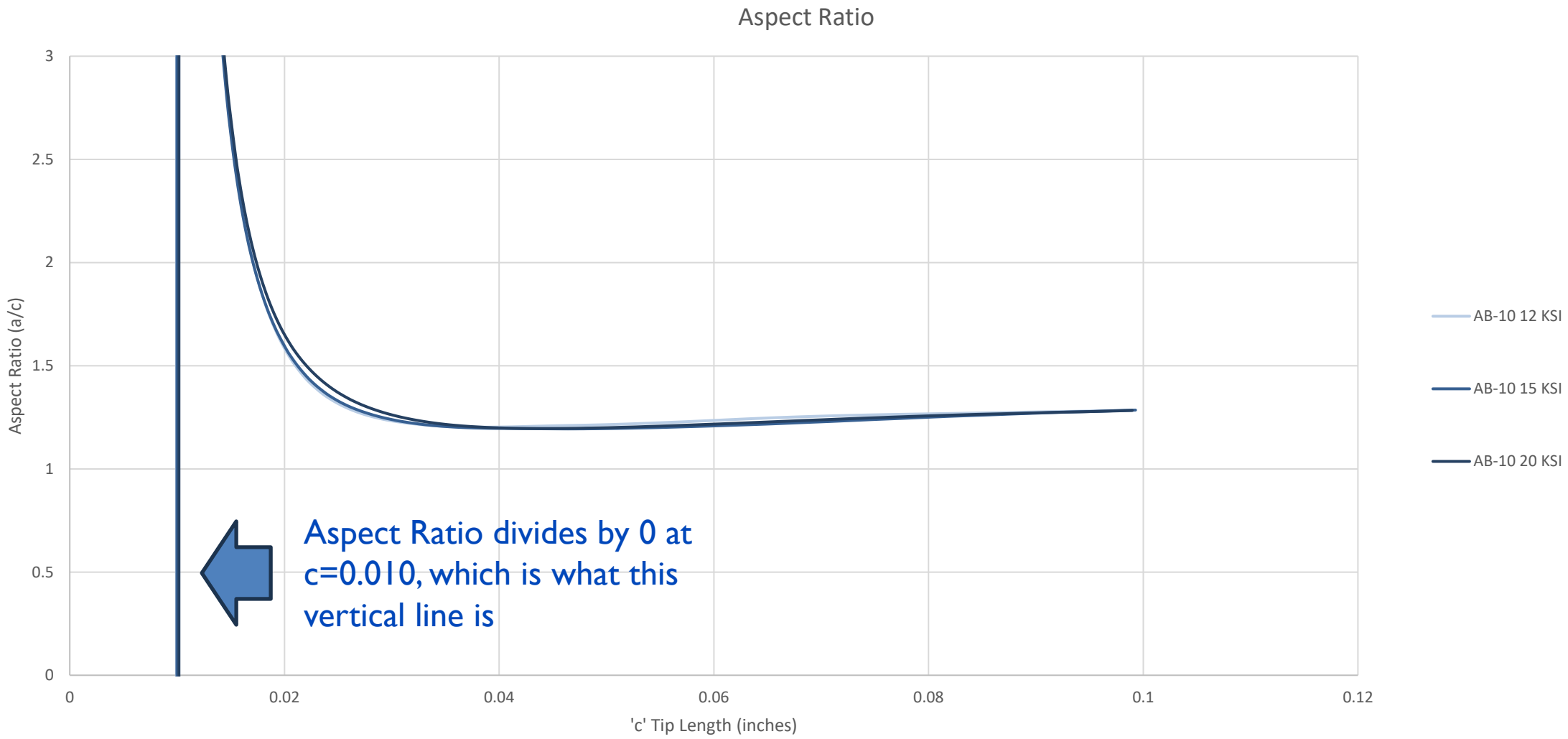
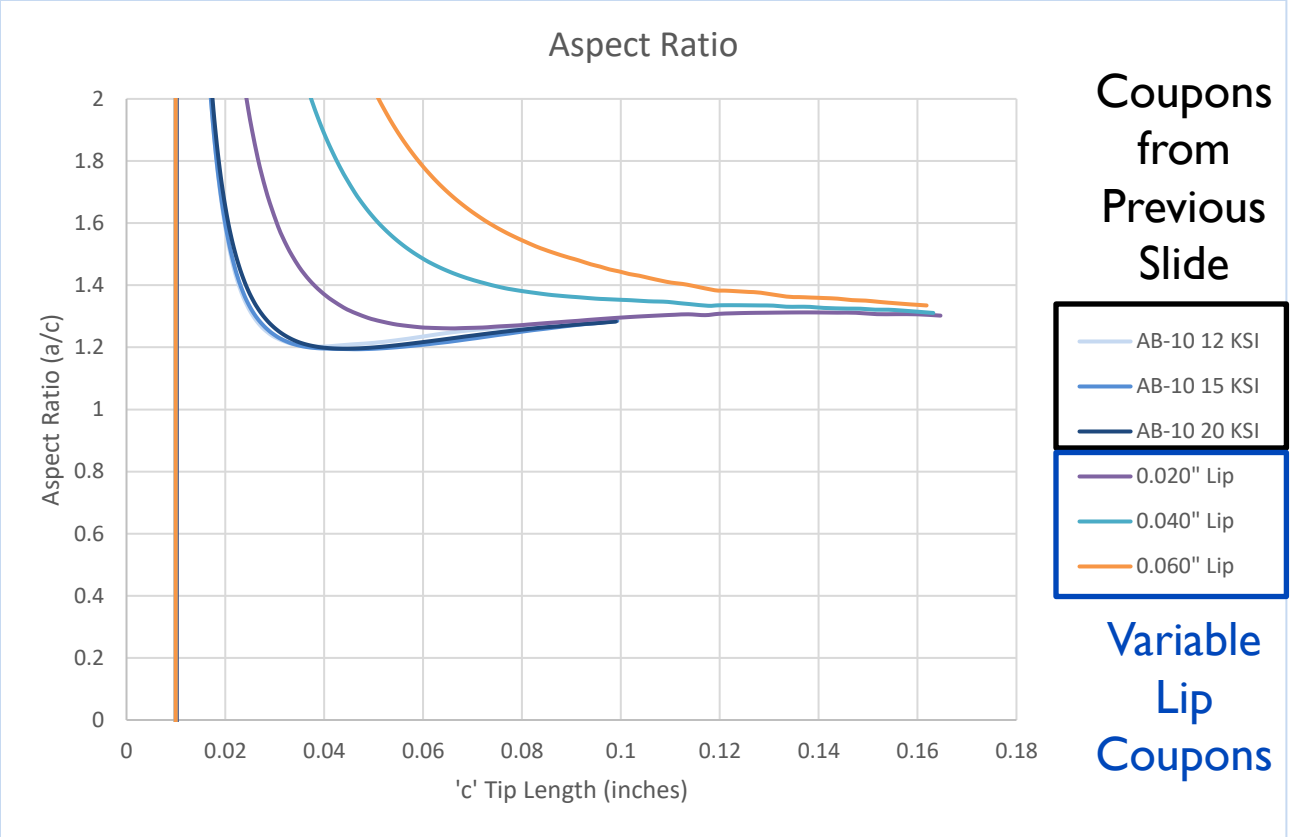
Load Level - Results



Variable Lip Geometry

- 3 lip thicknesses (‘a’ direction)
  - 0.060” thick
  - 0.040” thick
  - 0.021” thick
    - 0.020” would not mesh, hence 0.021”
  - Plus the original analysis at 0.010” thick

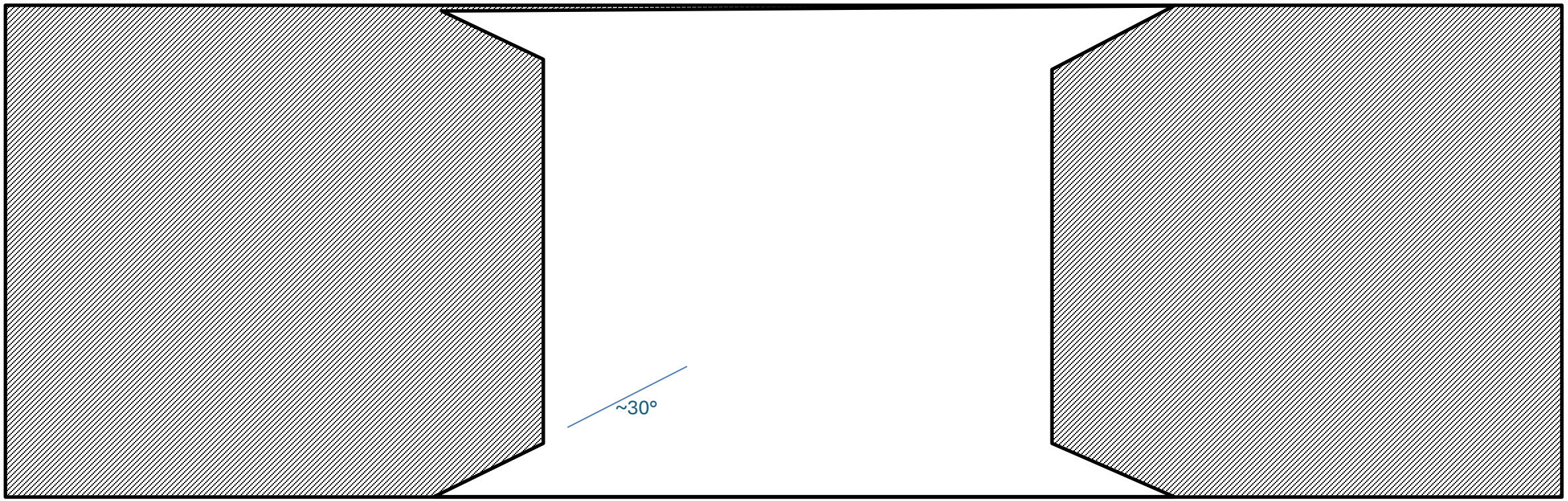
- The lip thicknesses basically make a larger starting ‘a’ flaw, which results in a large aspect ratio that decays as the crack grows larger.



$$AR = \frac{a}{(c - 0.010")}$$

(This subtracts the length of the lip from c, since it gets reamed off)

Chamfered Hole



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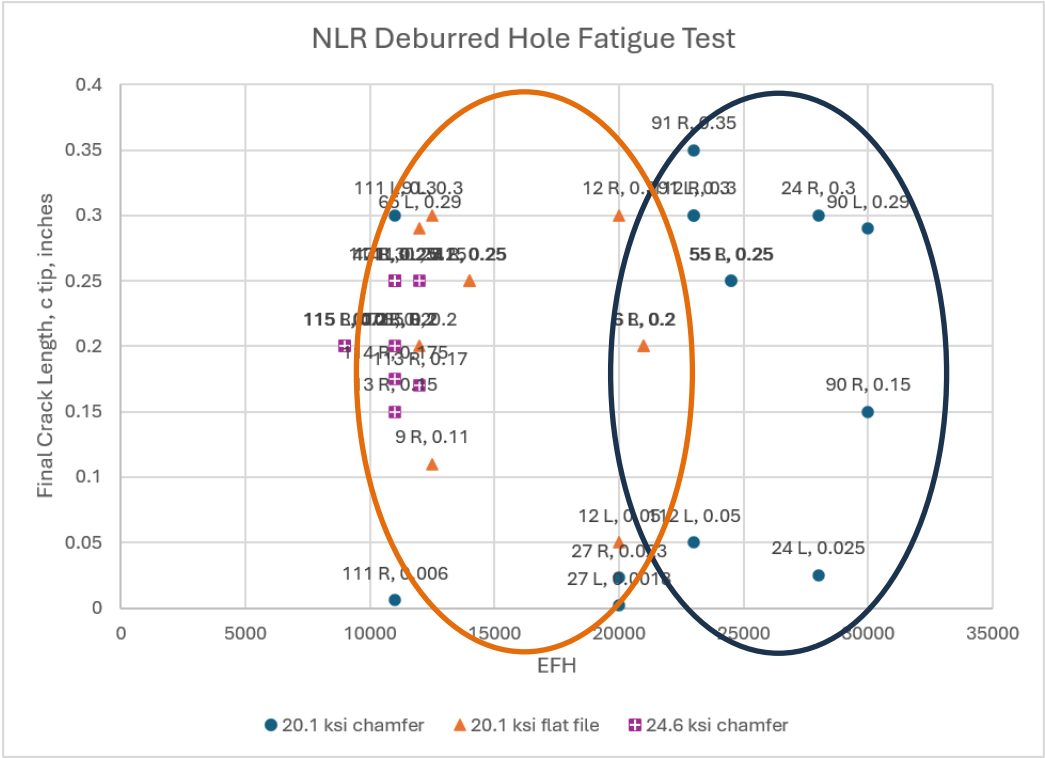
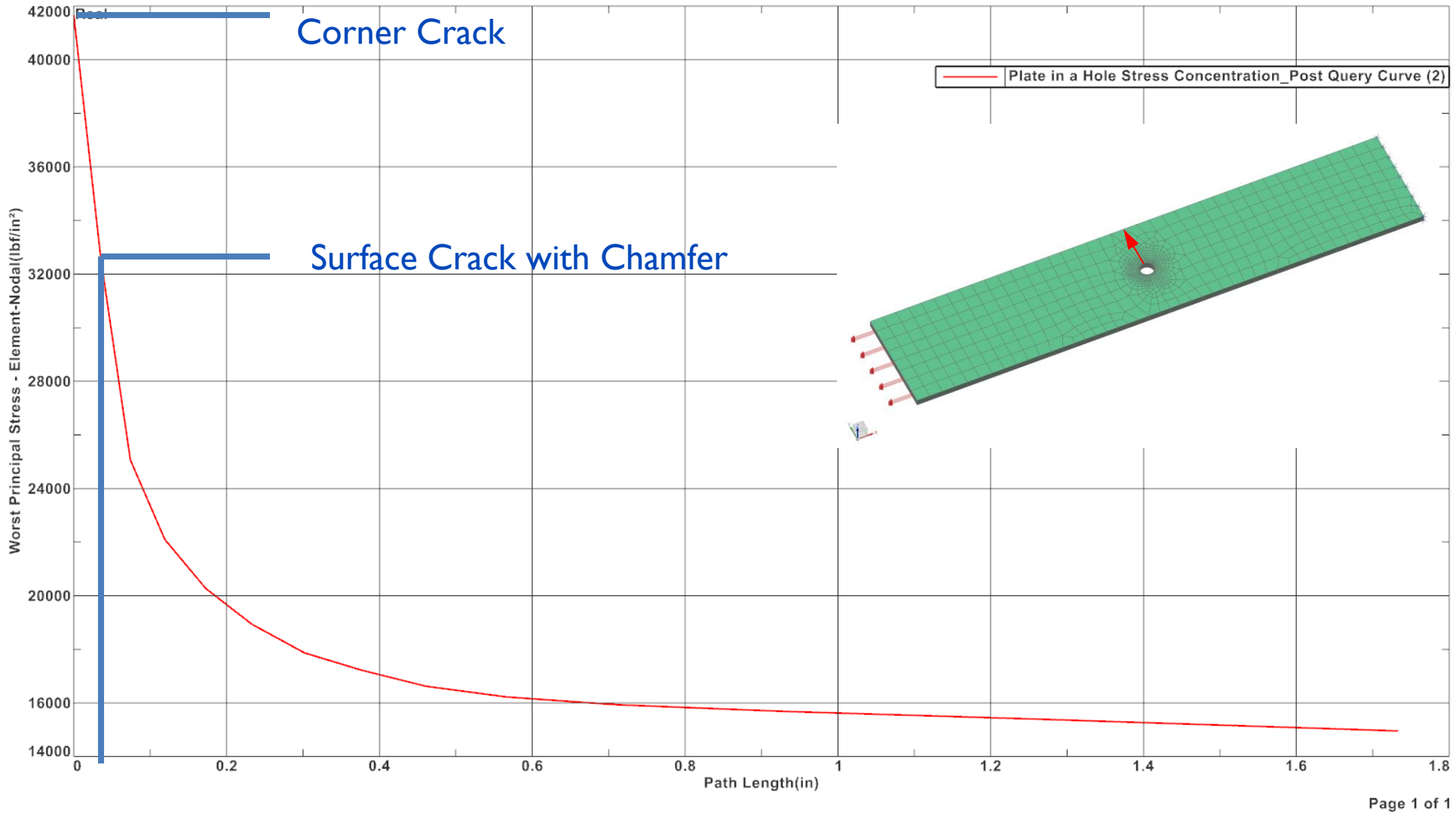
Chamfered Holes

- Kind of the inverse of the lip geometry
- This was looked at prior (but never presented in detail) due to research done by Netherlands Aerospace Center (NLR) and presented During the ASIP 2025 Conference in Austin, Tx., on December 4th, 2025 (in the 8:00 AM slot)
  - NLR research was into statistical characterization of small flaws based on deburring method
  - But there was an improvement in life for the chamfered holes
  - I built a series of models to try to figure out why, and whether this could be used to improve life
  - It turns out all the chamfer does is move a faying surface flaw further from the hole, reducing the stress concentration factor
  - It gets you negative life improvement if there's a knee flaw instead
  - So probably not useful
- However, the model results were useful again for this effort.



Blue Results – chamfered holes
Orange Results – filed holes
Purple Results – higher stress level, not relevant

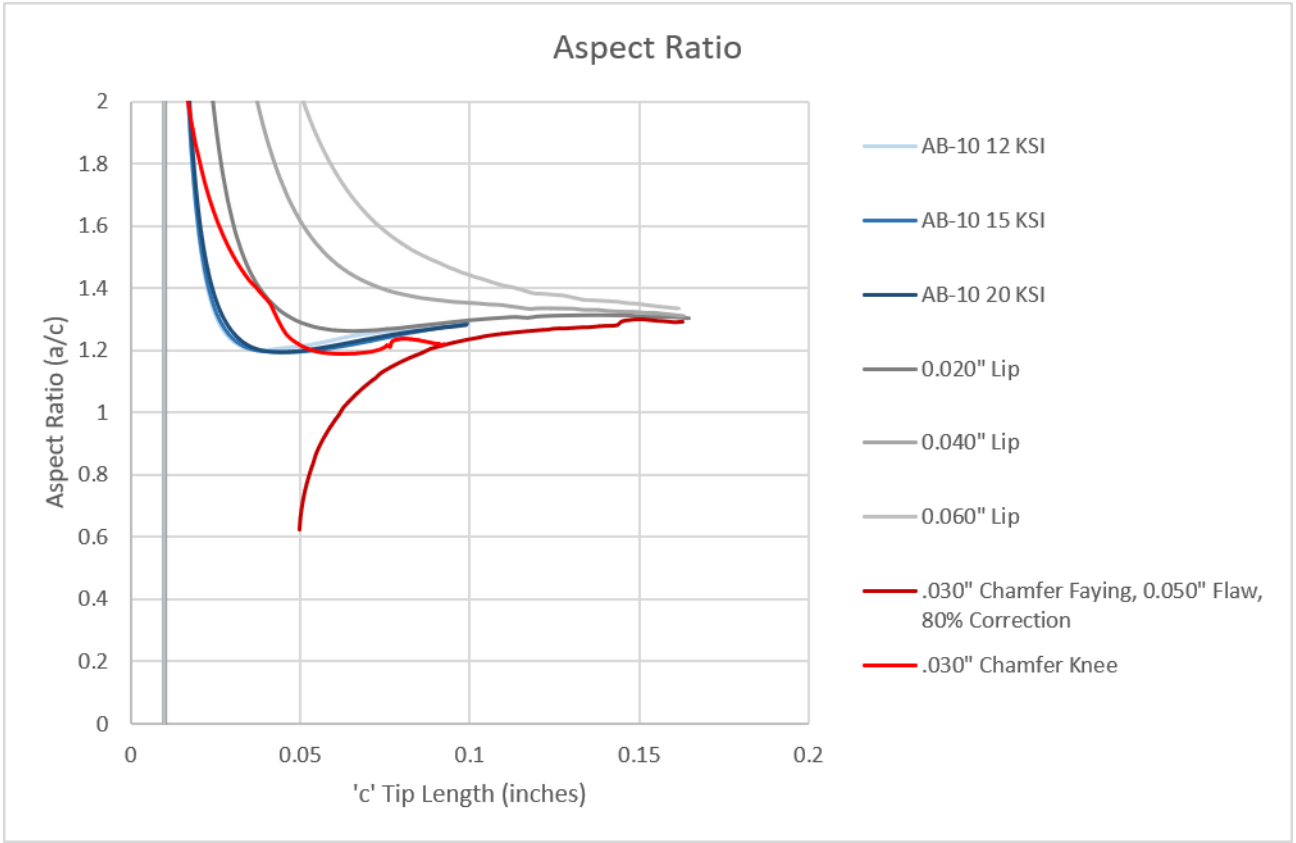
Chamfered Hole



Example Stress Concentration from NX Simcenter Model representing the AB-10 Coupon, 15 KSI

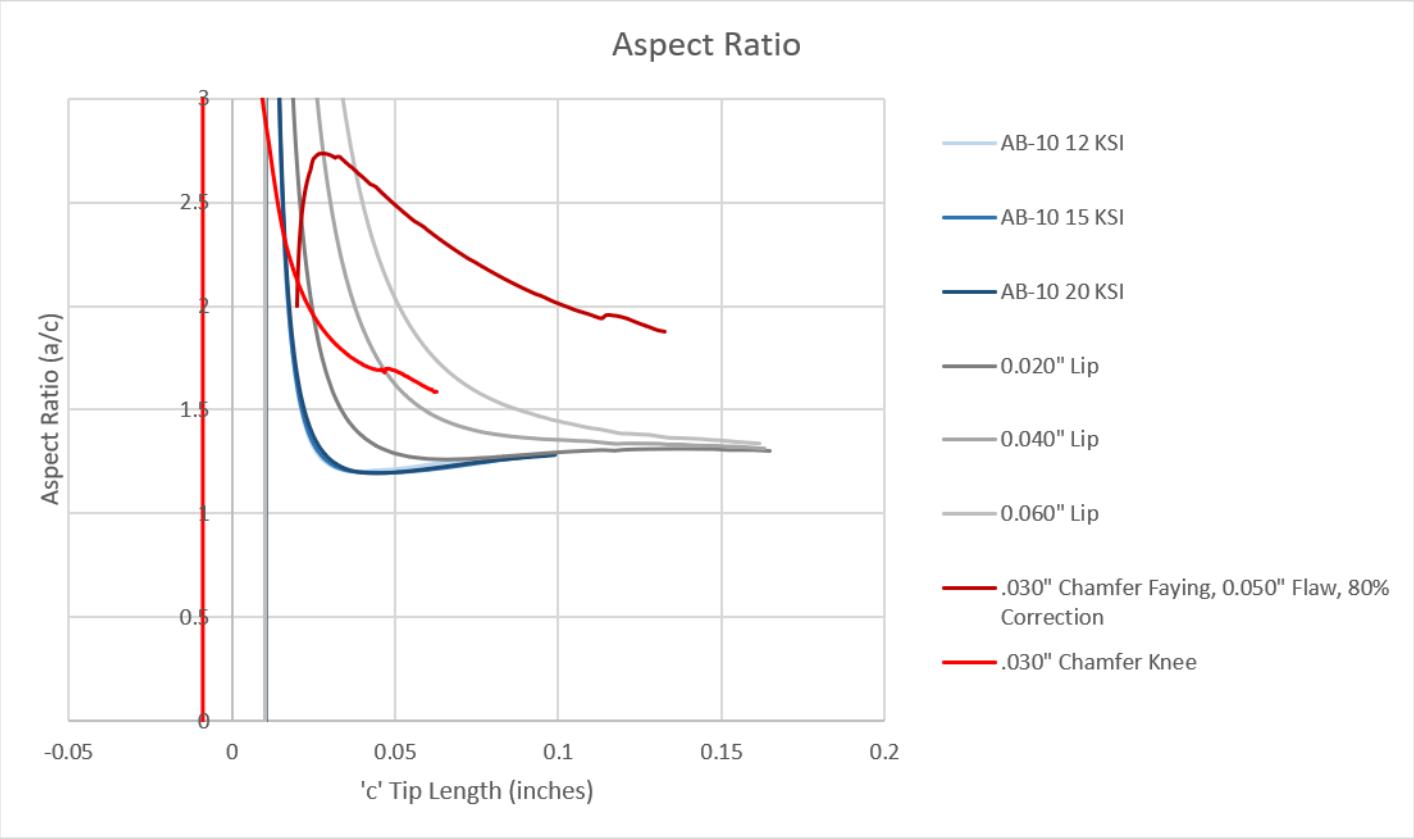
Chamfered Holes

- Chamfered holes shown in red
- Knee flaw has a weird shape with two ‘lumps’
  - These lumps are the 0.030” chamfers on the top and bottom of the hole
- Other than the chamfer ‘lumps’, the results converge on the same value (~1.3) as the models with the lip.
  - Would probably converge if grown past the chamfer too
- However, where a faying crack is still growing through the chamfer, there is an aspect ratio improvement
  - This is NOT including the effects of any material removal if it were desired to remove the chamfers.
  - Effect is mainly just because the C tip is 0.030” further from the bore



Chamfered Holes

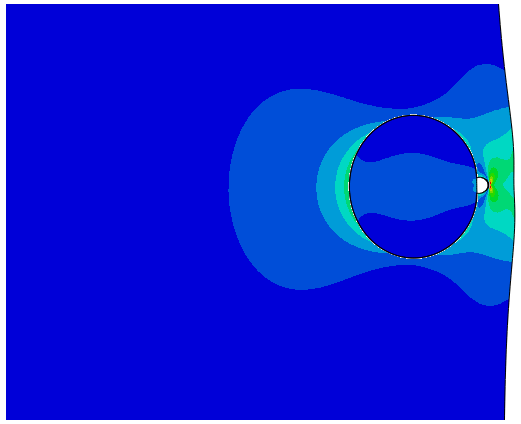
Same chart but with 0.030” subtracted from ‘c’ tip
to represent reaming out the chamfers

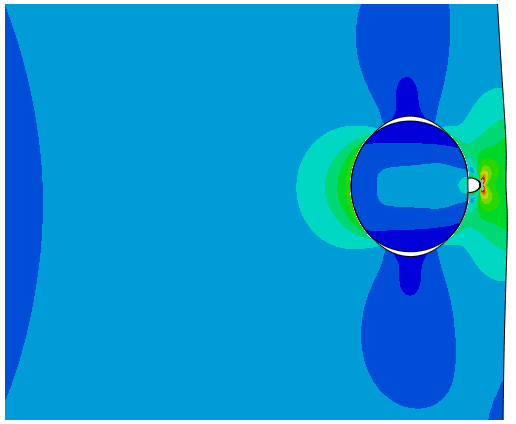


Any advantage is lost once this is accounted for

Interference Fit Pin

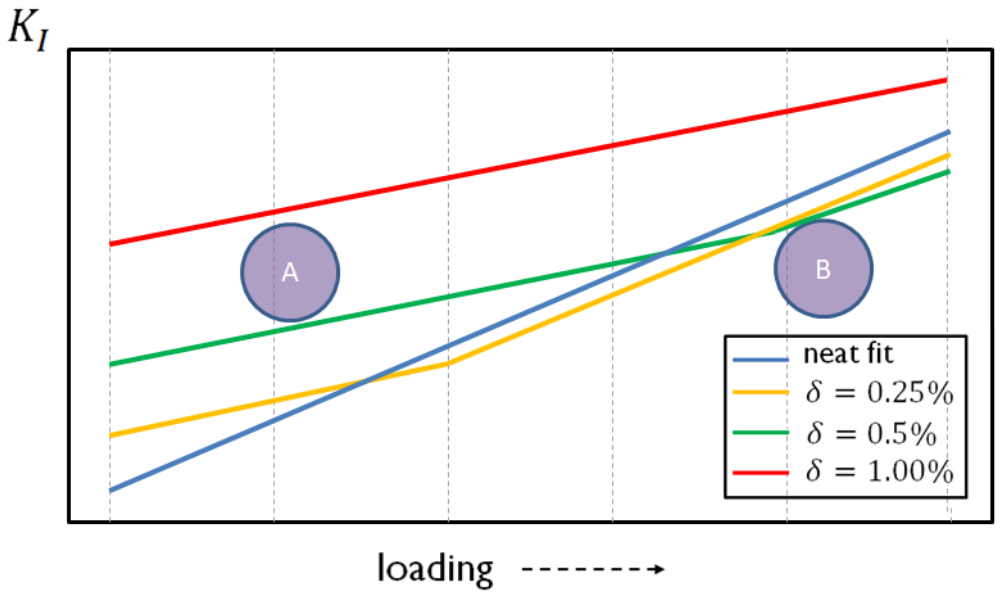
- Interference reduces crack growth rate under certain circumstances
- The mechanism is not the same as cold work or a residual stress
- Instead, the pin creates hoop stresses (tension) that can make fatigue worse
  - BUT it also changes the 0-stress stress intensity, and the slope of the response to load
  - This increases K but can reduce delta-K, which reduces da/dN and therefore crack growth rate
  - Potentially, this effect, like the stress concentration from the hole itself, is concentrated near the hole and therefore might neutralize the more rapid growth at the bore of the hole





Phase A

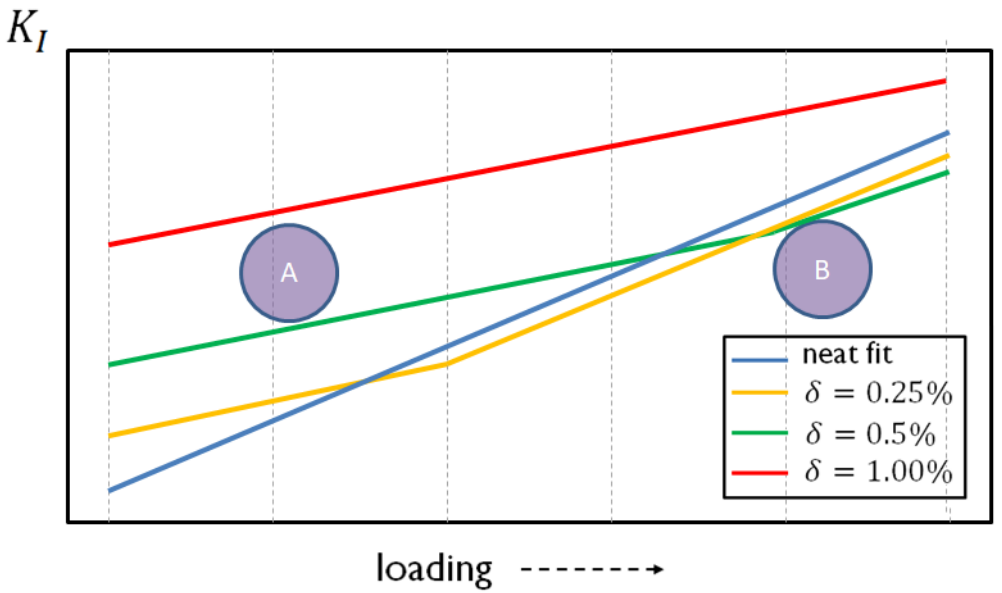
Phase B



Graph and Figure from Haikal, 2021 ASIP Presentation

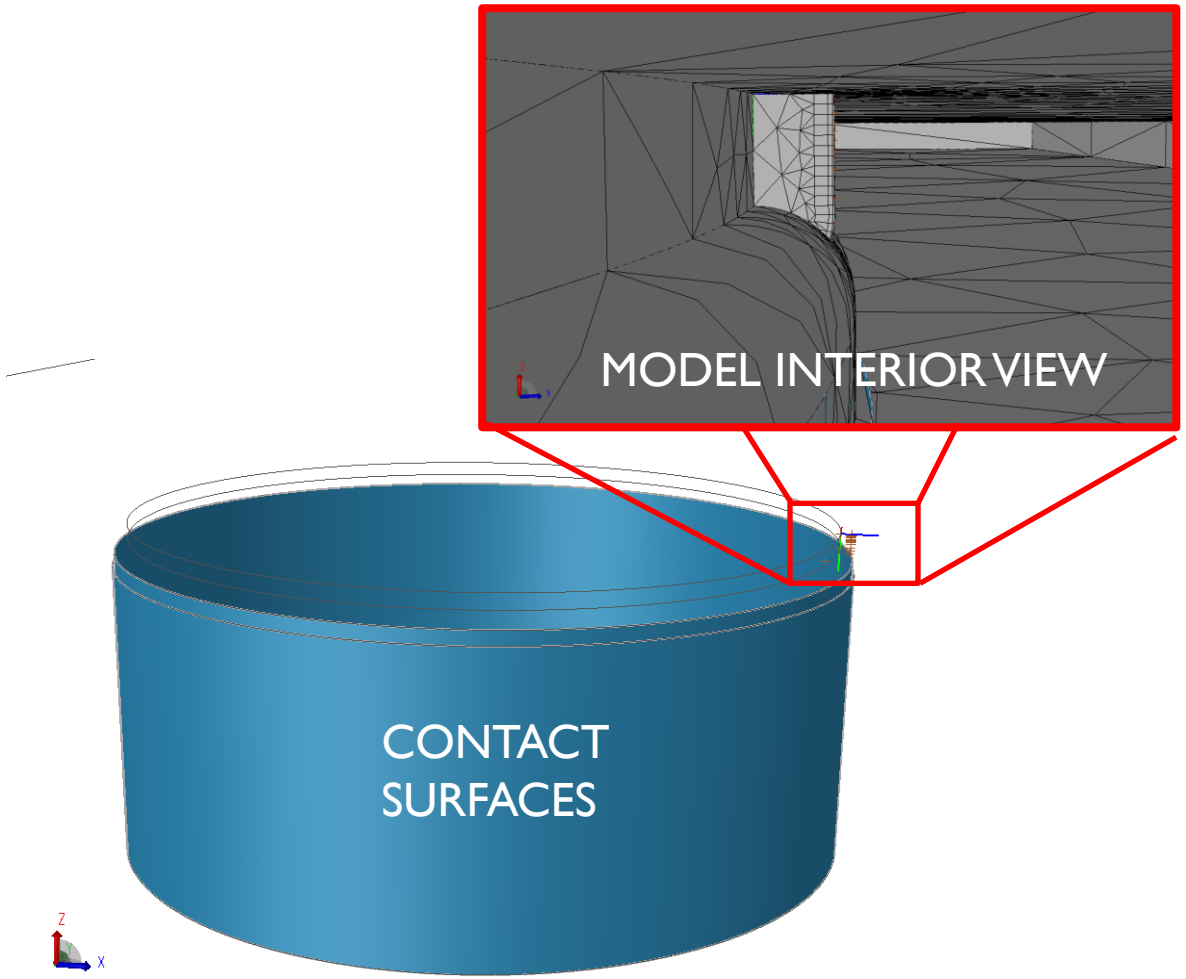
K Array

- By default, AFGROW assumes that the stress intensity (K) at no load/stress, is zero.
  - This corresponds to the blue, neat-fit line on the graph
- To model the phenomenon that produces a life improvement for interference fit fasteners, you need a non-zero K at 0 load.
- This is what a K Array is.
  - BAMpF model runs at specified points in the array
  - For no negative loading and entirely in phase A, 2 points are sufficient; S = 0 ksi and S = 15 ksi
  - Under other circumstances, you could need 4
    - S_{min}, S_{max}, S_0 and $S_{threshold}$



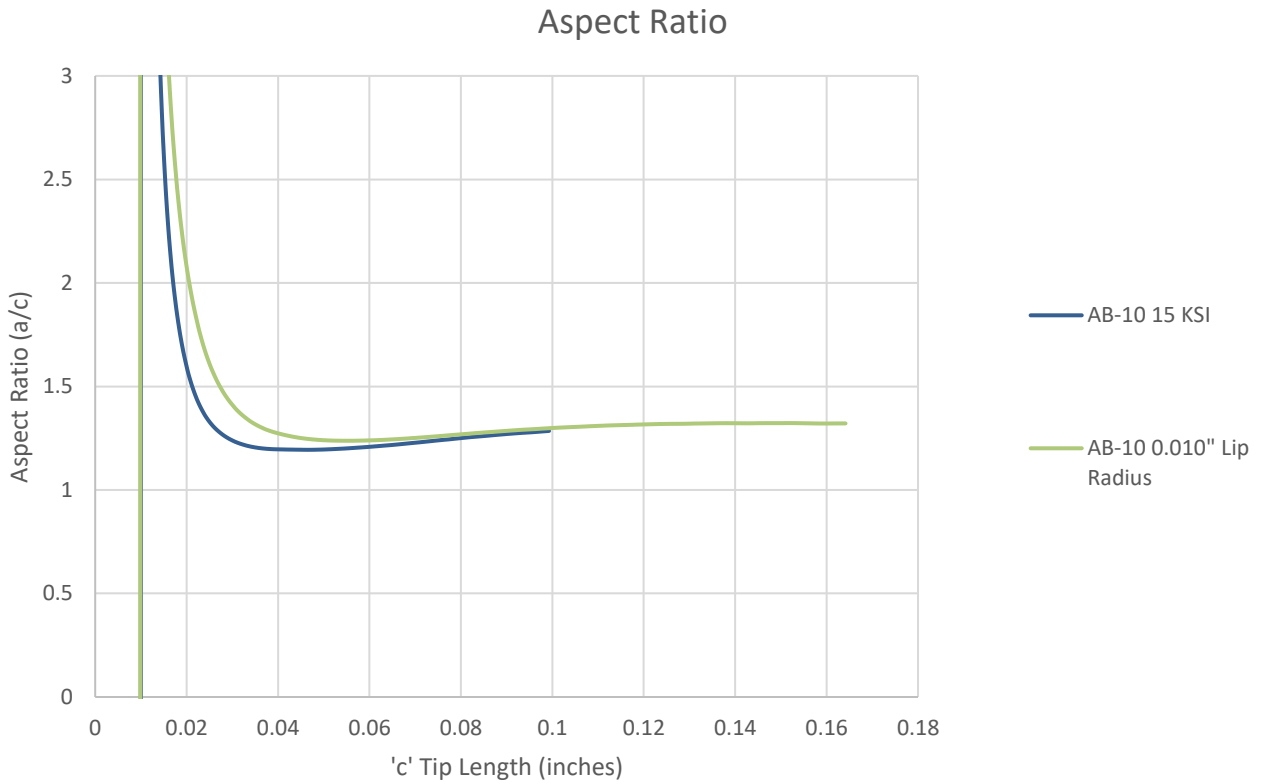
Interference Fit Pin

- Approach is to make StressCheck models with a pin in contact solution with the coupon, and the initial notch.
  - Radius changed to 0.010”
- This is then grown as a crack in BAMpF.
- Initial runs did not use K Array.
  - Consequently, they don’t actually model the decreased K-slope mechanism.
- However, the results allow comparison between hoop stress effect and K-slope effect.
  - Also, you can learn from my mistake.



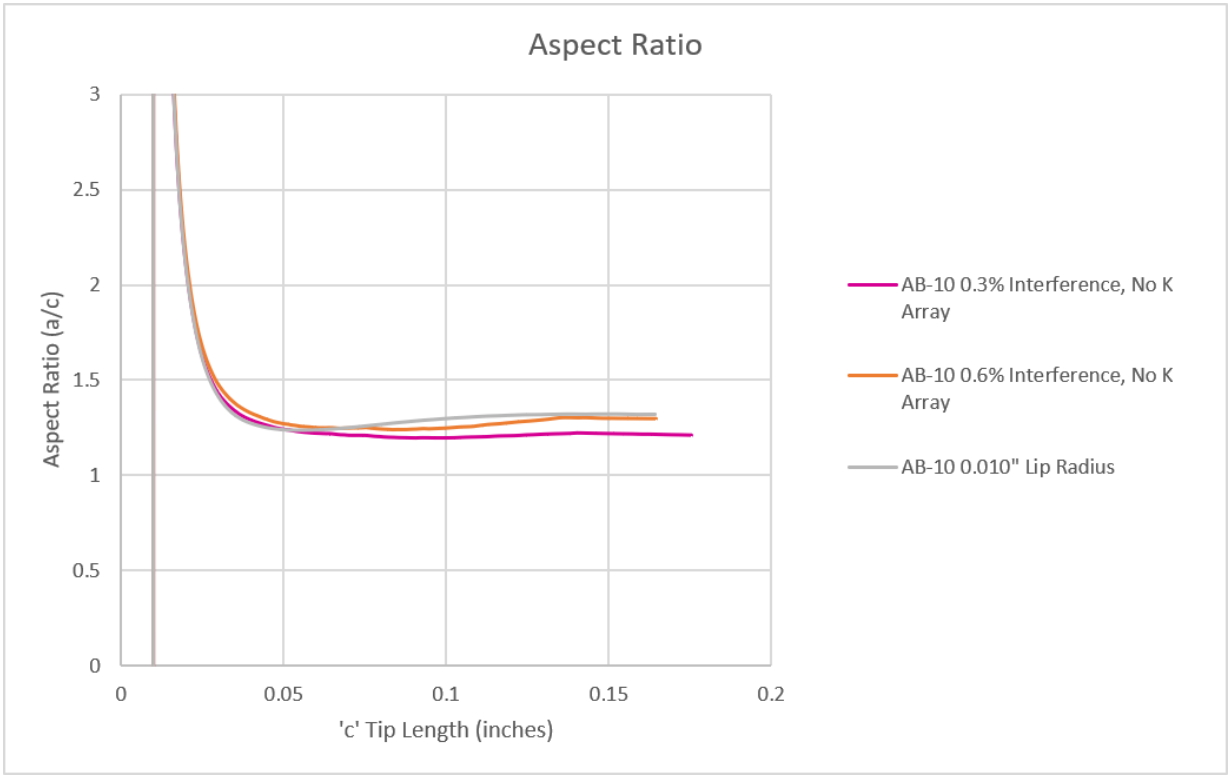
Interference Fit Pin – Geometry Change

- Because of the change in radius, the basic AB-10 coupon was re-run
- Lip radius = 0.010”
- Same constraints, mesh parameters, loading = 15 ksi, etc. as basic AB-10 coupon
- Crack run to a length of 0.164”
  - (Originals were run to 0.114”)



Interference Fit Pin – Results, No K Array

- Models took about 4 days each to run
  - About 150 iterations each
- There was a small improvement from the presence of both pins
  - best at the 0.3% level
  - This despite not modelling the actual mechanism responsible
  - Could be due to more rapid crack growth in the ‘c’ direction producing an aspect ratio closer to 1



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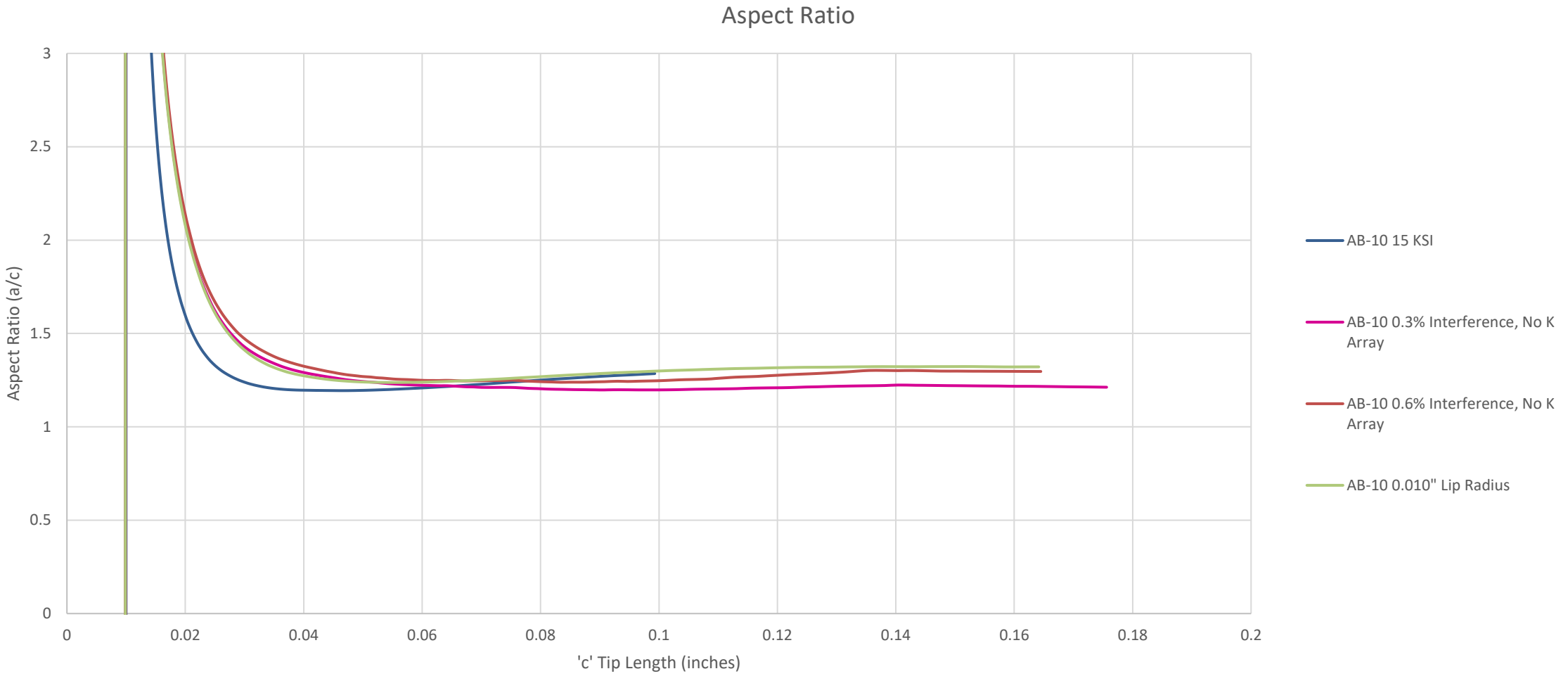
Interference Fit Pin – Results, No K Array

For comparison, here it is with the original (0.006” radius) AB-10 model as well



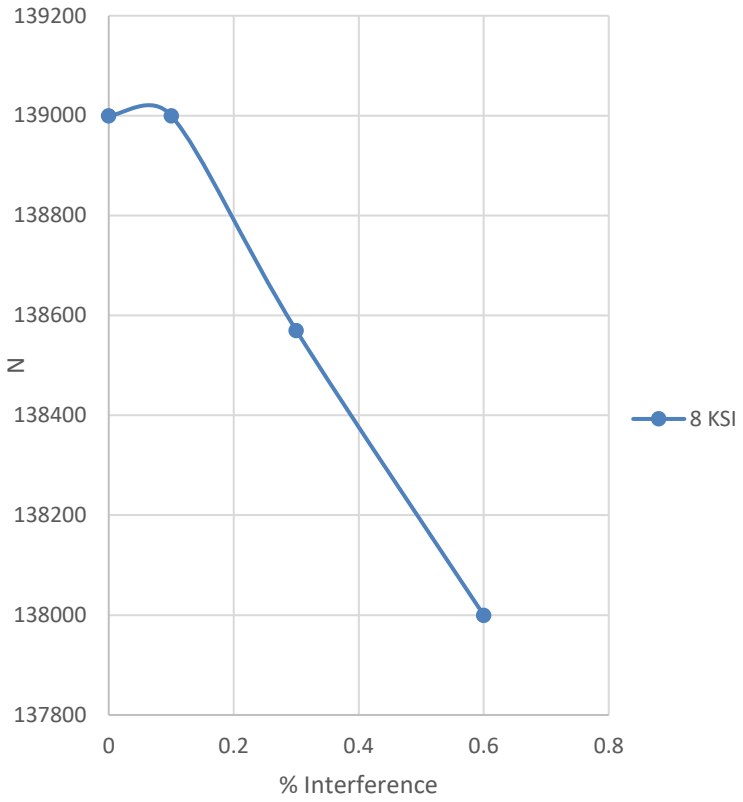
NASGRO Runs

Since the interference levels analyzed didn't have much of an effect, some NASGRO runs were done to try to identify an effective interference level

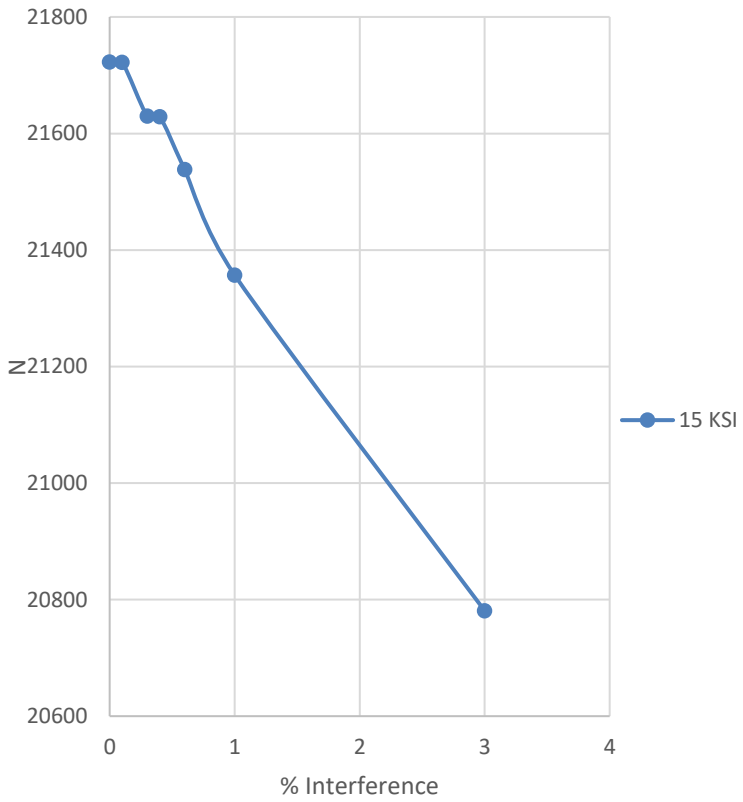
- Initial pin interference levels were chosen arbitrarily
- NASGRO has an interference fit pin model (TC38)
  - This is a thru crack, not a corner crack
- This was run at several interference levels and stresses to find where a benefit could be achieved
  - This is a life benefit (not an aspect ratio prediction)
  - The assumption is there can't be an aspect ratio improvement unless the pin is slowing crack growth near the bore of the hole

NASGRO Runs

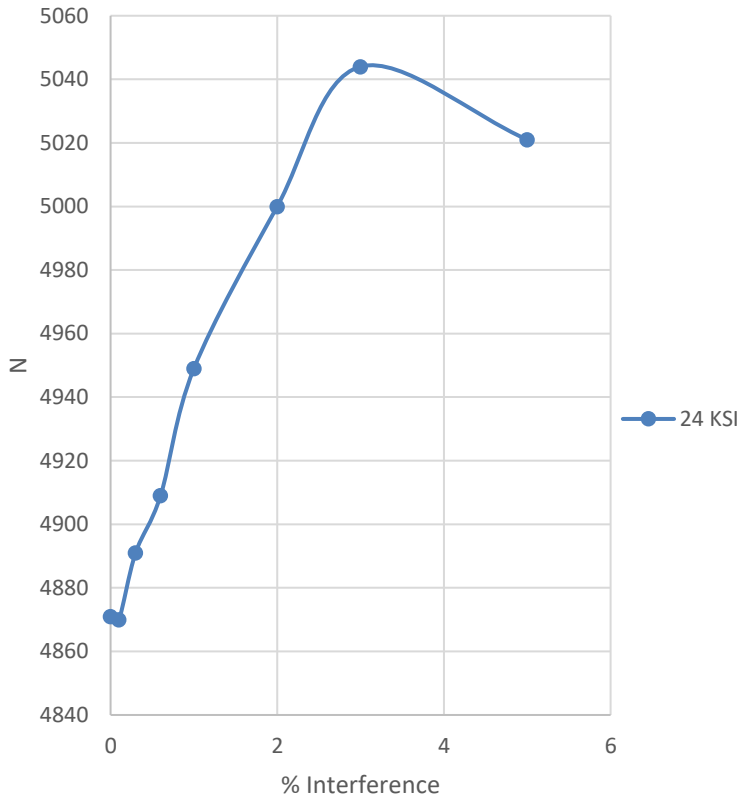
8 KSI



15 KSI



24 KSI



A life improvement is only achieved for the highest stress level investigated (24 KSI)
This suggests that the pin will only be effective in influencing aspect ratio at similarly high stresses

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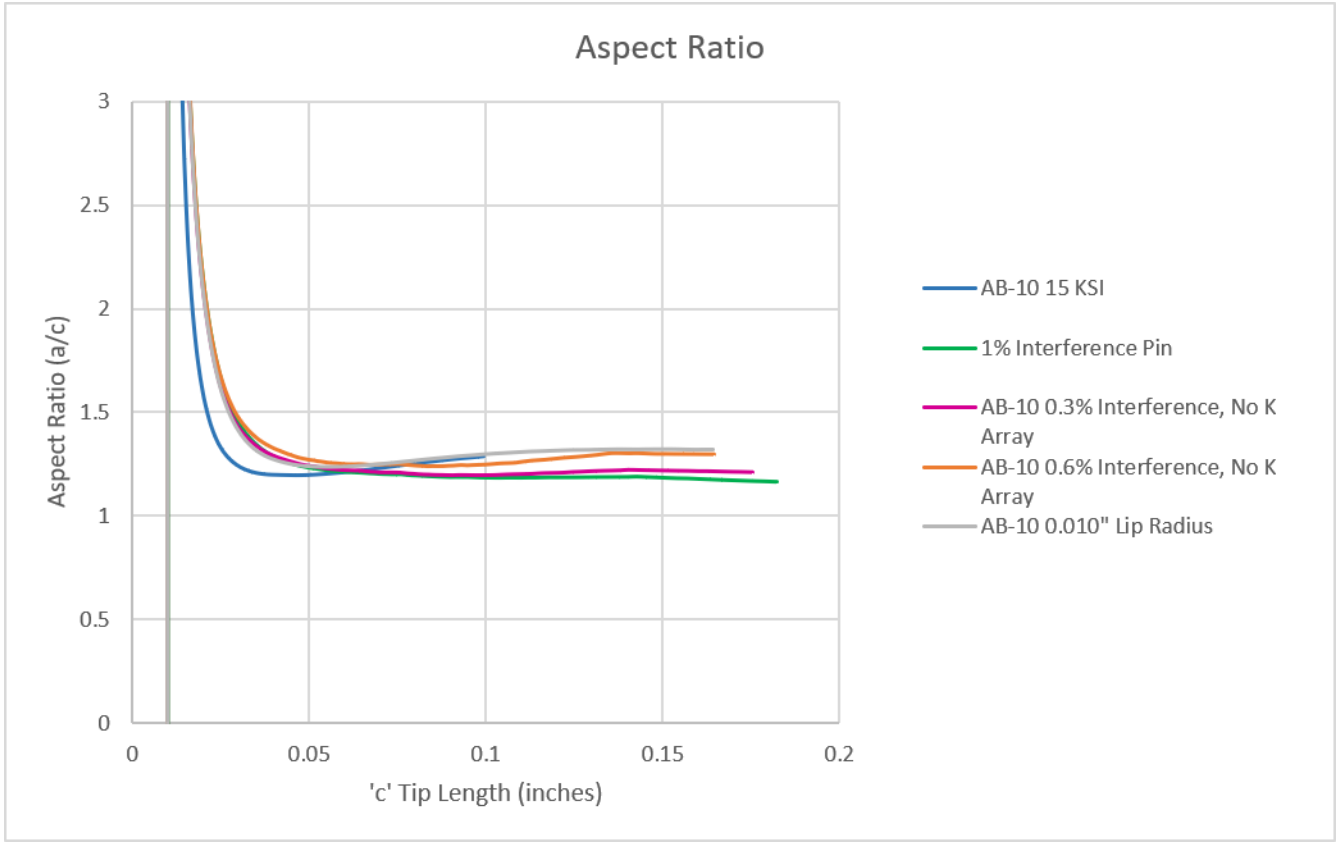
Interference Fit Pin – K Array, 1% Interference



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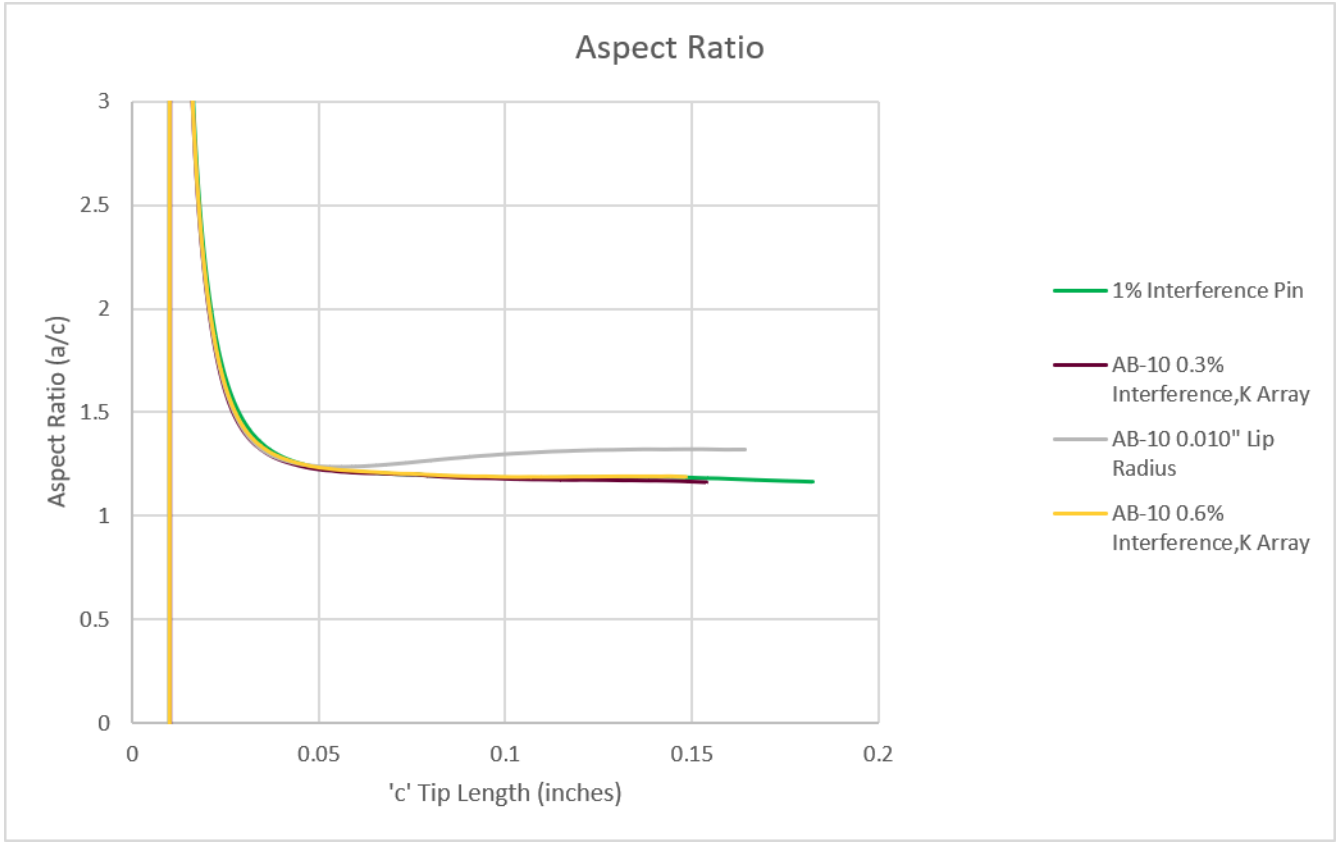
Interference Fit Pin – K Array, 0.3%, 0.6% and 1%



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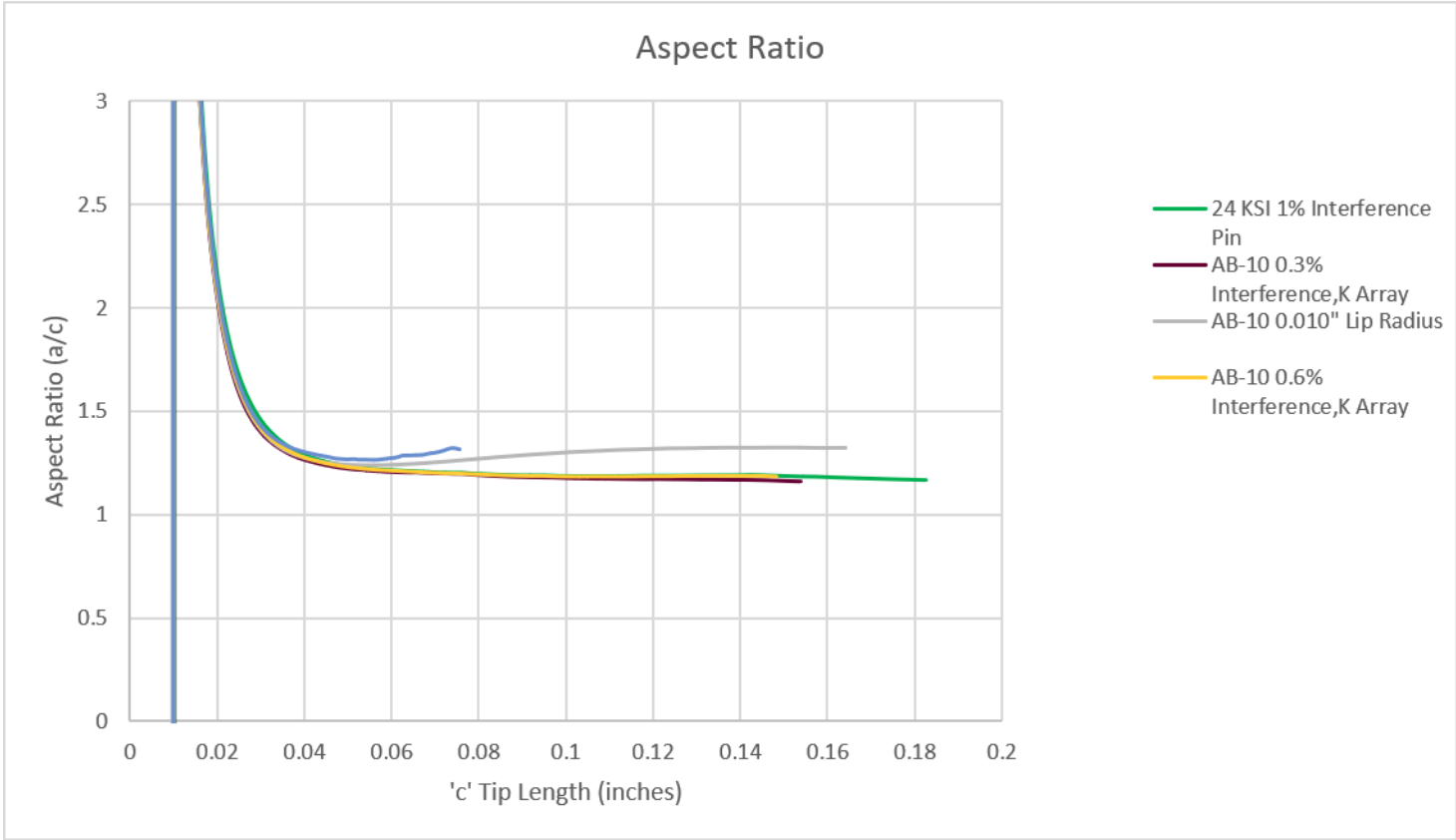
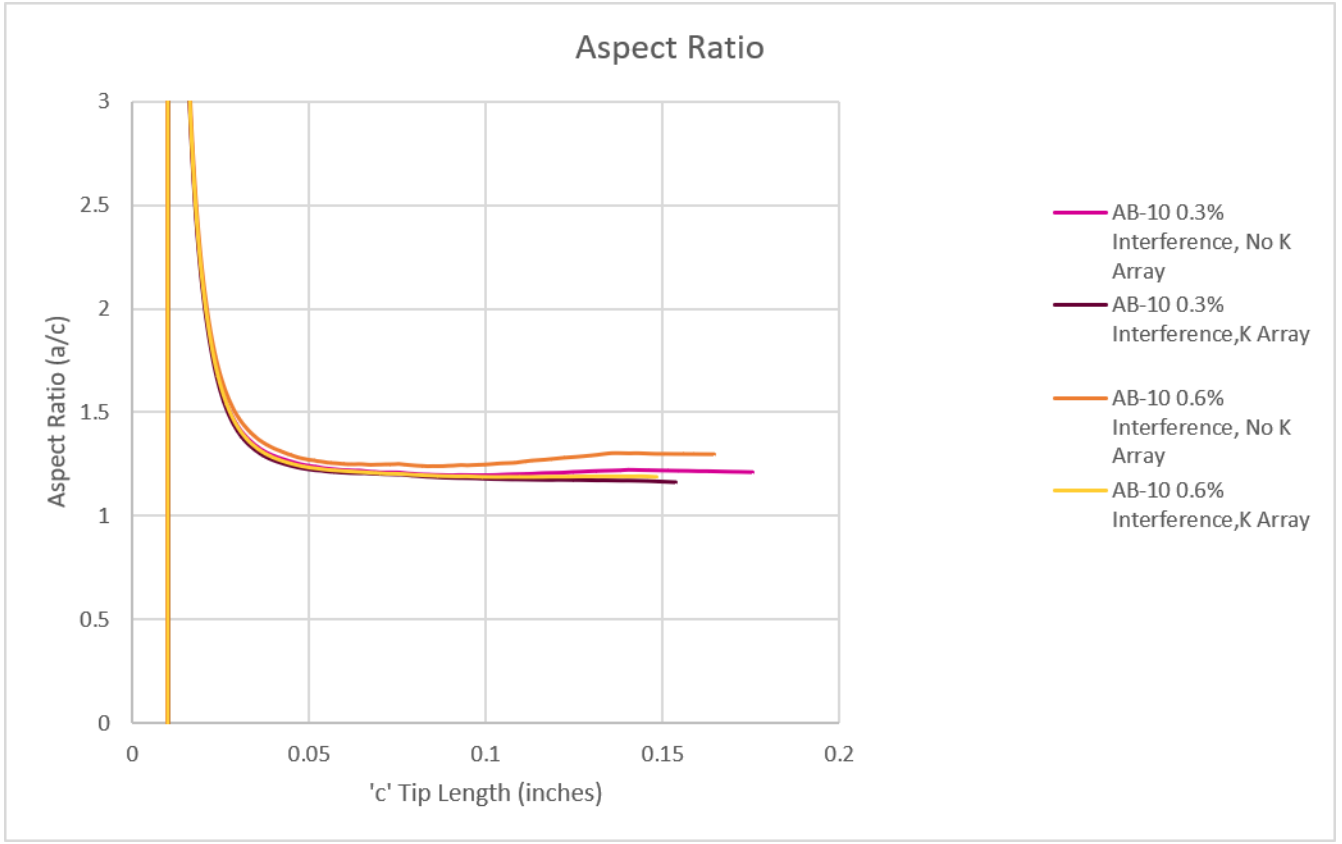
Interference Fit Pin – High Loading

- Extra high load and interference
  - 36 ksi
  - 3% interference
  - Blue curve at right
- Aspect ratio appears even higher than the non-interference fit pin
  - Model not run to completion due to time constraints
- Suggests we are past the point of diminishing returns at these levels



K Array vs No K Array



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Conclusions

- Load level on its own does not appreciably affect crack aspect ratio
- Load level in combination with interference pin may have some effect
- Lip/chamfer geometry affects aspect ratio at small sizes, but not in a beneficial way
  - As the crack grows away from the lip, the effect diminishes and all initial cracks trend toward the same aspect ratio
- Interference pin impact on aspect ratio is small, but it is real
  - But the amount of impact depends on load level
- K Array is needed to model effectively
  - Even without K Array there may be some impact on the models

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Some Other Considerations

- How does the constraint of the coupon affect it? Would a wider plate be more affected by the pin?
- Would the location of the pin change things? The pin was 0.020” from the lip surface (0.030” from coupon surface) for all models.
- Were the stress and interference levels investigated sufficient to affect the aspect ratio?

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