How to evaluate a weld inclusion through fracture analysis

Introduction

A typical structural analysis may end with a fatigue analysis that compares the expected loads and cycles to an S-N curve to determine the approximate "life" of components. However, an S-N curve can vary significantly with mean stress, geometry, and temperature, so what happens when a representative S-N curve is not available? What happens when a radiographic inspection reveals a crack-like flaw, like the example below? An S-N curve is not suited to accommodate large cracks. Should the part just be scrapped, costing time and money to replace it? Fracture mechanics can help answer these questions.

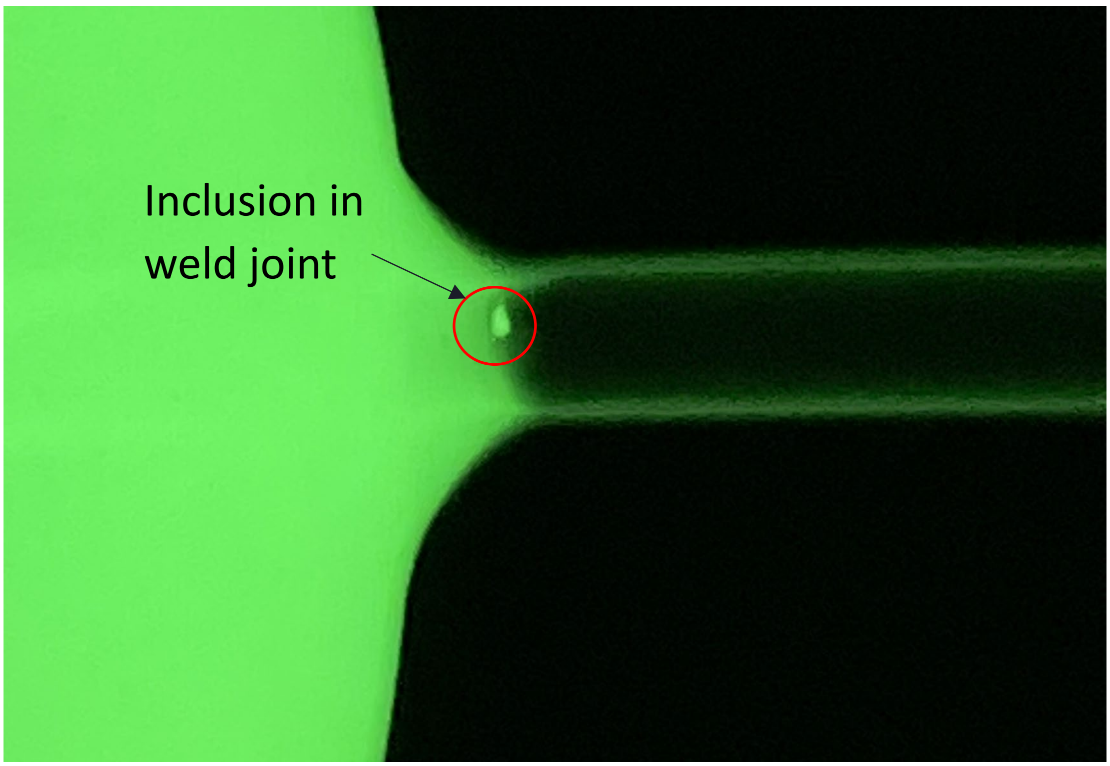

Figure 1. A radiographic inspection reveals an inclusion (flaw) in a weld. A fracture analysis can help determine whether or not to scrap the component.

Fracture mechanics is simply the study of the growth of large cracks. The crack size, geometry, and stress distribution (combined as the Stress Intensity Factor) are the driving forces of crack propagation while toughness is a material's resistance to crack propagation. A crack can grow during cyclic loading, such as vibrations from transportation, rocket launches, and rotating shafts. A growing crack will become unstable and cause failure when the crack size reaches a critical length, but not all loads/cycles will grow the crack. A fracture analysis should work together with a structural analysis to ensure a component fails only after a longer life than what is required. It is not typically necessary to ensure that the crack never grows at all. This is refered to as “Damage Tolerance” (DT) analysis.

In the above example, a tube is welded thru a vessel wall and it is observed that a crack-like flaw is present in the weld. A significant amount of work went into these components before the flaw (in this case, an inclusion in the weld) was identified. ACT was able to analyze the driving forces to determine whether the flaw would propogate to failure within its required test and service life.

Approach

This fracture mechanical analysis made some adjustments to the typical approach because the location, orientation, and initial size of the crack was known. The resulting approach was:

1. Identification of applicable stress intensity factor solution
2. Selection of material data
3. Derivation of stresses
4. Derication of stress specturm
5. Calculate crack growth

The analysis was performed in NASGRO. The relevant failure modes for this component are:

- Net section yielding
- Failure by crack instability
- Failure by thru crack (leak)

Identification of Applicable Stress Intensity Factor Solution

Considering the Mode 1 loadings below, surface crack case SC34 was chosen to represent the configuration.

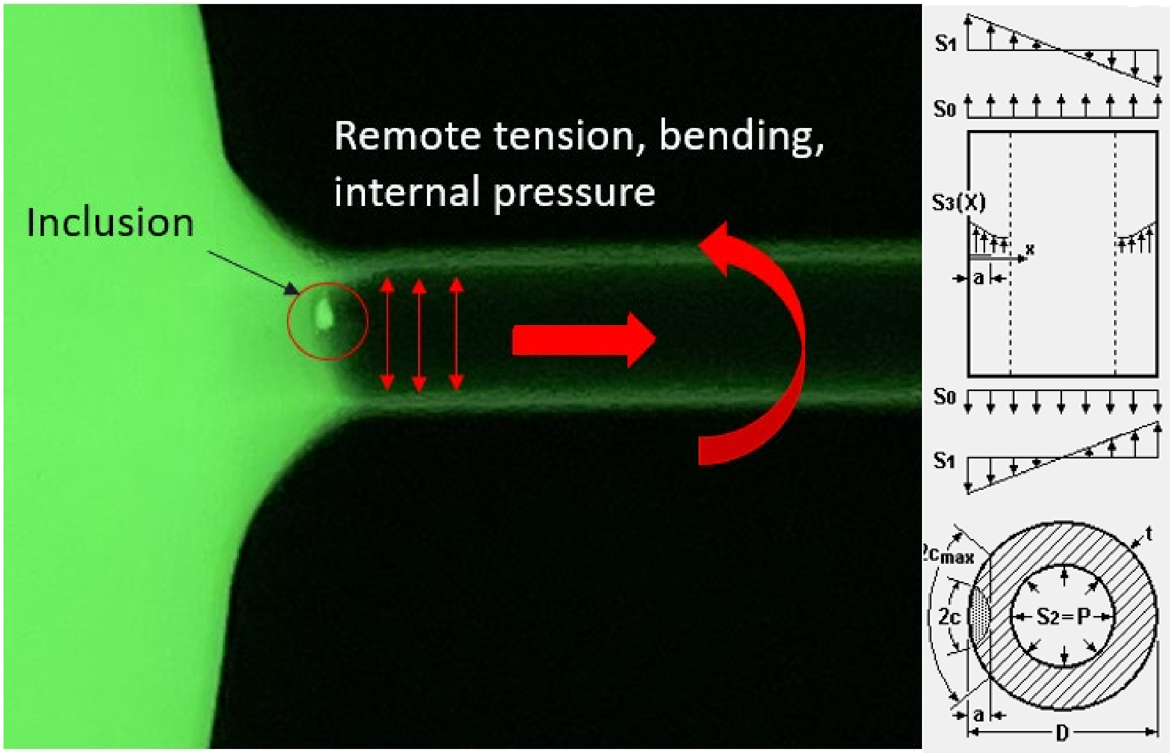

Figure 2. This flaw could grow in width and depth when subjected to tension, bending, and internal pressure loads.

Selection of Material Data

NASGRO has a large selection of material data for fracture analysis. The closest match in the database to the actual weld material was Stainless Steel 316/316L, Annealed, Submerged arc, stress relieved, in 800F/427C Air (ID F3KAH2AA16).

Derivation of Stresses

The FEM structural analysis was used to determine the forces on the tube. These forces were then used in hand calculations to determine the resultant stresses at the base of the tube. The internal pressure (S2) is handled directly in NASGRO; hoop and axial stress do not need to be calculated. The resulting max stresses to analyze are:

Table 1. The max tension, bending, and internal pressure loads are calculated or extracted from an FEM analysis.

S0max (tension)	S1max (bending)	S2max (internal pressure)
ksi	ksi	ksi
3.645	8.000	2.106

Derivation of Stress Specturm

The stresses from tension and bending come from vibration loads and are known to not happen at the same time as the internal pressure load, so they are analyzed in separate load blocks. A load block is a collection of load steps that are applied to the crack a certain amount of times (cycles). Each load step can involve tension, bending, internal pressure, and other loads that each cycle between two values in time (t1 and t2). All t1 loads of a step are applied at the same time (same with t2).

To be conservative, the max stresses during vibration are assumed to be fully reversed. The number of cycles of vibration loads are determined from the random vibration profile and correspond to percentages of the maximum vibration loads. The number of pressure cycles up to max pressure are assumed to be 10 or less. Load Blocks 1 and 2 are shown below.

Table 2. Loads are broken down by percentages of the maximum load and the estimated number of cycles of each load are assigned. These tension and bending loads happen concurrently, so they are grouped together in the same "Load Block."

Load Block 1					
Step	Cycles	S0 at t1 [ksi]	S0 at t2 [ksi]	S1 at t1 [ksi]	S1 at t2 ksi]
1	40	-3.645	3.645	-8.000	8.000
2	52	-3.281	3.281	-7.200	7.200
3	112	-2.625	2.625	-5.760	5.760
4	468	-1.837	1.837	-4.032	4.032
5	1312	-1.102	1.102	-2.419	2.419
6	6256	-0.551	0.551	-1.210	1.210
7	22140	-0.220	0.220	-0.484	0.484
8	53832	-0.066	0.066	-0.145	0.145
9	178992	-0.013	0.013	-0.029	0.029
10	319856	-0.001	0.001	-0.003	0.003

Table 3. Internal pressure loads occur separately from the tension and bending loads, so they are applied in a separate "Load Block."

Load Block 2			
Step	Cycles	S2 at t1 [ksi]	S2 at t2 [ksi]
1	10	0	2.106

Calculate Crack Growth

After running the calculations in NASGRO, it is determined that the combination of crack size, geometry, and loading are below the threshold for crack growth, meaning the crack does not grow at all during its expected life. A screenshot of the output window in NASGRO is shown below. The maximum deltas in stress intensity factors (DK) are shown to be lower than their corresponding thresholds (DKth). Since the crack will not grow in the width (c) or depth (a), the component will not fracture from crack instability or from a leaking thru crack. Although not explicitly mentioned in the output below, it is calculated that the component does not fail due to net section yeilding.

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FINAL RESULTS:
** Life is longer than the required no. of schedules **
All Stress Intensities are below the Fatigue Threshold.
NO Growth in Schedule No.       1
Crack Size a =  0.300000E-01  ,   a/c =   1.5000

 Behavior at a-tip:
 ------------------
 Threshold value DKth =   5.408
 Applied value of  DK =   2.956
 Lowest Margin        =   2.452
# Occurs at Step No. =        1     , Block No.  =        1

 Behavior at c-tip:
 ------------------
 Threshold value DKth =   5.344
 Applied value of  DK =   4.794
 Lowest Margin        =   0.550
# Occurs at Step No. =        1     , Block No.  =        1
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Figure 3. The results from NASGRO indicate that the expected structural loads will not grow the flaw to component failure. This component was not scrapped, saving time and money.

Conclusion

In the example above, it was determined that the flaw would not grow during its expected loads. This gives evidence for accepting the non-conformance as-is, saving time and money.

The example provides a great showcase of the capabilities of fracture mechanics. However, the case of analyzing a flaw after a part is manufactured is a reactive approach, and not the best use of fracture mechanics. The best use would be a proactive approach, performing a fracture analysis in the design phase along with a structural analysis. This strategy could incoporate fracture resistant design, determine material and manufactering approaches, and guide non-destructive inspection techniques and timing. ACT recommends a proactive approach to achieve the best possible products.