# Mapping Reliably Detectable Dye Penetrant Crack Size at External Corners with Fillet Radii

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## Background

- Typically, reliably detectable crack size for dye penetrant testing is determined by using test specimens with known size fatigue cracks.
- Certain surface crack size was qualified in original Standard dye penetrant probability of detection (POD) studies. The flaw size was qualified to a minimum 90% POD with 95% confidence (conf.).
- No corner crack size was qualified by direct POD testing. Typically, the corner and other crack sizes were established based on crack face area equivalency analysis.
- However, there is no supporting empirical data for crack face area equivalency. The volume of reservoir between crack faces available for dye penetrant to seep in and then bleed back after removal of excess surface dye penetrant is an important factor is forming a dye penetrant indication.
- The volume available for dye penetrant to seep into a crack would be proportional to the crack face area for cracks. Therefore, the approach has some merit, but other factors such as aspect ratio of crack length-to-depth must be considered.
- The paper provides an approach to interpret POD demonstrated surface crack size to a corner crack on a corner with any radius based on consideration for crack face area, crack chord equivalency and minimum depth. The dye penetrant reliably detectable flaw sizes are used for fracture mechanics safe life analysis. The paper provides an analysis approach to qualify the reliably detectable dye penetrant corner crack size based on POD demonstrated surface crack size.

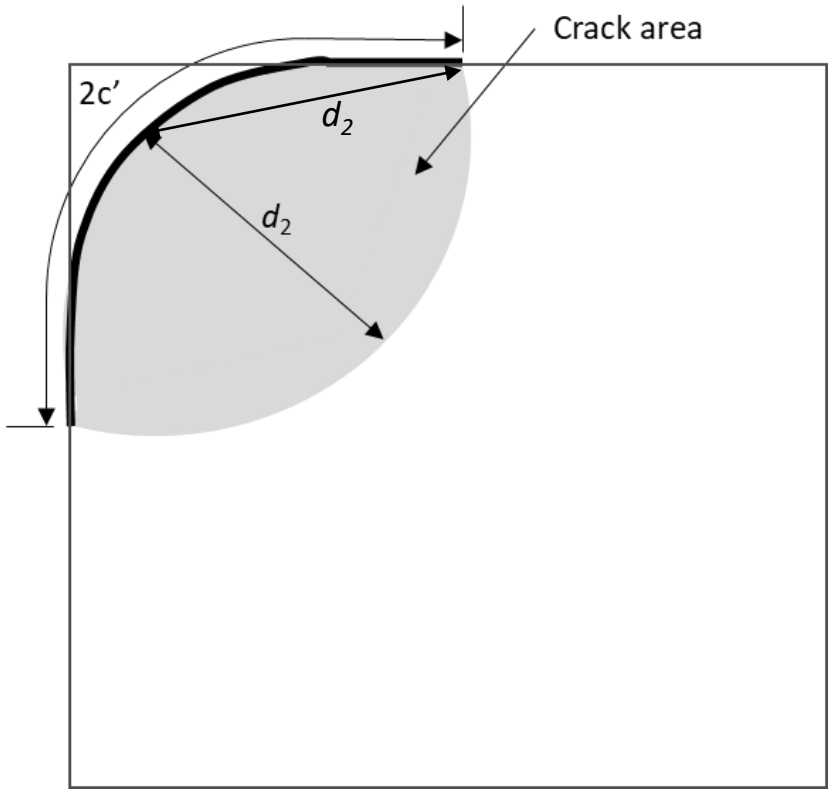
# Considerations for Mapping Demonstrated Surface Flaw Detection to Corner Flaw

- Surface crack size with depth a = 0.075” and length 2c = 0.150” has been qualified in original Standard dye penetrant probability of detection (POD) studies (Bishop1).
- In order to map a POD demonstrated surface crack to a corner, crack face area is considered as one of the factors.
- The approach must consider empirical data on minimum crack depth necessary to form a dye penetrant indication that does not wash away during processing and during evaluation of bleed-back during swab wipe test. Generally, dye penetrant procedures are divided in Standard and Special.
- A Standard procedure is expected to detect larger flaw size (e.g. depth a = 0.075” and length 2c = 0.150”) and a Special procedure is qualified to detect smaller flaw size (e.g. depth a = 0.015” and length 2c = 0.030”) reliably.
- Therefore, minimum flaw depth is also expected to be different in the two cases; with Special procedure detecting smaller minimum depth flaws.
- The minimum depth is based on empirical flaw detectability data. Therefore, there should be a lower limit on crack depth for reliable detection of cracks.
- Thus, crack face area and minimum depth are two important considerations in mapping corner crack size with radius.
- The other consideration is based on perception of the dye penetrant crack indication or observed length by the operator. If these three factors i.e. crack face area, minimum crack depth criteria, and observed flaw length for the corner crack indication are evaluated, then any dye penetrant POD demonstrated surface crack length can be interpreted for any corner with given corner radius. This assumes that there is adequate access to the corner for developing and assessing the indication.
- Koshti[2] provided discussion on corner crack mapping approaches including crack face area, crack surface length and crack chord length. The dye penetrant reliably detectable flaw sizes are important because they are used for fracture mechanics[3] damage tolerance safe life analysis.
- The current approach of choosing chord length with minimum depth and evaluating crack face area is described by Koshti4. Acceptance of results of such an approach is a responsibility of the responsible fracture control board.

# Factors Affecting Dye Penetrant Crack Detectability

- **Crack face area equivalency** implies that a very short (e.g., 0.005” long) but deep crack with same area as a crack with 0.075” depth x 0.150” length is equally detectable.
  - This assumption is not true as the length dimension compares with required visual acuity of the operator (Jaeger J1 letter width ~0.015” and line width ~ 0.003”) and, therefore, 0.005” long deep crack is not as easily detectable without magnification.
  - For human detection of a crack by dye penetrant inspection, indication length (~ crack length), indication width, indication contrast and background noise are the key parameters.
- It is assumed that **pre-penetrant etching has removed smeared metal** over any crack opening. Etching slightly widens the crack opening by preferentially etching away material at corners of the crack opening. Widening at the crack opening also helps dye penetrant to seep into the crack.
  - It is also assumed that the cracks are free of other entrapped material.
  - Ultrasonic cleaning removes the developer and other material trapped in the crack. Ultrasonic cleaning is used to clean dye penetrant demonstration test panels after each dye penetrant test. Dye penetrant demonstration test crack panels are periodically inspected under high magnification microscope to verify that the crack openings are not smeared, eroded and are free of developer or other particles.
- **Length of an indication should be greater than or equal to visual J1 letter size** for detection of a crack indication with an unaided eye. Dye penetrant indication blooms with time after removal of excess dye penetrant due to bleed back, especially after application of a developer.
  - A layer of developer particles provides blotting action to draw some of the dye penetrant trapped in the crack back to surface. Therefore, the indication would become sufficiently wide and be adequately detectable to the operator after allowing sufficient developer dwell time.
  - The dwell time, unless otherwise specified, shall be a minimum of 10 minutes per ASTM E1417. Generally, fluorescent dye penetrant contrast is controlled by controlling ambient light to a low level. Visible light background shall not exceed 2 fc (or 21.5 lx) per ASTM E1417.
- Fluorescent dye penetrant is checked to verify fluorescence above an acceptable lower limit. Black light intensity is verified to a minimum of 1000 $\mu W/cm^2$ per ASTM E1417.
- **Controlled ambient, black light intensity and fluorescence** as described above are assumed during dye penetrant inspection. Depth of the crack should be sufficient so that the indication should not be wiped/washed away during the step of removal of excess dye penetrant; but also during swab wipe tests to verify the indication by observing bleed back after swab wipe test.
- Rough background decreases contrast to noise ratio (CNR) of the indication and reduces reliability of flaw detection. **Smooth surface finish** (125 µin or better) is assumed, providing a uniform background.

# Defining Crack Face Geometry

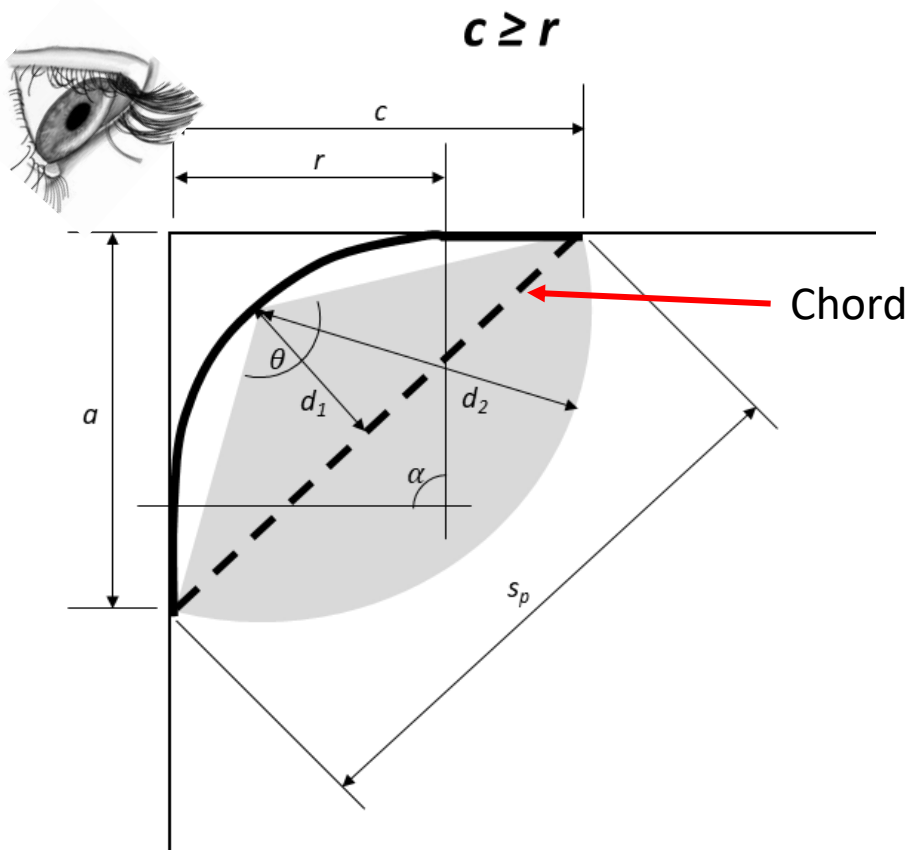


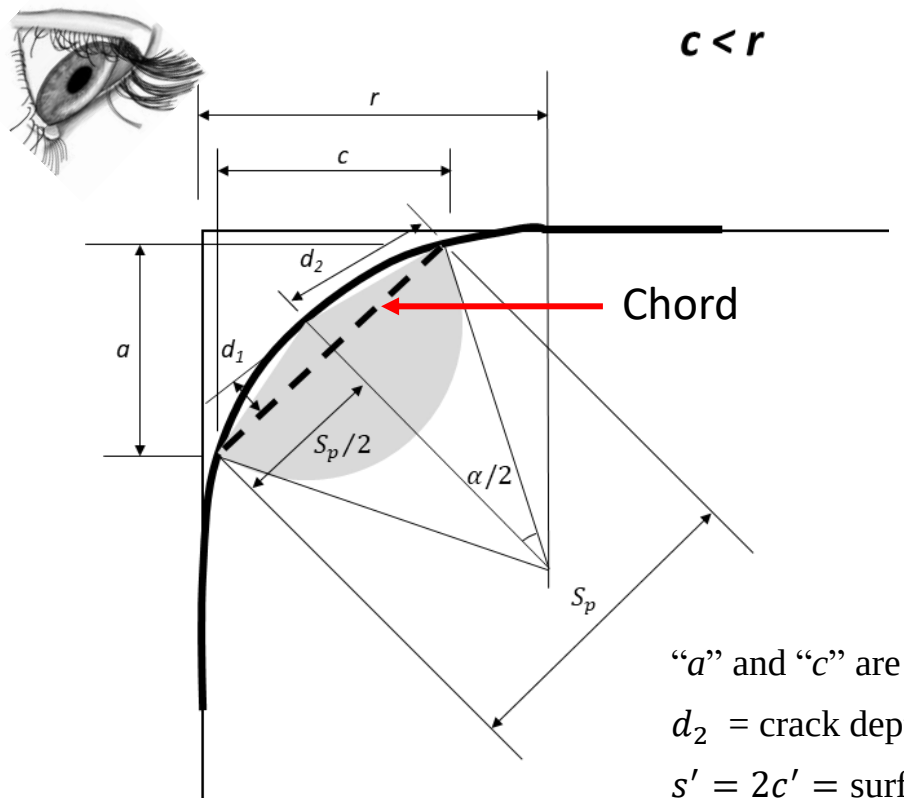

$d_2$ = crack depth,

$s' = 2c'$ = surface length of the crack (not shown),

Crack face geometry case for crack in radiused external corner
i.e., radiused corner/surface crack

# Two Cases of Corner Crack with Radius




Chord length is perceived as dye penetrant indication length by the eye looking at the corner

"$a$" and "$c$" are fracture mechanics dimensions.

$d_2$ = crack depth,

$s' = 2c'$ = surface length of the crack (not shown),

$s_p = 2c_p$ =projected length or chord length,

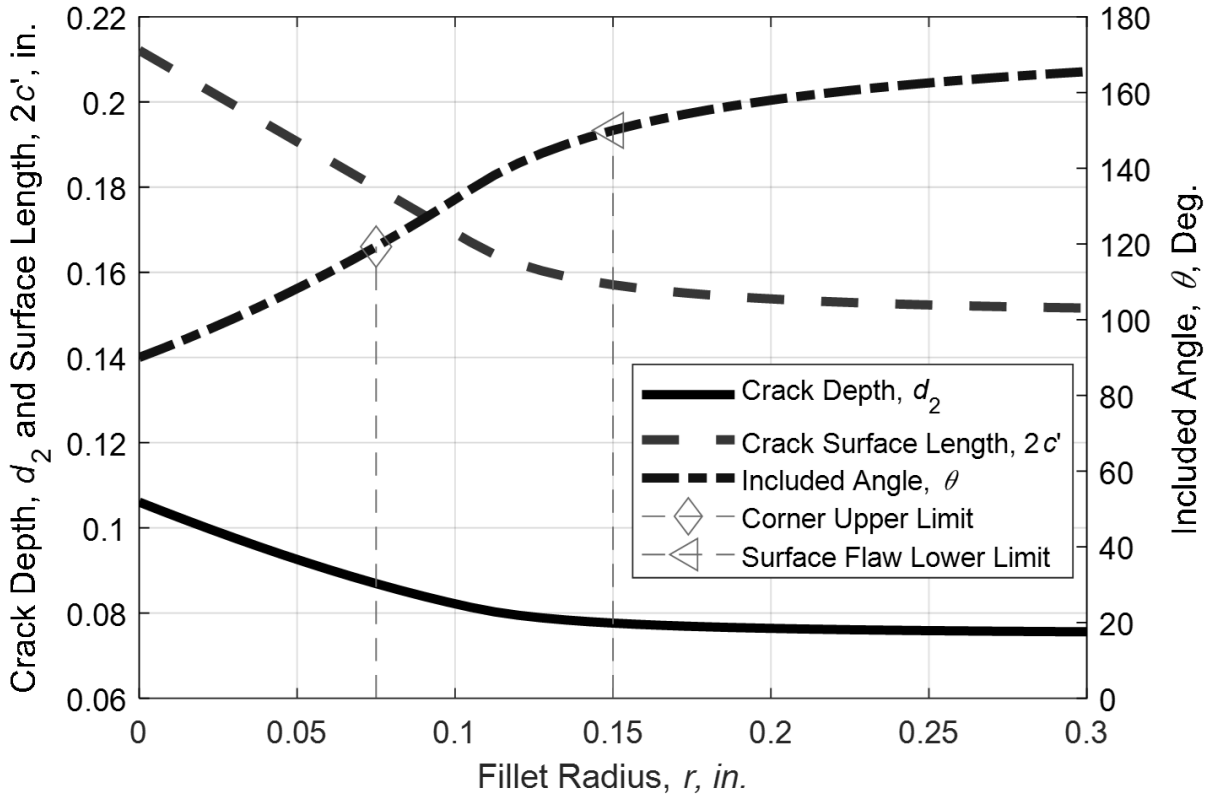
$r$ = fillet radius,

$\theta$ = included fan angle, and

$\alpha$ = included angle of radiused portion of crack.

# Radiused Corner/Surface Crack Size in Radiused "Edge or Hole" for $t \geq 0.106$"

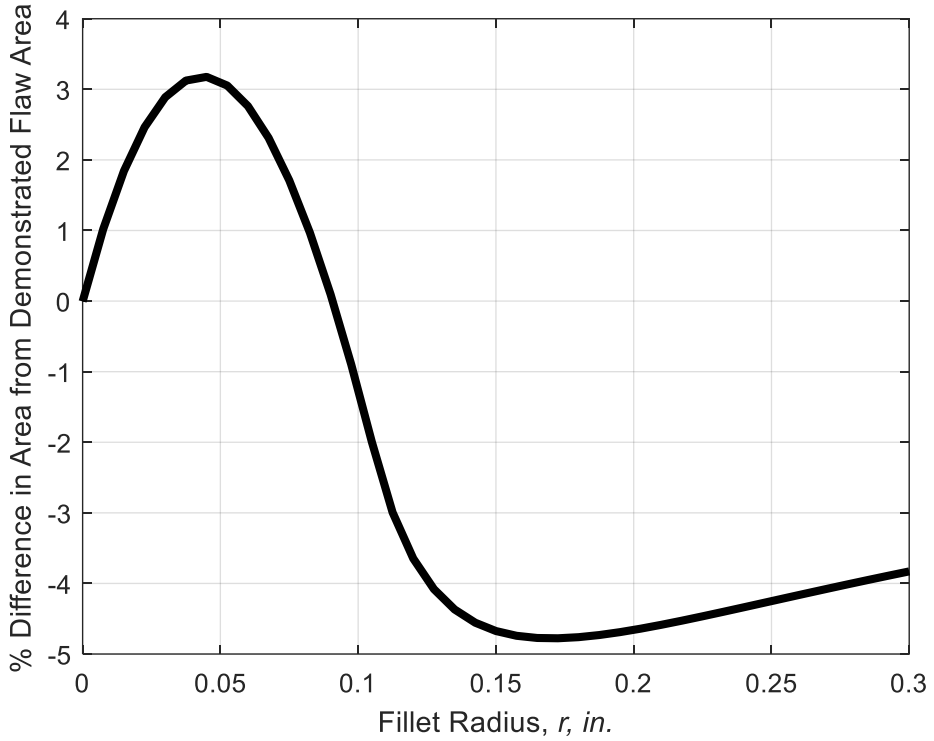
- Standard dye penetrant demonstrated surface crack length 2c = 0.150".




Demonstrated Surface Flaw Size, 2$c$ = 0.150 in., $a$ = 0.075 in.

# Difference in Crack Face Area from That of Demonstrated Flaw

- Standard dye penetrant demonstrated surface crack length 2c = 0.150”.



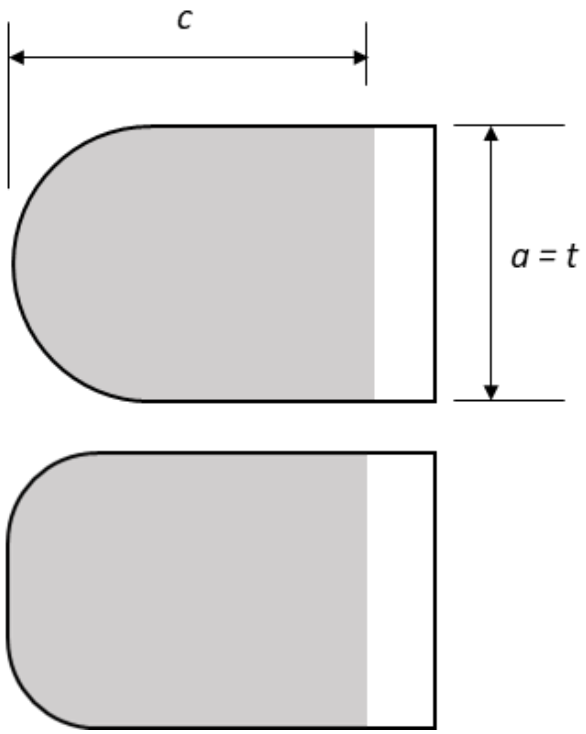

Demonstrated Surface Flaw Size, 2*c* = 0.150 in., *a* = 0.075 in.

# Table Mapping Surface Thumbnail Crack to Chord Equivalent Corner Crack

Table 2: Mapping surface thumbnail crack (*2c* = 0.150", *a* = 0.075") to chord equivalent corner crack

| Radius r, in | Depth $d_2$, in | Surface Length 2c', in | Included Fan Angle θ, deg. | Radius r, in | Depth $d_2$, in | Surface Length 2c', in | Included Fan Angle θ, deg. |
|---|---|---|---|---|---|---|---|
| 0.0000 | 0.1061 | 0.2121 | 90.0 | 0.1575 | 0.0774 | 0.1563 | 151.6 |
| 0.0075 | 0.1039 | 0.2089 | 92.4 | 0.1650 | 0.0771 | 0.1557 | 153.0 |
| 0.0150 | 0.1018 | 0.2057 | 95.0 | 0.1725 | 0.0769 | 0.1552 | 154.2 |
| 0.0225 | 0.0997 | 0.2025 | 97.6 | 0.1800 | 0.0768 | 0.1547 | 155.4 |
| 0.0300 | 0.0977 | 0.1993 | 100.3 | 0.1875 | 0.0766 | 0.1543 | 156.4 |
| 0.0375 | 0.0957 | 0.1960 | 103.2 | 0.1950 | 0.0765 | 0.1540 | 157.4 |
| 0.0450 | 0.0938 | 0.1928 | 106.2 | 0.2025 | 0.0764 | 0.1537 | 158.3 |
| 0.0525 | 0.0920 | 0.1896 | 109.3 | 0.2100 | 0.0763 | 0.1534 | 159.1 |
| 0.0600 | 0.0902 | 0.1864 | 112.5 | 0.2175 | 0.0762 | 0.1531 | 159.8 |
| 0.0675 | 0.0885 | 0.1832 | 115.8 | 0.2250 | 0.0761 | 0.1529 | 160.5 |
| 0.0750 | 0.0869 | 0.1799 | 119.3 | 0.2325 | 0.0760 | 0.1527 | 161.2 |
| 0.0825 | 0.0854 | 0.1767 | 122.9 | 0.2400 | 0.0760 | 0.1526 | 161.8 |
| 0.0900 | 0.0839 | 0.1735 | 126.6 | 0.2475 | 0.0759 | 0.1524 | 162.4 |
| 0.0975 | 0.0826 | 0.1703 | 130.5 | 0.2550 | 0.0758 | 0.1523 | 162.9 |
| 0.1050 | 0.0813 | 0.1671 | 134.4 | 0.2625 | 0.0758 | 0.1521 | 163.4 |
| 0.1125 | 0.0803 | 0.1642 | 138.2 | 0.2700 | 0.0757 | 0.1520 | 163.9 |
| 0.1200 | 0.0795 | 0.1620 | 141.3 | 0.2775 | 0.0757 | 0.1519 | 164.3 |
| 0.1275 | 0.0789 | 0.1604 | 144.0 | 0.2850 | 0.0757 | 0.1518 | 164.7 |
| 0.1350 | 0.0784 | 0.1590 | 146.3 | 0.2925 | 0.0756 | 0.1517 | 165.1 |
| 0.1425 | 0.0780 | 0.1580 | 148.2 | 0.3000 | 0.0756 | 0.1516 | 165.5 |
| 0.1500 | 0.0776 | 0.1571 | 150.0 | | | | |

# Corner Through-crack Face Geometry

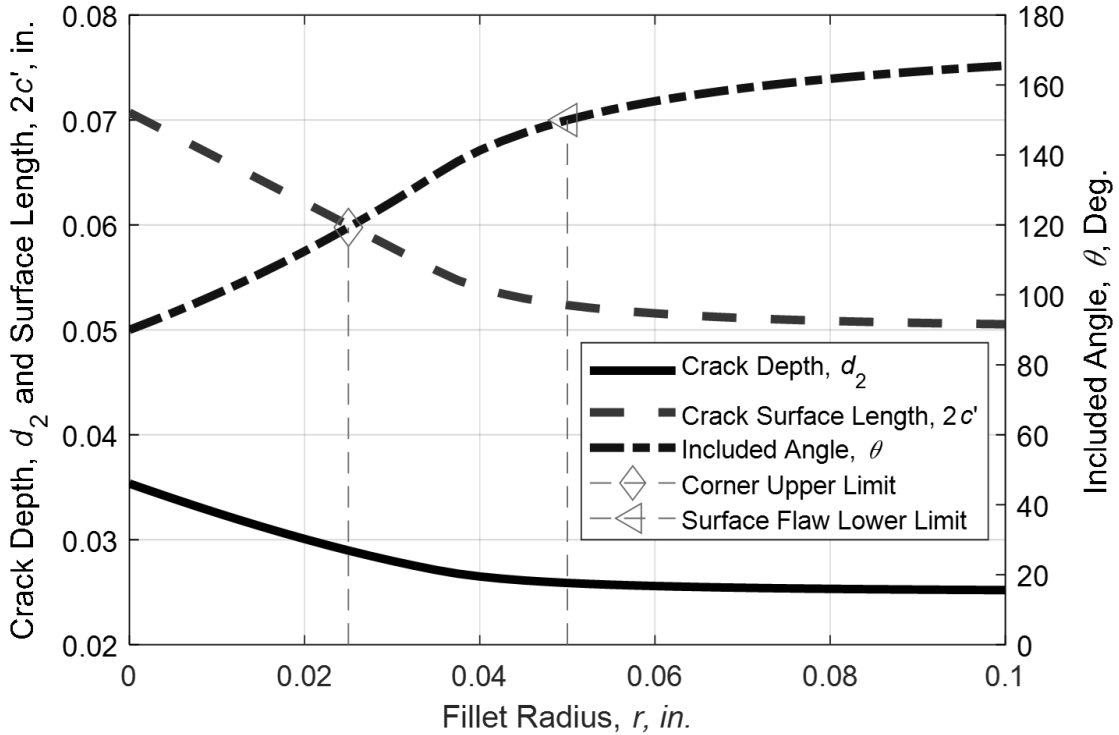



| Crack Location | Part Thickness, t | Crack Type | Crack Dimension, a* | Crack Dimension c* |
|---|---|---|---|---|
| Open Surface | t ≥ 0.025 | PTC | 0.025 | 0.075 |
| Corner (Edge or Hole) | 0.025 ≤ t < 0.106 | Through | t | $\sqrt{0.0225 - (t/2)^2}$ |
| | t ≥ 0.106 and r ≤ 0.075 | Corner | 0.106 | 0.106 |

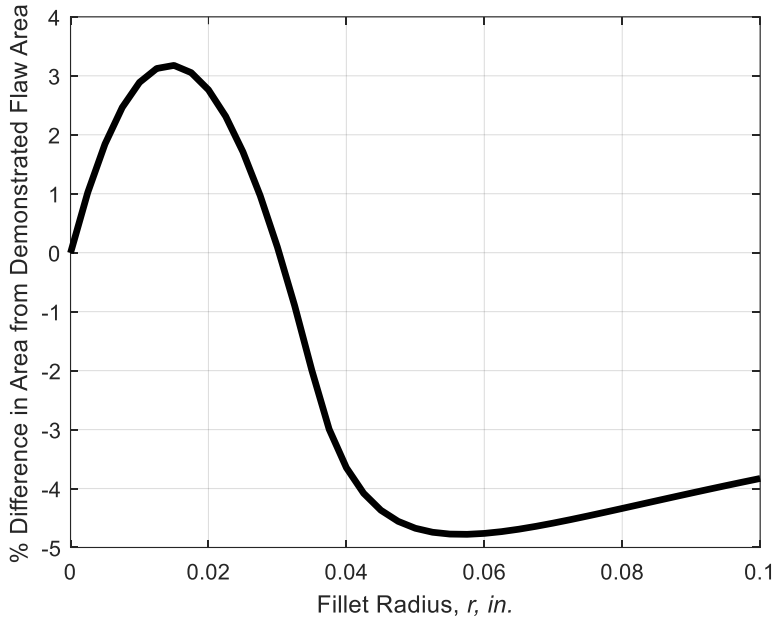
**Corner through-crack face geometry is indicated by gray shading**

# Radiused corner/surface crack size in radiused corner for t ≥ 0.035”

- Special dye penetrant demonstrated surface crack length 2c = 0.050”.




Demonstrated Surface Flaw Size, 2*c* = 0.050 in., *a* = 0.025 in.




Demonstrated Surface Flaw Size, 2*c* = 0.050 in., *a* = 0.025 in.

Case of $\theta \leq 120$-deg. or $r \leq c$ is considered to be corner crack face geometry.

Case of $150 \leq \theta \leq 180$-deg. is considered to be surface crack face geometry.

Case of $120 < \theta < 150$-deg. (or $c < r < 2c$) is considered to be transition region between corner and surface crack face geometries.

# General Special Dye Penetrant Mapping Demonstrated Surface Flaw to Corner Flaw

| Crack Location | Part Thickness, t | Crack Type | Crack Dimension, a | Crack Dimension c |
|---|---|---|---|---|
| Open Surface | t ≥ s/2 | PTC | s/2 | s/2 |
| Edge or Hole | s/2 ≤ t < $s/\sqrt{2}$ | Through | t | $\sqrt{s^2-(t/2)^2}$ |
| | t ≥ $s/\sqrt{2}$ and r ≤ s/2 | Corner | $s/\sqrt{2}$ | $s/\sqrt{2}$ |

**Special dye penetrant crack sizes for selected case for corner crack size *r* ≤ *s*/2,**

*r* = fillet radius

*s* = surface length of demon stared flaw

# Conclusion

- The paper provides rationale to use chord length equivalency combined with lower limit on crack depth to map the POD demonstrated surface thumbnail crack size to Standard and Special dye penetrant corner cracks.
- It is recommended that lower limit on crack depth be verified by dye penetrant demonstration test.
- It is recommended to perform at least some limited empirical validation of crack detectability sizes for cases of radiused corner/surface and through cracks for both Standard and the Special dye penetrant cases of interest.