KD-412.2 Vessels With Two or More Layers.
(a) For vessels with two or more layers, the final crack depth in the inner layer may be equal to the layer thickness, provided the theoretical collapse pressure (1.732 times the value calculated in KD-221.2) of the combined remaining layers is at least 20% higher than the design pressure of the unflawed vessel.

Otherwise, the allowable final crack depth shall not exceed 25% of the inner layer thickness.

The theoretical collapse pressure of the combined remaining layers shall be calculated using the inside diameter of the innermost of the remaining layers as the pressure loading diameter.

(b) For all other layers, the allowable final crack depth shall not exceed 25% of the layer thickness except as in (c).

(c) The allowable final crack depth of the outermost layer also shall not exceed the dimension equal to the assumed initial flaw depth defined in KD-411 plus 25% of the dimensional difference between the theoretical critical crack depth and that of the assumed initial flaw.

KD-420 STRESS INTENSITY FACTOR $K_I$ CALCULATION

(a) For finite length cracks, crack growth along the surface and in the through-thickness directions shall be considered. Crack growth shall be calculated using eqs. KD-430(a)(1) and KD-430(a)(2). The aspect ratio shall be updated as the crack size increases. Methods for calculating the fracture mechanics stress intensity factors and reference stresses for several geometries in a typical high pressure vessel are given in Nonmandatory Appendix D and in API 579-1/ASME FFS-1. Methods in API 579-1/ASME FFS-1 for the calculation of stress intensity factors and reference stresses shall be used where applicable.

(b) All forms of loading shall be considered, including pressure, thermal, discontinuity, and residual stresses. Weld residual stresses may be estimated using API 579-1/ASME FFS-1, BS 7910, finite element, or other analytical methods. In some cases, the stresses produced by the action of the fluid pressure in the crack shall be considered. Guidelines are given in Nonmandatory Appendix D.

(c) The $K_I$ values for all loadings except residual stresses shall be assessed by considering their minimum and maximum values and their chronological relationship. The combined effects of these loadings shall be reported as minimum $K_{Imin}$ and maximum $K_{Imax}$ stress intensity factors. The effects of residual stresses, such as those due to autofrettage, shrink fitting, welding, or wire winding, shall be assessed by calculating an equivalent positive or negative stress intensity factor due to these residual stresses $K_{ires}$. Paragraph KD-430 specifies how $K_{ires}$, $K_{Imin}$ and $K_{Imax}$ are combined to calculate a crack growth rate which shall be integrated to solve for a calculated number of design cycles $N_p$ based on crack propagation.

KD-430 CALCULATION OF CRACK GROWTH RATES

(a) The crack growth rate at the deepest point on the crack periphery $da/dN$, in./cycle (mm/cycle), is assumed to be a function of the range of stress intensity factor $\Delta K$, ksi-in.$^{1/2}$ (MPa-m$^{1/2}$), and the stress intensity factor ratio $R_K$ where

$$\frac{da}{dN} = C[f(R_K)](\Delta K)^m$$

$$\Delta K = K_{I max} - K_{I min}$$

and

$$R_K = \frac{K_{I min} + K_{ires}}{K_{I max} + K_{ires}}$$

and near the surface from

$$\frac{dl}{dN} = 2C[f(R_K)](\Delta K)^m$$

where $\Delta K$ is calculated as described above using the methods in KD-420(a). Equation (2) is only required for calculation of elliptical crack growth.

When calculating crack growth rates, the plastic zone correction to the stress intensity factor may be neglected. If $(K_{I max}^0 + K_{ires}) \leq 0$, $da/dN$ may be assumed to be equal to zero. The values of $C$ and $m$ to be used for some materials are given in Table KD-430 for the case of $f(R_K) = 1$. If $R_K = 0$, then $f(R_K) = 1$. The relationship $f(R_K)$, which may be used for some materials, is given in Nonmandatory Appendix D.

(b) If the value of $\Delta K$ is less than the value of the threshold $\Delta K (\Delta K_{th})$ as given by the following equation, the value of $da/dN$ may be assumed to be zero.

(1) If $(K_{I max}^0 + K_{ires}) \leq 0$, $\Delta K$ may be assumed to be equal to zero.

(2) If $R_K < 0$, i.e., $(K_{I min}^0 + K_{ires}) < 0$, $\Delta K$ compared with $\Delta K_{th}$ shall be $\Delta K = (K_{I max}^0 + K_{ires})$ instead of eq. (1).

For carbon and low alloy steels [$S_y \leq 90$ ksi (620 MPa)]

$\Delta K_{th} = \text{the lesser of } G(1 - HR_{K}) \text{ or } I, \text{ but not less than } 1.0 \text{ ksi-in.}^{1/2}(11.1 \text{ MPa-m}^{1/2})$

For high-strength low alloy steels and martensitic precipitation-hardened steels [$S_y \leq 90$ ksi (620 MPa)]

$\Delta K_{th} = \text{the lesser of } G(1 - HR_{K}) \text{ or } I, \text{ but not less than } 1 \text{ ksi-in.}^{1/2}(11.1 \text{ MPa-m}^{1/2})$

\[2.2\]
The theoretical collapse pressure of the combined remaining layers shall be calculated using the inside diameter of the innermost of the remaining layers as the pressure loading diameter. (b) For all other layers, the allowable final crack depth shall not exceed 25% of the layer thickness except as in (c).

(c) The allowable final crack depth of the outermost layer also shall not exceed 25% of the theoretical critical crack depth.

**KD-420 STRESS INTENSITY FACTOR K<sub>i</sub> CALCULATION**

If (K<sub>i,max</sub> + K<sub>i,res</sub>) < 0, ΔK may be assumed to be equal to zero. If R<sub>k</sub> < 0, i.e. (K<sub>i,min</sub> + K<sub>i,res</sub>) < 0, ΔK compared with ΔK<sub>th</sub> shall be ΔK = (K<sub>i,max</sub> + K<sub>i,res</sub>) instead of Equation (1).

ΔK of Equation (1) is full range of stress intensity factor including the compression portion.

If K<sub>i,max</sub> + K<sub>i,res</sub>:0, ΔK may be assumed to be equal to zero.

Weld residual stresses may be estimated using API 579-1/ASME FFS-1, BS 7910, finite element, or other analytical methods. In some cases, the stresses produced by the action of the fluid pressure in the crack shall be considered. Guidelines are given in Nonmandatory Appendix D.

(c) The K<sub>i</sub> values for all loadings except residual stresses shall be assessed by considering their minimum and maximum values and their chronological relationship. The combined effects of these loadings shall be reported as minimum K<sub>i,min</sub> and maximum K<sub>i,max</sub> stress intensity factors. The effects of residual stresses, such as those due to autofrettage, shrink fitting, welding, or wire winding, shall be assessed by calculating an equivalent positive or negative stress intensity factor due to these residual stresses K<sub>i,res</sub>. Paragraph KD-430 specifies how K<sub>i,res</sub>, K<sub>i,min</sub>, and K<sub>i,max</sub> are combined to calculate a crack growth rate which shall be integrated to solve for a cracked number of design cycles N<sub>p</sub> based on crack propagation.

**KD-430 CALCULATION OF CRACK GROWTH RATES**

(a) The crack growth rate at the deepest point on the crack periphery d<sub>a</sub>/d<sub>N</sub>, in./cycle (mm/cycle) is assumed to be a function of the range of stress intensity factor ΔK, ksi-in.\(^{1/2}\) (MPa-m\(^{1/2}\)), and the stress intensity factor ratio R<sub>k</sub> where

\[
\frac{da}{dN} = C[(R_k)]^{m/2}\left[\frac{\Delta K}{2C(f(R_k))}\right]^{m}
\]

and

\[
\Delta K = K_{i,max} - K_{i,min}
\]

(1)

and near the surface from

\[
dt / dN = 2C[f(R_k)][\Delta K]^{m}
\]

(2)

where ΔK is calculated as described above using the methods in KD-420(a). Equation (2) is only required for calculation of elliptical crack growth.

When calculating crack growth rates, the plastic zone correction to the stress intensity factor may be neglected. If (K<sub>i,max</sub> + K<sub>i,res</sub>) ≤ 0, d<sub>a</sub>/d<sub>N</sub> may be assumed to be equal to zero. The values of C and m to be used for some materials are given in Table KD-430 for the case of f(R<sub>k</sub>) = 1. If R<sub>k</sub> = 0, then f(R<sub>k</sub>) = 1. The relationship f(R<sub>k</sub>) which may be used for some materials, is given in Nonmandatory Appendix D.

(b) If the value of ΔK is less than the value of the threshold ΔK (ΔK<sub>th</sub>) as given by the following equation, the value of d<sub>a</sub>/d<sub>N</sub> may be assumed to be zero.

For high-strength low alloy steels and martensitic precipitation-hardened steels

\[
\Delta K_{th} = \text{the lesser of } G (1-HR_k) \text{ or } I, \text{ but not less than } 2 \text{ ksi-in.}^{1/2} (2.2 \text{ MPa-m}^{1/2})
\]

For aluminum alloys

\[
\Delta K_{th} = \text{the lesser of } G (1-HR_k) \text{ or } I, \text{ but not less than } 0.64 \text{ ksi-in.}^{1/2} (0.7 \text{ MPa-m}^{1/2})
\]

Values of G, H, and I for some common pressure vessel materials are given in Table KD-430.

(c) If corrosion fatigue is involved, crack growth rates can increase significantly. Environmental effects in conjunction with loading frequency shall be considered when calculating crack growth rates.

For carbon and low alloy steels [S<sub>y</sub> ≤ 90 ksi (620MPa)]:

\[
\Delta K_0 = \text{the lesser of } G (1-HR_k) \text{ or } I, \text{ but not less than } 1.0 \text{ ksi-in.}^{1/2} (1.1 \text{ MPa-m}^{1/2})
\]