A Study on the effect of Welding Residual Stresses on Fracture Strength of Specimens Made of Aluminium Alloys

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ABSTRACT: In this paper, the failure behavior of heat-treated wrought 2xxx Aluminium alloys is examined by generating failure assessment diagrams (FAD) utilizing point stress criterion. Changes are made in one of the stress fracture criteria of Whitney and Nuismer (viz., the point stress criterion), to improve the fracture strength estimations of cracked bodies. A realistic relation is established for the characteristics length in terms of the fracture strength and ultimate tensile strength of the material, to take into account the change of characteristic length with crack size in fracture model. From the improved point stress criterion, an empirical relation is presented for the generation of FAD. Changes made in the fracture model associate well with fracture test data. Additionally the SINTAP procedure is utilized for defect assessment as a part of butt-welded joint of these aluminium alloy plates contain transverse through thickness crack. FAD is drawn for AA2219-T87 welded plates for different crack sizes for as-welded (Residual stress only) and mechanical loading with the existing weld induced residual stresses to show the safety level of a particular crack size and mechanical loading.

KEYWORDS: Failure assessment diagram, Fracture strength, Point stress criterion, SINTAP procedure, wrought aluminium alloys.

I. INTRODUCTION

Yielding and fracture are the two sorts of failure criteria identified by airspace industry. Failure because of yielding is connected to a criterion in which some useful of the stress or strain is surpassed and fracture is connected to a criterion in which an effectively existing crack reaches out an energy balance hypothesis. The safety assessment of structures without a crack mechanics analysis is lacking and may bring about an unexpected decrease in the load carrying capacity of an actual structure because of the presence of unavoidable crack-like defects not being taken into consideration. It is additionally needed to consider the residual stresses present in the structures for safety assessment. Few fracture analysis methods to anticipate the fracture behavior of flawed structures used as a piece of a test and predictive round robin coordinated in 1979-80 by the American Society for Testing and Materials (ASTM) Task Group E 24.06.02 were portrayed in reference [1]. None of these strategies was discovered to be the best for all the structural materials analyzed. Gordon [2] has inspected a few of the significant pipeline codes, which have included fracture-mechanics-based fitness-for-service concepts. Various designing systems have been proposed to study the fracture behavior of cracked configurations [3-5]. In the failure assessment diagram or the R6 technique [6], the integrity of the structure is evaluated and depicted in a two-dimensional manner: a component of the failure strength according to LEFM is plotted as ordinate and that compliant with plastic fall as abscissa. The Dugdale model [7] set up the stress limits for any transitional stages between linear elastic failure and plastic collapse. Trials generally ended up being these limits to be conservative. The two-parameter fracture criterion of Newman [1, 8] also, implements relations obtained within the scope of LEFM. In this criterion, the two fracture parameters make note of the deviation of the stress-to-failure from the stress calculated in accordance with LEFM principles.

These parameters must be resolved before in pretests, alleged benchmark tests, led under indistinguishable states of the material. Keller et al [9] have completed fracture analysis of surface cracks in cylindrical shaped vessels applying the
two-parameter fracture criterion. It was neither conceivable to focus satisfactorily the failure stresses of vessels by
method for fracture parameters got from fracture mechanics specimens, nor to anticipate the loads to failure of the
specimens by means of the fracture parameters of the vessels. Jeyakumar and Christopher [10] established a simple and
realistic relation for the characteristic length in terms of the fracture strength and ultimate tensile strength of the
considering a definitive tensile strength value and the fracture data of AA2219-T87 alloy base metal and weldment
produced from centre-surface cracked tensile specimens having different thicknesses at cryogenic temperatures
utilizing an altered inherent flaw model. Brighton Isaac and Christopher [12] analyzed tensile-fracture strength of heat-
treated AA2xxx series using average stress criterion. Zerbst et al. [13] have formed European flaw assessment
procedure SINTAP (Structural Integrity Assessment Procedures for European Industry). This SINTAP was
implemented to the published fracture information [14] on steel pipes having through-wall and surface cracks subjected
to internal pressure. Gubeljak et al. [15] applied SINTAP procedure to the failure analysis of a broken fork of a forklift.
Gubeljak and Predan [16] applied the SINTAP procedure to failure prediction of cracked structural component
regarding to increasing applied load or crack size. The SINTAP procedure offers a CDF (Crack Driving Force) and a
FAD route. Both are complementary and give identical results.

Fusion welding is an unfailing and proficient joining process in which the blend of metals is accomplished by fusion.
This type of welding has been broadly utilized as a part of various industries, for example, aviation; boat building,
atomic, bridge development. Since the implementation of cutting edge welding strategies, the assessment of crack tip
stress intensity factor (SIF) coming about because of welding induced residual stresses has turn into a crucial part to
the damage tolerance analysis. This alleged residual stress intensity factor ($K_{res}$) is needed in the forecast of fatigue
crack growth rates and also in the residual strength calculation [17-19]. The continuation of high welding induced
residual stresses with the high operating stresses to which engineering structures and components are subjected can
advance fatigue and fracture. Residual stresses can have a detrimental effect on the integrity of a structure and are
therefore an important component of any integrity assessment of a welded structure. Dangerous under prediction of
fracture risk occur, if they are not correctly accounted for, while over conservative estimates lead to over estimation of
fracture estimates. In literatures, work on defect assessment of structures considering residual stresses are found very
rare.

The objective of this article is to demonstrate the applicability of the improved point stress criterion through correlation
of fracture data of heat-treated 2xxx series of wrought Al alloys using point stress criterion and to carried out a defect
assessment of butt-welded joint of AA2219-T87 plates containing transverse through thickness crack of size $2c$ using
SINTAP procedure incorporating weld induced residual stresses. Failure Assessment Diagram is also drawn for welded
AA2219-T87 plates for different crack sizes for as-welded (only Residual stress),100 MPa and 200 MPa mechanical
loading along with the existing weld induced residual stresses to show the safety level for a particular crack size and
mechanical loading.

II. MODIFIED POINT STRESS CRITERION

For cracked configurations, a relation between the stress intensity factor ($K_{max}$) and the corresponding stress ($\sigma_f$) at
failure is suggested as [20]:

$$K_{max} = K_F \left(1 - m \left(\frac{\sigma_f}{\sigma_u}\right) - (1 - m) \left(\frac{\sigma_f}{\sigma_u}\right)^p\right),$$

(1)

Where, $\sigma_f$ is the failure stress normal to the direction of the crack in a body and $\sigma_u$ is the nominal stress required to
produce a plastic hinge on the net section.

For the loaded cylinders, $\sigma_f$ is the hoop stress at the failure pressure of the flawed cylinder, and $\sigma_u$ is the hoop
stress at the failure pressure of an unflawed cylinder. For the determination of three crack parameters ($K_F$, $m$ and $p$),
test results of specimens can be used. For fracture strength evaluation of some other structural configuration, the stress
intensity factor comparing to that geometry is to be utilized as a part of Equation (1) to add to the important fracture
strength equation.
A knowledge of the state of stress is essential in the case of a body with a crack in order to judge the nature of its propagation and thereby its strength. Paris and Sih [21] and Parton and Morozov [22] have explained the Westergaard method for stress analysis of cracks by applying the principles of linear and small deformation elasticity. In practice, of these three modes, the most applicable is the opening mode, which is being considered in the present study.

\[
\sigma_y(x, 0) = \frac{\sigma x}{\sqrt{x^2 - c^2}}, \quad x > c
\]  

(2)

Where \( \sigma \) is the applied stress and \( c \) is half crack length.

The point stress criterion of Whitney and Nuismer postulates that the final fracture of a cracked body occurs when the stress at the end of the crack tip damage equals the ultimate tensile strength \( \sigma_0 \) of the material [24], i.e.

\[
\sigma_y(x = c + a_{cp}, 0) = \sigma_0
\]  

(3)

Where, \( a_{cp} \) is the crack tip damage size at failure.

Substituting \( \sigma = \sigma_{\infty} \) and \( x = c + a_{cp} \) in equation (2) and using the condition (3), one can obtain a relation between the fracture strength and the crack length as

\[
\sigma_{\infty} = \sigma_0 \sqrt{1 - \left(\frac{c}{c + a_{cp}}\right)^2}
\]  

(4)

The unknown characteristic length \( a_{cp} \) is to be obtained from the test data of a finite width tensile cracked specimen.

The fracture Strength \( \sigma_{\infty} \) of the center crack wide tensile specimen is obtained from that of a finite width specimen \( \sigma_{\infty} \) as

\[
\sigma_{\infty} = \sigma_{\infty} \sqrt{Y}
\]  

(5)
Where the finite width correction factor [25] is,

\[ Y = \sqrt{\frac{\sec(\frac{\pi c}{W})}{\pi}} \]  

(6)

Where ‘c’ is half the crack length and W is the specimen width.

Using \( \sigma_{NC}^\infty \), \( \sigma_0 \) and c, the unknown characteristic \( (a_{cp}) \) is found from equation (4) as

\[ a_{cp} = c \left\{ \frac{\sigma_0}{\sqrt{\sigma_0^2 - (\sigma_{NC}^\infty)^2}} - 1 \right\} \]  

(7)

After determining the characteristic length \( (a_{cp}) \), the fracture strength \( (\sigma_{NC}^\infty) \) can be obtained directly from equation (4) specifying the crack length \( (2c) \). Fracture strength \( (\sigma_{NC}) \) of the finite width plate can be obtained from the equation (5) or dividing \( (\sigma_{NC}^\infty) \) with the correction factor \( (Y) \). It is noted from the fracture data on different materials that the fracture strength decreases with increase in the crack size. Equation (7) indicates that the characteristic length \( (a_{cp}) \) is not a material constant. It increases with increase in the crack size. This calls for a modification in the point stress criterion.

From the above observations one can write a relation between \( (a_{cp}) \) and \( (\sigma_{NC}^\infty) \) in the non-dimensional form as

\[ \frac{\sigma_0}{K_{PSC}} \sqrt{\frac{\pi a_{cp}}{\sigma_{NC}^\infty}} = \delta_{a_{cp}} \sigma_{NC}^\infty \]  

(8)

The parameters \( K_{PSC} \) and \( \delta_{a_{cp}} \) in equation (8) are to be determined by a least square curve fit to the data for \( \sigma_{NC}^\infty \) and \( \frac{\sigma_{NC}^\infty}{\sigma_0} \). For the determination of these parameters, two cracked specimen tests in addition to an unflawed specimen test are required; normally more tests are performed to take scatter in test results into account. It should be noted that \( \delta_{a_{cp}} = 0 \) in equation (8) represents the case of constant damage size as per the original point stress criterion [25]. For the case: \( \delta_{a_{cp}} > 1 \) and \( \sigma_{NC}^\infty = \sigma_0 \), equation (8) results

\[ \frac{\sigma_0}{K_{PSC}} \sqrt{\frac{\pi a_{cp}}{\sigma_0}} < 0 \]  

Hence, the variation of the parameter in equation (8) can be: \( 0 \leq \delta_{a_{cp}} \leq 1 \).

Whenever \( \delta_{a_{cp}} \) is found to be greater than unity, the parameter \( \delta_{a_{cp}} \) has to be truncated to 1 by suitably modifying the parameter \( K_{PSC} \) with the fracture data. If \( \delta_{a_{cp}} \) is found to be less than zero, the parameter \( \delta_{a_{cp}} \) has to be truncated to zero and the average of \( \frac{\sigma_0}{K_{PSC}} \sqrt{\frac{\pi a_{cp}}{\sigma_0}} \) values from the fracture data yields the parameter \( K_{PSC} \).

Once \( K_{PSC} \) and \( \delta_{a_{cp}} \) in Equation (8) are known, it is possible to eliminate the characteristic length \( (a_{cp}) \) from the fracture strength equation (4). The resulting nonlinear equation for the fracture strength \( (\sigma_{NC}^\infty) \) is

\[ 1 - \left( \frac{\sigma_{NC}^\infty}{\sigma_0} \right)^2 \left\{ \frac{1}{\pi} \left( \frac{K_{PSC}}{\sigma_0} \right)^2 \left( 1 - \delta_{a_{cp}} \frac{\sigma_{NC}^\infty}{\sigma_0} \right)^2 \right\} = c \]  

(9)
This non-linear fracture strength Equation (9) is solved using the Newton–Raphson iterative scheme to obtain \( \sigma_{NC}^\infty \) for the specified crack size. The fracture strength \( \sigma_{NC}^\infty \) of the finite width plate is obtained dividing \( \sigma_{NC}^\infty \) with the correction factor \( Y \).

A relation between \( \frac{K_{Q} \equiv \sigma_{NC}^\infty \sqrt{\pi c}}{\sigma_o} \) and \( \frac{\sigma_{NC}^\infty}{\sigma_o} \) can be written by eliminating the characteristic length using the relation (8) and the fracture strength Equation (4) as

\[
K_{Q} = K_{PSC} \left\{ 1 - \delta_{scp} \frac{\sigma_{NC}^\infty}{\sigma_0} \right\} \sqrt{1 - \left( \frac{\sigma_{NC}^\infty}{\sigma_0} \right)^2} + \sqrt{1 - \left( \frac{\sigma_{NC}^\infty}{\sigma_0} \right)^2} \]

(10)

The advantage of developing such a relation is mainly for its further use for fracture strength prediction of any other cracked configuration. It should be noted that Equation (10) represents a failure assessment diagram (see Figure-2). Figure-2 shows a typical failure assessment diagram. For the specified crack size and stress level \( \sigma_A \), the corresponding stress intensity factor \( K_A \) can be found for the cracked configuration. If the point \( A (K_A, \frac{\sigma_{NA}^\infty}{\sigma_0}) \) lies inside the envelope of the failure assessment diagram, the cracked configuration is safe under that stress level. The Point \( C \) refers to the failure point. From this point, the failure strength of the cracked configuration for the specified crack size can be estimated. The factor of safety under the specified stress level is defined as: \( FS = \frac{OC}{OA} \). It can be verified from this expressions that the fracture strength decreases with increasing crack size.

Fracture data from the center crack tensile specimens made of heat-treated wrought 2xxx aluminium alloys [26] is considered in the present study to verify the validity of the fracture criterion. From the test results, fracture parameters \( K_{PSC} \) and \( \delta_{scp} \) are determined and fracture strengths are estimated.

A standard error (SE) between analytical and test results is obtained from

\[
SE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( 1 - \frac{\text{Analysis Result}}{\text{Test Result}} \right)^2}
\]

(11)
Where \( N \) is the number of test specimens. 
The relative error (%) is computed as

\[
\text{Relative error (\%)} = 100 \left( 1 - \frac{\text{Analysis Result}}{\text{Test Result}} \right)
\]  

(12)

Fig. 3 Generation of failure assessment diagrams for AA2219-T87 and its comparison with test data [26].

Fracture analysis has been carried out considering the ultimate tensile strength values and the fracture data of heat-treated wrought 2xxxaluminium alloys (viz.,2014-T6, 2020-T6, 2024-T3, 2024-T351, 2024-T4, 2024-T81, 2024-T86, 2219-T87) generated from center-crack tensile specimens having different thicknesses. Table-1 gives the determined fracture parameters (\( K_{PSA} \) and \( \delta_{ACP} \)) from the test data of the above materials. Tables 2 to 6 give the comparison of fracture strength estimations with the test results. Figure-3 shows the failure assessment diagram for AA2219-T87 including the fracture data of the materials. It is observed that most of the fracture strength estimations are within ±10% of the test results.

This fracture analysis is made by assuming no residual stresses present in the material. For accurate and reliable fracture analysis, the residual stresses present in the material cannot be ignored. The SINTAP procedure can be used to get the residual stress profile for weld joint. This profile is used for fracture analysis for combined residual stress and mechanical loading.

Table 1 Fracture toughness parameters (\( K_{PSA} \) and \( \delta_{ACP} \)) evaluated from the test results [26] of center crack tension specimens made of heat-treated wrought aluminium alloys.
Table 2 Comparison of analytical and test results of center crack tension specimens made of AA 2014-T6 (Specimen thickness, t = 1.6 mm).

<table>
<thead>
<tr>
<th>Specimen Dimensions (mm)</th>
<th>Unnotched strength, $R_0$ (MPa)</th>
<th>Fracture strength, $S_{fr}$ (MPa)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, W</td>
<td>2c</td>
<td>Test [26]</td>
<td>Analysis</td>
</tr>
<tr>
<td>76.2</td>
<td>3.3</td>
<td>607.5</td>
<td>444.8</td>
</tr>
</tbody>
</table>

* N = Number of Specimens
Table 3 Comparison of analytical and test results of center crack tension specimens made of AA2020-T6 (Specimen thickness, \( t = 1.6 \) mm).

<table>
<thead>
<tr>
<th>Specimen Dimensions (mm)</th>
<th>Unnotched strength, ( \sigma_u ) (MPa)</th>
<th>Fracture strength, ( \sigma_{fr} ) (MPa)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, ( W )</td>
<td>Crack length, ( 2c )</td>
<td>Test [26]</td>
<td>Analysis</td>
</tr>
<tr>
<td>50.8</td>
<td>15.85</td>
<td>530.2</td>
<td>183.4</td>
</tr>
<tr>
<td>76.2</td>
<td>27.56</td>
<td>530.2</td>
<td>286.1</td>
</tr>
<tr>
<td>401.57</td>
<td>76.45</td>
<td>530.2</td>
<td>242.6</td>
</tr>
<tr>
<td>401.57</td>
<td>152.65</td>
<td>530.2</td>
<td>224.1</td>
</tr>
</tbody>
</table>

Standard error (SE) = 0.011

Table 4 Comparison of analytical and test results of center crack tension specimen made of AA2024-T3 (Specimen thickness, \( t = 0.81 \) mm).

<table>
<thead>
<tr>
<th>Specimen Dimensions (mm)</th>
<th>Unnotched strength, ( \sigma_u ) (MPa)</th>
<th>Fracture strength, ( \sigma_{fr} ) (MPa)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, ( W )</td>
<td>Crack length, ( 2c )</td>
<td>Test [26]</td>
<td>Analysis</td>
</tr>
<tr>
<td>508</td>
<td>16.26</td>
<td>490.2</td>
<td>269.6</td>
</tr>
<tr>
<td>508</td>
<td>28.45</td>
<td>490.2</td>
<td>220.6</td>
</tr>
<tr>
<td>508</td>
<td>87.63</td>
<td>490.2</td>
<td>194.4</td>
</tr>
<tr>
<td>508</td>
<td>133.6</td>
<td>490.2</td>
<td>148.9</td>
</tr>
<tr>
<td>508</td>
<td>189.48</td>
<td>490.2</td>
<td>257.9</td>
</tr>
</tbody>
</table>

Standard Error (SE) = 0.051

Table 5 Comparison of analytical and test results of center crack tension specimen made of AA2024-T4 (Specimen thickness, \( t = 1.02 \) mm).

<table>
<thead>
<tr>
<th>Specimen Dimensions (mm)</th>
<th>Unnotched strength, ( \sigma_u ) (MPa)</th>
<th>Fracture strength, ( \sigma_{fr} ) (MPa)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, ( W )</td>
<td>Crack length, ( 2c )</td>
<td>Test [26]</td>
<td>Analysis</td>
</tr>
<tr>
<td>190.5</td>
<td>12.95</td>
<td>417.8</td>
<td>275.11</td>
</tr>
</tbody>
</table>
Table 6 Comparison of analytical and test results of center crack tension specimens made of AA2024-T81 (Specimen thickness, t = 1.6 mm).

<table>
<thead>
<tr>
<th>Specimen Dimensions (mm)</th>
<th>Unnotched strength, $F_u$ (MPa)</th>
<th>Fracture strength, $F_{fract}$ (MPa)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, W</td>
<td>Crack length, 2c</td>
<td>Test [26]</td>
<td>Analysis</td>
</tr>
<tr>
<td>152.4</td>
<td>50.8</td>
<td>470.2</td>
<td>261.6</td>
</tr>
<tr>
<td>381</td>
<td>127</td>
<td>470.2</td>
<td>263.4</td>
</tr>
<tr>
<td>457.2</td>
<td>152.4</td>
<td>470.2</td>
<td>147.2</td>
</tr>
<tr>
<td>533.4</td>
<td>177.8</td>
<td>470.2</td>
<td>118.6</td>
</tr>
<tr>
<td>609.6</td>
<td>203.2</td>
<td>470.2</td>
<td>91.0</td>
</tr>
</tbody>
</table>

Standard Error (SE) = 0.025

Table 6 continues...

III. SINTAP PROCEDURE

As suggested by BS 7910 as well as SINTAP, transverse through-wall center crack at welds (see Figure-4), subject to longitudinal surface residual stresses represented as trapezoidal stress profile [27], (see Figure-5). The solution for a through-wall center crack in an infinite flat plate subject to a trapezoidal residual stress profile was obtained by integrating the weight function given for a symmetrical point load $P$, at a distance $x$, from the center of a crack length $2c$ in an infinite plate. In case of transverse through-wall center crack which is subjected to longitudinal residual stress $\sigma(x)$, the point load $P$ is equated to the force $\int_{-\infty}^{x} \sigma(x) dx$, which is acting on an infinitesimal length $dx$ of the crack [27].

$$K_{TFS} = \frac{\sigma(x)}{\sqrt{\pi}} \sqrt{\frac{x}{W_0}}$$

(13)

Where $c$, is half crack length. Assume $W_{c2} = \bar{a}$ (see Figure-5)

$$K_{TFS} = \frac{\sigma(x)}{\sqrt{\pi}} \sqrt{\frac{2(\bar{a})}{W}}$$

(14)

for $\bar{a} \leq \bar{a}$

$$K_{TFS} = \frac{\sigma(x)}{\sqrt{\pi}} \sqrt{\frac{2(\bar{a})}{W}} \left( \frac{W}{\pi \bar{a}^2} - \frac{x^2}{W} \right)$$

(15)

for $\bar{a} \leq c \leq x_0$

$$K_{TFS} = \frac{\sigma(x)}{\sqrt{\pi}} \sqrt{\frac{2(\bar{a})}{W}} \left( \frac{W}{\pi \bar{a}^2} - \frac{x^2}{W} \right)$$

(16)

for $c > x_0$
where

- \( \sigma_{yw} \) = Yield strength of weld metal (MPa)
- \( c \) = Half crack length
- \( b \) = Half-width of weld metal
- \( W_2 \) = Maximum width of weld metal
- \( b_0 \) = Half width of tensile zone

Fig. 4 Transverse Center crack and profile of longitudinal residual stresses at butt welded plate

Butt-welded 2219-T87 Aluminium Alloy plate

For butt-welded AA2219-T87 plate, the transverse residual stress profile is directly taken as trapezoidal profile (as in Figure-5) and its values are calculated as given in SINTAP [27] using Equation (17).

\[
\tau_l = \frac{E\sigma_{yw}}{2b_0 b W}
\]

(17)

Where

- \( \theta_b \) = Radius of yield zone (mm)
- \( \sigma_{yw} \) = Yield strength of parent metal (MPa)
- \( E \) = Young's modulus (N mm/J)
- \( a \) = Arc power \( P \), J/sec, \( V \) = 10, \( I/100 \) and \( \eta = 0.78 \)
- \( t \) = Plate thickness = 1.6 mm
- \( v \) = Welding speed = 11 mm/sec
The total stress intensity factor (due to residual stress and applied stress) can be evaluated by super position principle as [28]:

\[
K_{tot} = K_{res} + K_{app}
\]

Where

- \(K_{tot}\) = Total stress intensity factor
- \(K_{res}\) = Residual stress intensity factor
- \(K_{app}\) = Stress intensity factor due to applied load

Now using Equations (14), (15) and (16), the residual stress intensity factor \(K_{res}\) is calculated for three different cases of crack length.
Figure-7 gives the plot of residual SIF ($K_{res}$) and SIF due to mechanical load of 100 MPa for the welded plate for different crack sizes. Utilizing Figure-7, anyone can obtain total SIF by using Equation (18) for a specific crack size. This can be compared with the fracture toughness of the material for damage tolerance analysis. Figure-8 gives the plot of total SIF ($K_{tot}$) due to residual stress and mechanical load of 50 MPa, 100 MPa and 200 MPa. Using Figure 8, one can get total SIF for a particular crack size for the particular load. This total SIF can be compared with the fracture toughness of the material for damage tolerance analysis. Figure-9 shows the Failure Assessment Diagram (FAD) for AA2219-T87, in which for a particular crack size the values of $K_{res}$ and $K_{mech}$ are plotted. In SINTAP procedure the residual stress values are available up to yield zone only. Away from yield zone it is zero. Hence the points A to H are taken in such a way that the half- crack length to be within yield zone (see Figure-5). Tables 7 and 8 show the fracture parameters of AA2219-T87 without and with mechanical loading. For a 100 MPa mechanical load, applied along the existing residual stress, all points are inside the curve. It shows that 100 MPa mechanical load for this particular crack length are safe. Also when a mechanical load of 200 MPa is applied along with the existing residual stress, the points D, E, F, G and H are moved out of the curve. It indicates that 200 MPa mechanical load for this corresponding crack length is not safe. All other points are safe. From this procedure for any other crack length, the safe loading can be obtained.
Fig. 7  SIF due to residual stress and mechanical load for a butt-welded plate of AA 2219-T87

Fig. 8  Super imposed SIF due to residual stress and mechanical load for a butt-welded plate of AA 2219-T87 through SINTAP
V. CONCLUDING REMARKS

A relation for the characteristic length in the point stress criterion is developed for precise evaluation of fracture strength of cracked bodies. The procedure is validated considering the fracture data of heat–treated wrought aluminum alloys generated from center crack tension specimens. Failure assessment diagrams were produced from the derived fracture parameters and demonstrated the fracture data near to the failure boundary. Fracture strength of other cracked configurations can be assessed using the present hypothesis with the amendment factor for the stress intensity factor of the the cracked body and the unflawed strength of the configuration. Defect assessment is carried out in butt-welded joint of AA2219-T87 plates contain transverse through thickness crack using SINTAP procedure. Additionally a Failure Assessment Diagram is generated for welded AA2219-T87 plates for various crack sizes for as welded (only residual stress) and various mechanical loading along with the existing weld induced residual stresses to demonstrate the safety level for a specific crack size and mechanical loading. From this analysis it is possible to decide safety level of the structure for service with the presence of crack and residual stress.
Table 8 Fracture parameters of AA2219-T87 with mechanical loading

<table>
<thead>
<tr>
<th>Points</th>
<th>Crack size (c) (mm)</th>
<th>Residual Stress + Mechanical load 100 MPa</th>
<th>Residual Stress + Mechanical load 200 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\sigma_{f#}$</td>
<td>$\sigma_{m#}$</td>
</tr>
<tr>
<td>A</td>
<td>0.1</td>
<td>493</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>1.3</td>
<td>493</td>
<td>30</td>
</tr>
<tr>
<td>C</td>
<td>2.1</td>
<td>490</td>
<td>40</td>
</tr>
<tr>
<td>D</td>
<td>3.2</td>
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REFERENCES

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