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Defect assessment of welded specimen considering weld induced residual stresses using SINTAP procedure and FEA

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Abstract: The defect assessment in butt-welded joint of ASTM A36 steel plates and 7075-T7351 aluminum alloy plates containing transverse through thickness crack was analyzed using SINTAP procedure and FEA incorporating weld induced residual stresses. Weld induced longitudinal residual stress profile can be obtained through SINTAP procedure, FEA or experimental analysis. This residual stress profile can be fitted with the trapezoidal residual stress profile available in SINTAP. For three different cases, crack length and residual stress intensity factor (SIF) are calculated and its comparison with the results obtained through FEA is plotted with respect to crack length. The stress intensity factor for mechanical loading is also plotted in the same graph. Using this graphical plot, the total SIF, including residual stress and mechanical loading, can be calculated for any particular crack size. The total SIF can be compared with the fracture toughness of the material for damage tolerance analysis. Also a failure assessment diagram is drawn for welded 7075-T7351 aluminum alloy plates with different crack sizes for as-welded (only residual stress) and mechanical loading along with the existing weld induced residual stresses to show the safety level for a particular crack size and mechanical loading.
Key words: failure assessment diagram; fracture toughness; stress intensity factor; through thickness crack; welding residual stress

1 Introduction

Fusion welding is a reliable and efficient joining process in which the coalescence of metals is achieved by fusion. This form of welding has been widely used in diverse industries such as aerospace, ship building, nuclear, bridge construction. Since the adoption of modern welding techniques, the evaluation of crack tip stress intensity factor (SIF) resulting from welding induced residual stresses has become an indispensable part to the damage tolerance analysis. This so-called residual stress intensity factor (K_{res}) is required in the prediction of fatigue crack growth rates as well as in the residual strength calculation [1−3]. The continuation of high welding induced residual stresses with high operating stresses to which engineering structures and components are subjected can promote failure by fatigue and fracture. The most widely used defect assessment procedure enables the contribution of the residual stress on the prediction of fracture to be quantified. However, the residual stress distribution is usually unknown, and it is then necessary to make very conservative assumptions [4]. The treatment of residual stresses in defect assessment was investigated in the Structural Integrity Assessment Procedures for European Industry (SINTAP) project [5], whose aim was to develop a unified procedure for the structural integrity assessment of structures and components. SINTAP included a specific task on residual stresses with the overall aim of determining and validating the most appropriate methods of accounting for residual stresses in as-welded, weld-repaired and post-weld heat treated welded joints for use in structural integrity assessment.

Residual stress has a detrimental effect on the integrity of structure and is therefore an important component of any integrity assessment of a welded structure. Danger under prediction of fracture risk occurs, if it is not correctly accounted for, while over-conservative estimates lead to over-estimation of fracture estimates, which lead to over-estimation of fracture risk. Under-prediction is of concern to structural integrity whilst overestimation may have severe financial implications in the industrial situation. Studies on defect assessment of structures considering residual stresses are very rare. In this work, residual stress intensity factor

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for welded plates of ASTM A36 steel and 7075-T7351 aluminium alloy based on the procedure given in SINTAP for a transverse through thickness center crack of size (2*a*) was analyzed and compared with the results obtained through finite element analysis (FEA). For ASTM A36 steel, the residual stress profile obtained through two-dimensional plane stress finite element analysis [6] is used. Failure assessment diagram is also drawn for welded 7075-T7351 aluminium alloy plates with different crack sizes for as-welded (only residual stress, RS), 50 MPa and 100 MPa mechanical loading along with the existing weld induced residual stresses to show the safety level for a particular crack size and mechanical loading.

2 Calculating K_{res} by FEM

There are a few methods for evaluating the stress intensity factor (SIF) by FEM, such as the crack tip displacements extrapolation, the J-integral, the strain energy approach, and the virtual crack extension technique. The displacement extrapolation, stress extrapolation and J-integral methods are widely used in practices and implemented in commercial FE software packages. However, the J-integral method is no longer path-independent in the presence of thermal strains and path dependent on plastic strains, body forces within the integration area, and pressure on the crack surface. Therefore, J-integral method is not suitable for evaluating SIF (K_I) due to the weld thermal stress [7]. In this work, the stress extrapolation method is used for evaluating SIF. To determine K_I at the crack tip, that is, when r=0, this technique avoids the stress singularities. On the crack plane (θ=0), K_I is related to the stress in the y-axis direction (see Fig. 1) according to Eq. (1) when $r\rightarrow 0$.

$$K_{\mathrm{I}}=\lim_{r\to 0}[\sigma_y\sqrt{2\pi r}] \tag{1}$$

where K_I is the stress intensity factor (mode I); σ_y is stress along y direction; r is the distance measured from the crack tip.

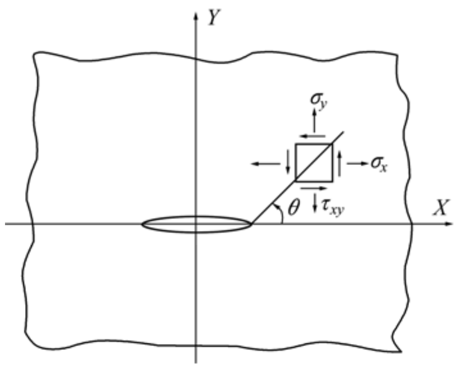

Fig. 1 Description of stress near crack-tip in Cartesian coordinate system

With the knowledge of the stress σ_y at a particular point specified by r, one can get the value of K_I at that point. Before estimating K_I at the crack tip one should get more values of refinement in points without stress singularities, that is, for different values of r>0 (away from the crack-tip). Now extrapolating the values of K_I for different points (r>0), K_I at the crack tip (r=0) is obtained.

Initially a thermo-mechanical FEA is carried out to assess the weld-induced residual stress. For residual stress intensity factor (K_{res}) analysis of this welded plate along with the residual stresses, the analysis is restarted from the terminating (final) load step of thermal stress analysis along with the applied stress.

From finite element analysis on the crack plane (θ=0), corresponding to the r value, σ_y is obtained. Now using Westergaard's stress, K_I can be calculated [8].

$$\sigma_y=\left[\frac{K_{\mathrm{I}}}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\right] \tag{2}$$

where θ is the angle measured from the crack plane, here θ=0.

3 SINTAP procedure

Transverse through-wall center crack at welds (see Fig. 2), subjected to longitudinal surface residual stresses was recommended in BS7910 and SINTAP as trapezoidal stress profile [9] (see Fig. 3). The solution for a through-wall center crack in an infinite flat plate subjected to a trapezoidal residual stress profile is obtained by integrating the weight function given for a symmetrical point load p, at a distance y, from the center of a crack length 2a in an infinite plate. For a transverse through-wall center crack subjected to longitudinal residual stress $\sigma_{\mathrm{R}}^{\mathrm{L}}(y)$ the point load p is equated with the force $\sigma_{\mathrm{R}}^{\mathrm{L}}(y)\mathrm{d}y$, acting on an infinitesimal length dy of the crack [9].

$$K_{\mathrm{I}}=\frac{2}{\sqrt{\pi a}}\int_0^a\frac{\sigma_{\mathrm{R}}^{\mathrm{L}}(y)\mathrm{d}y}{\sqrt{1-(y/a)^2}} \tag{3}$$

Let $b=W_1/2$ and $c=y_0$.

For $a\le b$,

$$K_{\mathrm{I}}=\sigma_{\mathrm{yw}}\sqrt{\pi a} \tag{4}$$

For $b<a\le c$,

$$K_{\mathrm{I}}=\sigma_{\mathrm{yw}}\sqrt{\pi a}(2/\pi)\{(\pi/2)-[(a^2-b^2)^{1/2}-b\pi/2+b\sin^{-1}(b/a)]/(c-b)\} \tag{5}$$

For $a>c$,

$$K_{\mathrm{I}}=\sigma_{\mathrm{yw}}\sqrt{\pi a}(2/\pi)\left\{\sin^{-1}(c/a)\cdot\frac{[(a^2-b^2)^{1/2}-(a^2-c^2)^{1/2}-b\sin^{-1}(c/a)+b\sin^{-1}(b/a)]}{(c-a)}\right\} \quad (6)$$

where σ_{yw} is the yield strength of the weld metal; a is the half crack length; b is the half-width of the weld metal; W_1 is the maximum width of the weld metal; $c=y_0$ is the half width of the tensile zone.

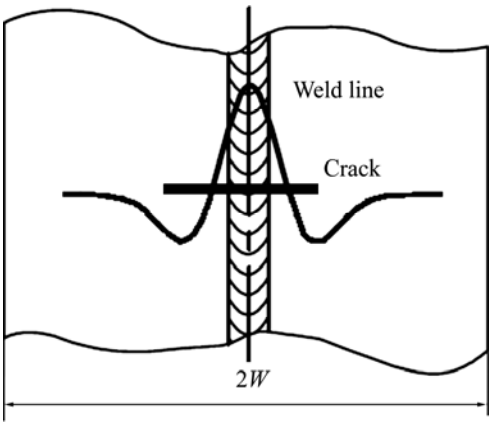

Fig. 2 Transverse center crack and profile of longitudinal residual stresses at butt welded plate

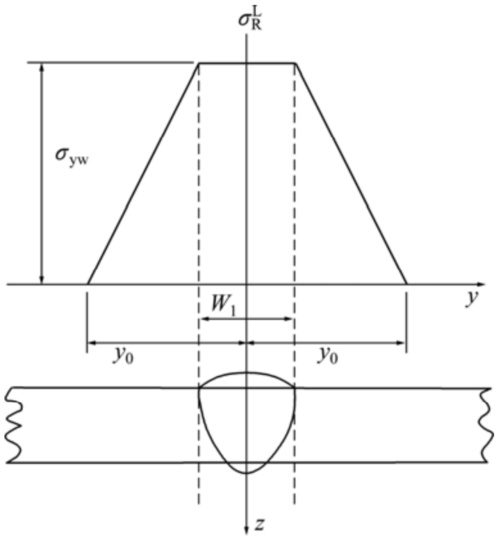

Fig. 3 SINTAP trapezoidal distribution of longitudinal residual stress profile

3.1 Butt-welded ASTM A36 steel plate

The longitudinal residual stress profile obtained through FEA [6] (see Fig. 4) is simplified as trapezoidal profile similar to Fig. 3 with following dimensions and then it is solved for residual stress intensity factor (K_{res}) using Eqs. (4)−(6) for various crack lengths: W_1=16 mm, b= W_1/2=8 mm and $c=y_0$=13.5 mm.

$$K_{\mathrm{tot}}=K_{\mathrm{res}}+K_{\mathrm{app}} \quad (7)$$

where K_{tot} is the total stress intensity factor; K_{app} is the stress intensity factor due to the applied load.

The values of residual SIF (K_{res}) and SIF for mechanical loading of 100 MPa for the welded plate are plotted in Fig. 5. From Fig. 5 one can get total SIF using Eq. (7) for a particular crack size, and it can be compared with the fracture toughness of the material for damage tolerance analysis.

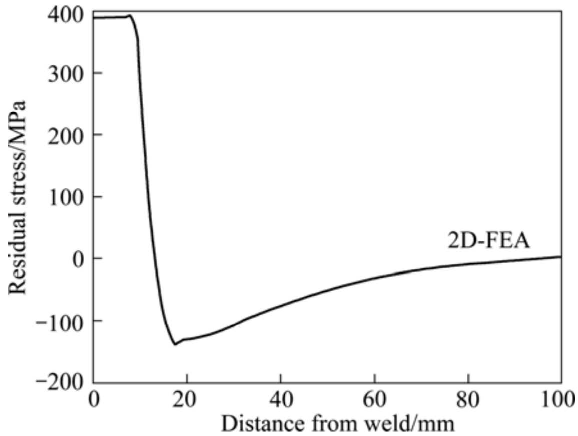

Fig. 4 Longitudinal residual stresses profile of welded ASTM A36 steel plate [6]

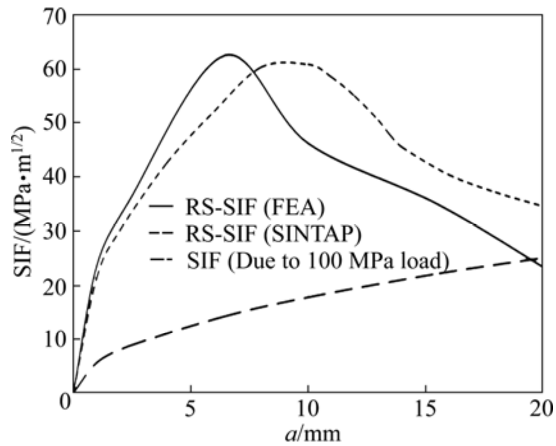

Fig. 5 SIF due to residual stress and mechanical load for butt-welded ASTM A36 steel plate

3.2 Butt-welded 7075-T7351 aluminium alloy plate

For butt-welded 7075-T7351 aluminium alloy plate, the transverse residual stress profile is directly taken as trapezoidal profile (see Fig. 3) and its values are calculated as given in SINTAP [9] using Eq. (8).

$$y_0=\frac{1.033K}{\sigma_{\mathrm{yp}}}\frac{\eta q}{vt} \quad (8)$$

where y_0 is radius of yield zone; σ_{yp} is yield strength of parent metal; $K=2aE/(e\pi\rho c)$ is a material constant; q is arc power, $q=V$ (V=10, I=100 and η=0.75); t is the plate thickness, 2.54 mm; v is the welding speed, 6 mm/s.

The properties of aluminium alloy 7075-T7351 material and welding process parameters are σ_{yp}=435 MPa; σ_{ult}=517 MPa [9]; a is coefficient of thermal expansion, 24 $\times10^{-6}$/°C; E is elastic modulus, 70000 MPa; ρ is density; c is the specific heat capacity; K=164; c=y_0=20 mm; W_1=6 mm, b=W_1/2=3 mm.

Using Eqs. (4)−(6), the residual stress intensity factor (K_{res}) is calculated for three different cases of crack length. These available values of residual SIF (K_{res}) and SIF for mechanical load of 100 MPa for the welded plate are plotted together. One can get total SIF using Eq. (7) for a particular crack size and it can be compared with the fracture toughness of the material for damage tolerance analysis.

4 Results and discussion

Figure 5 shows the stress intensity factor due to the residual stress and mechanical load for a butt-welded ASTM A36 steel plate calculated through SINTAP and FEA. One can get total SIF using Eq. (7) for a particular crack size, and it can be compared with the fracture toughness of the material for damage tolerance analysis. Figure 6 shows the super-imposed SIF due to the residual stress and mechanical load for a butt-welded ASTM A36 steel plate through FEA. Figure 7 shows the normalized residual SIF for a butt-welded ASTM A36 steel plate. In Figs. 5 and 7, deviations can be seen between FEA and SINTAP. The residual stress profile obtained through FEA has tensile (positive) residual stress up to yield zone (y_0). After yield zone it becomes compressive (negative) and reaches zero, whereas in SINTAP the residual stress profile is available up to yield zone only (see Figs. 3 and 4). The effect of this compressive stress which is not available in SINTAP is the cause of deviation.

Figure 8 shows the SINTAP trapezoidal distribution of longitudinal residual stresses profile of butt-welded plate of 7075-T7351 aluminium alloy. It shows W_1=6 mm, b=W_1/2=3 mm and c=y_0=20 mm. Figure 9 shows the SIF due to residual stress and mechanical load for the butt-welded plate of 7075-T7351 aluminium alloy. From Fig. 9, one can get total SIF using Eq. (7) for a particular crack size, and it can be compared with the fracture

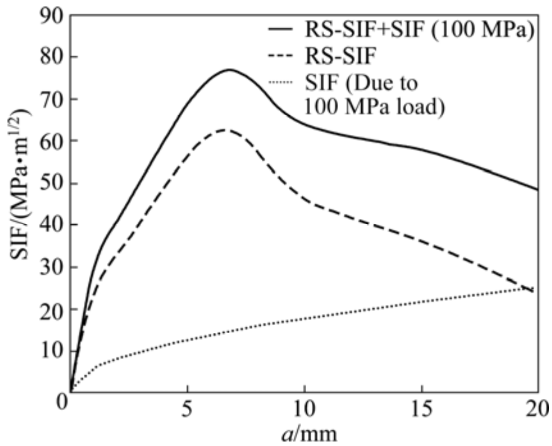

Fig. 6 Super-imposed SIF due to residual stress and mechanical load for butt-welded ASTM A36 steel plate through FEA

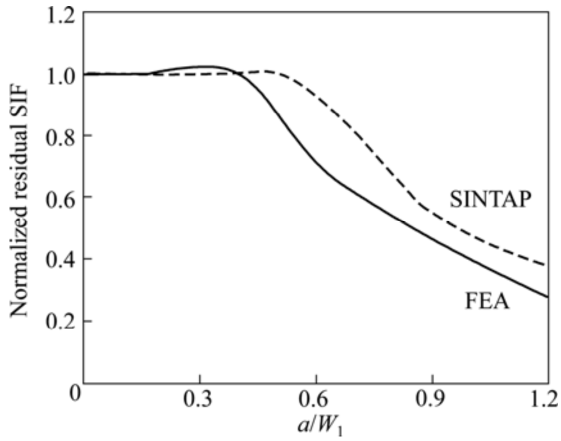

Fig. 7 Normalized residual SIF for butt-welded ASTM A36 steel plate

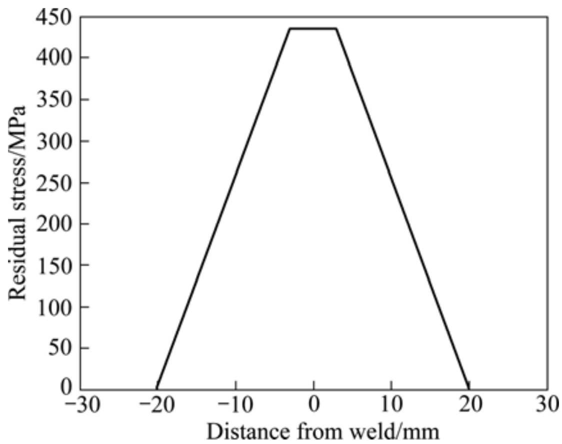

Fig. 8 SINTAP trapezoidal distribution of longitudinal residual stresses profile of butt-welded plate of 7075-T7351 aluminium alloy

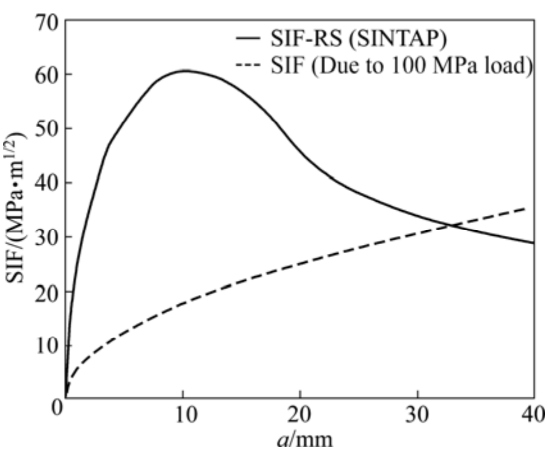

Fig. 9 SIF due to residual stress and mechanical load for butt-welded plate of 7075-T7351 aluminium alloy

toughness of the material for damage tolerance analysis. Figure 10 shows the super-imposed SIF due to residual stress and mechanical load for a butt-welded plate of 7075-T7351 aluminium alloy through SINTAP. Figure 11 shows the normalized residual SIF for a butt-welded plate of 7075-T7351 aluminium alloy. Figure 12 shows a typical failure assessment diagram. For the specified crack size and stress level σ_A, the corresponding stress intensity factor K_A can be found for the cracked configuration. If the point A (K_A, $\sigma_{NC}^{\infty}/\sigma_0$) 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 (F_s) under the specified stress level is defined as: $F_s = \overline{OC}/(\overline{OA})$. Figure 13 shows the failure assessment diagram (FAD) for 7075-T7351 aluminium alloy [10], in which for a particular crack size the values of K_{res} and

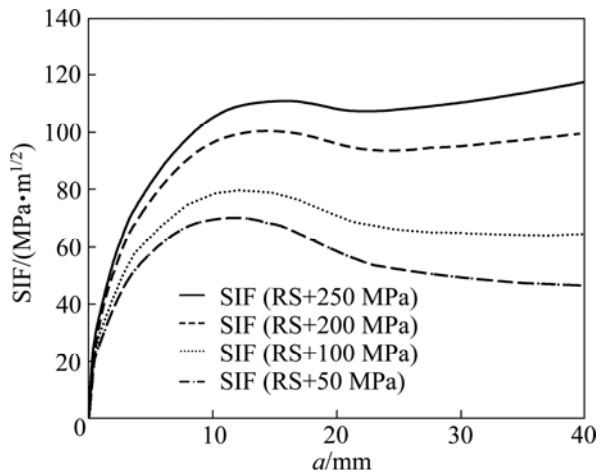

Fig. 10 Super-imposed SIF due to residual stress and mechanical load for butt-welded plate of 7075-T7351 aluminium alloy through SINTAP

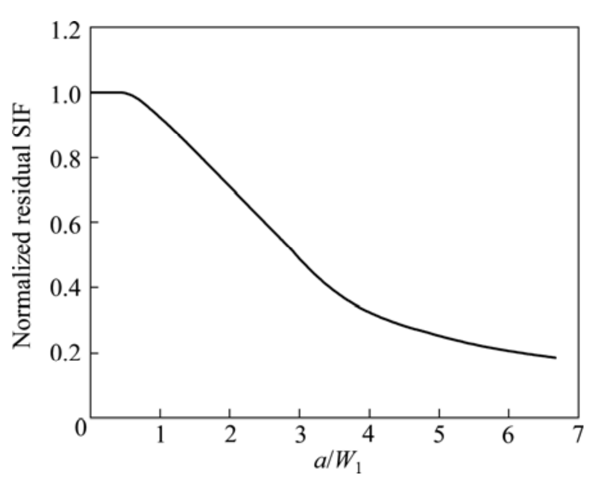

Fig. 11 Normalized residual SIF for butt-welded plate of 7075-T7351 aluminium alloy

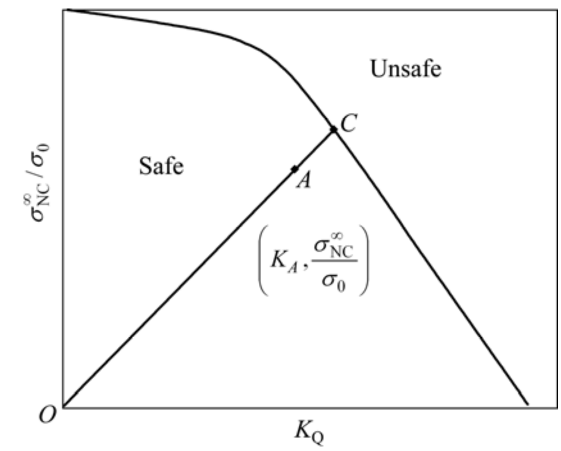

Fig. 12 Typical failure assessment diagram ($K_Q=\sigma_{NC}^{\infty}\sqrt{\pi C}$), a parameter; σ_{NC}^{∞} is fracture strength of wide specimen)

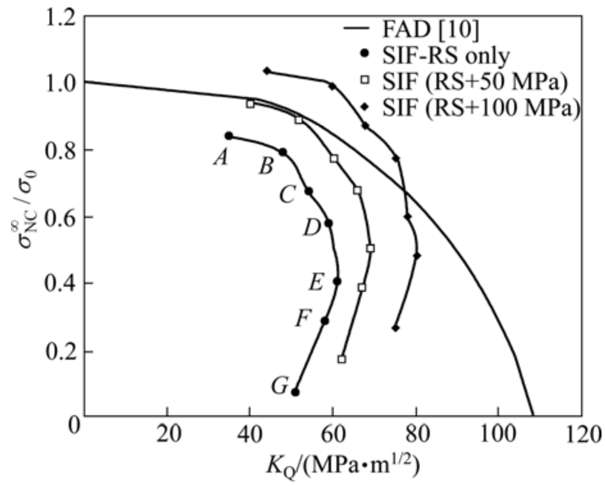

Fig. 13 Failure assessment diagram for 7075-T7351 aluminium alloy plate including weld induced residual stress

σ_{res}/σ_0 are plotted. In SINTAP procedure the residual stresses are available up to yield zone only. Away from yield zone it is zero. Hence, the points A to G are taken in such a way that the half crack length to be within yield zone (see Fig. 8). Tables 1 and 2 show the fracture parameters of 7075-T7351 aluminium alloy without or with mechanical loading. The points A to G are inside the curve. So it is clear that all the points are safe for service with the existing residual stress. When a load of 50 MPa is applied along with the existing residual stress, the points A and B move exactly on the curve. This indicates that 50 MPa load for this corresponding crack length is not safe. All the other points are safe. Also when a load of 100 MPa is applied along with the existing residual stress, the points A, B, C and D are moved out of the curve. This indicates that 100 MPa 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.

Table 1 Fracture parameters of 7075-T7351 aluminium alloy

Point	From Fig. 13				From Figs. 8 and 9			
	$\sigma_{NC}^{\infty}/\sigma_0$	K_Q/(MPa·m$^{1/2}$)	σ_0/MPa	σ_{NC}^{∞}/MPa	c/mm	σ_{RS}/MPa	K_{res}/(MPa·m$^{1/2}$)	σ_{RS}/σ_0
A	0.95	41.5	517.1	491.2	2.3	435	35	0.84
B	0.90	51.8	517.1	465.4	3.9	410	48	0.79
C	0.85	59.3	517.1	439.5	5.8	350	54	0.68
D	0.80	65.4	517.1	413.7	8.0	300	59	0.58
E	0.75	70.6	517.1	387.8	10.6	210	61	0.41
F	0.70	75.2	517.1	362.0	13.7	150	58	0.29
G	0.65	79.3	517.1	336.1	17.7	40	51	0.08

Table 2 Fracture parameters of 7075-T7351 aluminium alloy with mechanical load (From Fig. 10)

Point	c/mm	Residual stress+Mechanical load 50 MPa			Residual stress+Mechanical load 100 MPa		
		σ_{tot}/MPa	K_{tot}/(MPa·m$^{1/2}$)	σ_{tot}/σ_0	σ_{tot}/MPa	K_{tot}/(MPa·m$^{1/2}$)	σ_{tot}/σ_0
A	2.3	485	40	0.94	535	44	1.03
B	3.9	460	52	0.89	510	60	0.99
C	5.8	400	60	0.77	450	68	0.87
D	8.0	350	66	0.68	400	75	0.77
E	10.6	260	69	0.50	310	78	0.60
F	13.7	200	67	0.39	250	80	0.48
G	17.7	90	62	0.17	140	75	0.27

5 Conclusions

Defect assessment is carried out in butt-welded joint of ASTM A36 steel plates and 7075-T7351 aluminium alloy plates containing transverse through thickness crack using SINTAP procedure and FEA incorporating weld induced residual stresses. For both the above materials the residual stress intensity factor and stress intensity factor for mechanical load are plotted in the same graph. Using this graphical plot, the total SIF can be calculated for any particular crack size. The total SIF can be compared with the fracture toughness of the material for damage tolerance analysis. Also a failure assessment diagram is drawn for welded 7075-T7351 aluminium alloy plates with different crack sizes for as-welded (only RS) and different mechanical load along with the existing weld induced residual stress to show the safe level for a particular crack size and mechanical load.

It is observed that smaller cracks having crack tip in the high tensile residual stress region are more dangerous than larger cracks having crack tip in the stress free region. Also it is possible to decide safe level of the structure for service in the presence of crack and residual stress.

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基于结构完整性评定方法和有限元分析并考虑焊接残余应力的焊接缺陷评估

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摘　要：采用欧共体提出的结构完整性评定方法(SINTAP)与有限元分析(FEA)方法，结合焊接残余应力对存在横向贯穿裂纹的 ASTM A36 钢板和 7075-T7351 铝合金板对接焊接头的缺陷进行评估。由 SINTAP 方法、FEA 或者实验得到焊接产生的纵向残余应力曲线。该残余应力曲线与 SINTAP 方法中得到的梯形残余应力拟合较好。计算了 3 种不同情况下的裂纹长度和残余应力强度因子(SIF)，并与通过有限元分析得到的结果相比较，绘制了残余应力强度因子与裂纹长度的关系曲线。利用该图可以计算包括残余应力和力学载荷的总的 SIF，比较了总的 SIF 与损伤容限分析法得到的材料断裂韧性。绘制了焊接态的、力学载荷的和存在残余应力情况下的不同裂纹尺寸的 7075-T7351 铝合金板的失效评估图，以确定在某特殊裂纹尺寸和力学载荷下的安全水平。

关键词：失效评估图；断裂韧性；应力强度因子；贯穿裂纹；焊接残余应力

(Edited by Xiang-qun LI)