FRACTURE ASSESSMENT OF LASER BEAM WELDED ALUMINIUM PANELS

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ABSTRACT

The weld strength mismatch option of the **S**tructural **Int**egrity **A**ssessment **P**rocedure (SINTAP) has been applied to middle cracked laser beam welded (LBW) large aluminium panels for aerospace applications to predict their maximum tensile load carrying capacities. The material of 2.6 mm thickness was a weldable Al-alloy 6013 T6 and strength undermatched welded panels were tested in as-welded condition. The fracture resistance curves in terms of CTOD δ_5 for the base and weld materials were experimentally generated from small scale standard C(T)50 specimens and used in the SINTAP procedure to assess large structure-like thin-walled welded panels. The SINTAP procedure yielded a conservative prediction of the failure load being 5% lower than the experimental value.

1 INTRODUCTION

Structural integrity assessment procedures are providing techniques that can be used to assess the fitness-for-service (FFS), fitness-for-purpose (FFP) and for failure analysis purposes as well as at the design phases of critical components and welded structures. These procedures have generally been applied to thick section cracked components to provide structural assurance in manufacturing and at the operational phases. The SINTAP procedure [1] was the first structural integrity assessment method which has introduced a comprehensive weld joint assessment route with consideration of weld strength mismatch. If the ratio between the weld and base metal strengths is larger then 10%, the procedure recommends to use the „mismatch level" to take account of beneficial (in the case of overmatching) or detrimental (in the case of undermatching) effects of the weld metal strength on the behaviour of cracked weld metal. However, this procedure has been used so far only for limited cases of thin-walled welded structures. It is of particular interest of this study to conduct a SINTAP analysis of strength undermatched LBW weld joints in aerospace Al-alloys.

2 EXPERIMENTAL PROCEDURE

Middle cracked M(T) panels with a width of 2W=760mm and 2.6mm thickness (Fig.1) manufactured from the Al-alloy 6013 T6 were subjected to quasi-static uniaxial tensile loading in order to determine their residual strength due to the existence of a crack. The cross-section of the LBW joint is shown in Fig.2. The initial crack length-to-width ratio (a_0/W) was 0.33 and the crack of the LBW panel was located along the weld centreline. In order to avoid any out-of-plane displacements, that are likely to occur during tensile tests of thin sheets with relatively long cracks, anti-buckling guides made of stiff steel beams were used. This way, a pure Mode I type loading of panels could be ensured. The results of both base material and LBW panels were used for the validation of the SINTAP procedure predictions.

3 THE SINTAP PROCEDURE

The SINTAP procedure offers two complementary assessment routes of cracked components: Failure Assessment Diagram (FAD) and Crack Driving Force (CDF). Both routes give same results since the failure assessment lines are based on the same plasticity correction function. Within this paper, only the CDF route has been used and equations of the mismatch option for materials with continuous yielding (without Lüders plateau) will be presented since the Al-alloy considered shows this type of deformation. The principle of the CDF approach, which was used for the present case, is shown in Fig. 3. The general CDF expressions in terms of the J-integral and crack tip opening displacement (CTOD), δ, are:

$$J = J_e \times \left[f(L_r) \right]^{-2}, \qquad \delta = \delta_e \times \left[f(L_r) \right]^{-2} \tag{1}$$

with elastic parts of the J-integral, J_e, and CTOD, δ_e:

$$J_e = \frac{K^2}{E'}, \qquad \delta_e = \frac{K^2}{m\sigma_Y E'} \tag{2}$$

K denotes the elastic stress intensity factor, $L_r = F/F_Y$ is the ratio of externally applied load, F, and the yield load of the cracked component, F_Y, which is generally a function of the material's yield strength, σ_Y, and component/weld geometry. The parameter *m* (*m*=1 for plane stress and *m*=2 for plane strain) is considered a constraint parameter, E'=E for plane stress and $E'=E/(1-\nu^2)$ for plane strain (E=Young's modulus, ν=Poisson's ratio). For a weld strength mismatched configuration the yield load also depends on the yield strength of the weld material and the parameter $\psi=(W-a)/H$ which defines the ratio of the uncracked ligament length, W-a, and the weld width, 2H. The plasticity correction function, $f(L_r)$, is defined in the mismatch option of the SINTAP procedure as follows:

$$f(L_r) = \left[1 + \frac{1}{2} L_r \right]^{-1/2} \times \left[0.3 + 0.7 \exp(-\mu_M L_r^6) \right] \qquad for \qquad 0 \le L_r \le 1 \tag{3}$$

$$f(L_r) = f(L_r = 1) \times L_r^{(N_M - 1)/2N_M} \qquad for \qquad 1 < L_r \le L_r^{\max} \tag{4}$$

where

$$\mu_M = \frac{M-1}{(F_{YM}/F_{YB} - 1)/\mu_W + (M - F_{YM}/F_{YB})/\mu_B} < 0.6 \qquad else \qquad \mu_M = 0.6 \tag{5}$$

$$\mu_B = 0.001 \frac{E_B}{\sigma_{YB}} < 0.6 \qquad else \qquad \mu_B = 0.6 \tag{6}$$

$$\mu_W = 0.001 \frac{E_W}{\sigma_{YW}} < 0.6 \qquad else \qquad \mu_W = 0.6 \tag{7}$$

$$L_r^{\max} = \frac{1}{2}\left(1 + \frac{0.3}{0.3 - N_M} \right) \tag{8}$$

$M=\sigma_{YW}/\sigma_{YB}$ is the mismatch factor defining the ratio of weld (σ_{YW}) to base (σ_{YB}) metal yield strengths. E_B and E_W are the Young's moduli of base and weld materials, respectively. Strain hardening exponents for mismatch, N_M, base, N_B, and weld materials, N_W, are defined as follows:

$$N_M = \frac{M-1}{(F_{YM}/F_{YB} - 1)/N_W + (M - F_{YM}/F_{YB})/N_B} \tag{9}$$

$$N_B = 0.3\left(1 - \frac{\sigma_{YB}}{\sigma_{UTS,B}}\right) \tag{10}$$

$$N_W = 0.3\left(1 - \frac{\sigma_{YW}}{\sigma_{UTS,W}}\right) \tag{11}$$

σ_{UTS} denotes the ultimate tensile strengths of base (subscript B) and weld (subscript W) materials. F_{YM} and F_{YB} are the yield load solutions for the mismatch and base material plates, respectively, and their definitions for a weld strength undermatched M(T) panel will be given in the subsequent section.

The application of the SINTAP procedure to predict the failure load of the LBW panel requires materials as well as geometry related input parameters. The material parameters are tensile (yield and ultimate) strengths of both weld and base materials and the fracture resistance property (R-curve) of the region where the crack is located. Geometry related input parameters are the Mode I elastic stress intensity factor, K_I, and the mismatch yield load, F_{YM}, of the component to be assessed. The material properties were obtained experimentally, whereas the geometry related input parameters for an M(T) panel are available in closed form solutions in the SINTAP compendium [1].

4 SINTAP INPUT DATA

Material related input data (hardness, tensile and fracture toughness)

The Vickers hardness profile is shown in Fig. 4 to demonstrate the strength undermatching nature of the weld joint. Investigations with the optical microscope revealed that the transition zone (heat affected zone) from weld to base metal does not show significant microstructural changes. However, lower hardness than that of the base material indicates the loss of strengthening particles in this transition zone due to the weld thermal cycle. The hardness information given above serves only for a better understanding of the weld features and not as a procedural input for the SINTAP assessment.

Tensile properties of narrow weld area were determined from testing of micro-flat tensile specimens (0.5mm thick, 1.5mm wide). These specimens are designed to obtain „intrinsic“ properties of small zones which need to be used as input parameters. The engineering stress-strain curves together with geometrical dimensions of these specimens are shown in Fig.5. As expected from the hardness profile, the weld material shows very low strength values. The strength mismatch factor, M, defined as the ratio of weld metal yield strength, σ_{YW}, to that of the base metal, σ_{YB}, is for this particular case $M=\sigma_{YW}/\sigma_{YB}=0.42$. The case of $M>1$ is referred to as overmatching, whereas $M<1$ to as undermatching as in the present study.

A local and direct measurement of the crack tip opening displacement in terms of CTOD δ_5 by means of a special clip [2] was used to determine the fracture resistance of the weld and base materials using standard C(T) specimens (W=50mm, B=2.6mm). The technique consists of measuring the relative displacement between two gauge points at a distance of 5mm located directly across the fatigue crack tip. The R-curves in terms of CTOD δ_5 using multiple specimens technique are shown in Fig.6. The weld material shows a lower R-curve compared to the base material. These R-curves obtained from small scale specimens were used to predict the failure load of the large thin-walled M(T)760 panels containing laser beam welds.

Component related input data

The stress intensity factor solution for an M(T) panel is available in closed form [3] as :

$$K_I = \frac{F}{2WB}\sqrt{\pi a} \times \sqrt{Sec\frac{\pi a}{2W}} \qquad (12)$$

The yield load solution for an undermatched M(T) plate with a crack located in the center of the weld is defined as [4]:

$$\frac{F_{YM}}{F_{YB}} = M\left[\frac{2}{\sqrt{3}} - \left(\frac{2-\sqrt{3}}{\sqrt{3}}\right)\frac{1.43}{\psi}\right] \qquad for \qquad \psi > 1.43 \qquad (13)$$

where ψ=(W-a)/H is the ratio of the ligament size, W-a, and the weld width, 2H. The yield load of a homogeneous middle cracked base plate, F_{YB}, under plane stress condition is given by:

$$F_{YB} = 2B(W - a)\sigma_Y . \qquad (14)$$

5 APPLICATION OF THE SINTAP PROCEDURE

Using all input data described in the previous section the SINTAP analysis level 2 (mismatch option) was applied to the thin-walled LBW cracked plate. Fig.7 shows the comparison of the load-deformation behaviour between the SINTAP prediction and the experimental results. The maximum load carrying capacity, which coincides with the failure load of the LBW panel in this case, is predicted by the SINTAP procedure conservatively being 5% lower than the experimental value.

The diagram also shows the effect of the variation of the parameter *m* in eqn (2), which can be interpreted as a constraint parameter, on the load vs. deformation curve. In the case of strong undermatching weld, the plastic zone in front of the crack tip is entirely confined to the weld metal. Due to the very narrow weld (2H is small), the softer weld metal cannot freely deform in thickness direction, thus, exhibiting an out-of-plane constraint. The stress state within the weld, therefore, tends to be close to the plane strain condition although the overall thickness of the structure is considered thin. Also the determination of the mismatch yield load for an undermatched butt weld needs to consider a plane strain condition for large ψ=(W-a)/H ratio (i.e. long ligament, W-a, and small weld width, 2H). For large ψ the yield load solution approaches a plateau with a value equals the yield load of an all-weld-metal cracked plate under plane strain condition [4] (see also eqn (13)). This fact justifies the use of *m*=2 in eqn (2) when estimating the CTOD δ_5 crack driving force for thin-walled highly strength undermatched laser beam weld joints for the defect assessment using the SINTAP procedure.

The weld width, 2H, appears only (through the parameter ψ=(W-a)/H) in the yield load solution throughout the entire SINTAP analysis. Since the uncracked ligament size is relatively large resulting in the very large ψ, the influence of 2H on the mismatch yield load in eqn (13) is negligibly small. Thus, the weld width, 2H, is an insensitive parameter as long as ψ remains large. However, the structural significance of the weld width, 2H, should be taken into account due to the occurence of confined plasticity within the weld zone which increases the crack tip constraint and, hence, reduces the structural stability of the cracked weld joint. The successful application of the SINTAP procedure to the base metal plates as shown in Fig.1 yielded a very good prediction of the residual strength as well as the load-deformation behaviour. The details of these predictions are reported in [5].

6 CONCLUSIONS

The strength mismatch option of the SINTAP structural integrity assessment procedure has been applied to predict load carrying capacity of middle cracked thin-walled Al-panels containing strength undermatched laser beam welds. The comparison between predicted load-deformation behaviour and the experimental results gives a very good agreement (with 5% conservatism in terms of maximum load). The prediction was based on the assumption of a plane strain condition in the weld joint due to the occurence of confined plasticity in the welded thin-walled structure.

7 REFERENCES

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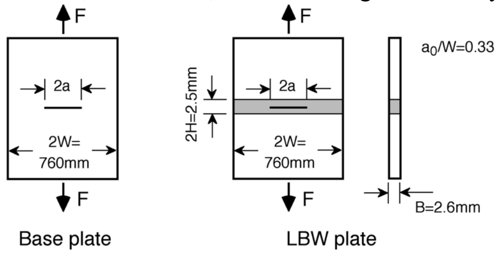

Fig.1: Configurations of the middle cracked M(T) base material and LBW specimens tested.

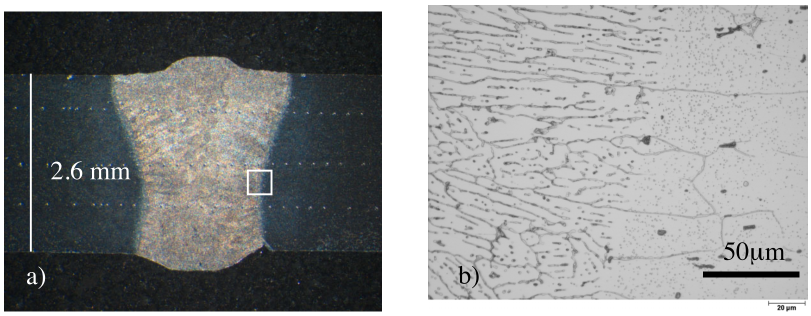

Fig. 2: a) Optical micrograph of the LBW joint. The square indicates the location of the interface shown at higher magnification in b).

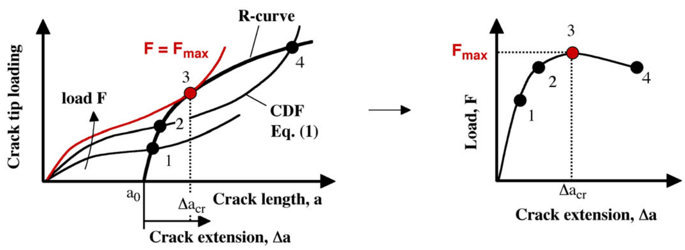

Fig.3: Principles of the CDF approach in the SINTAP procedure.

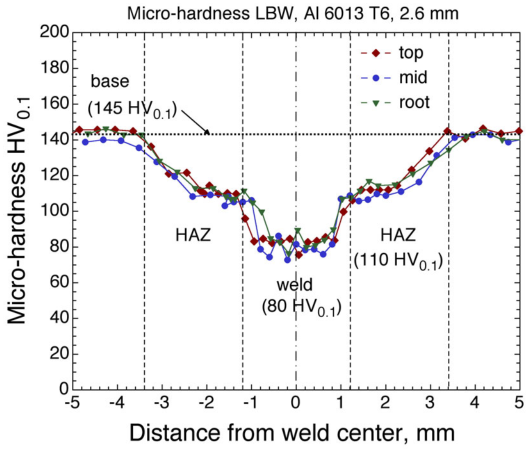

Fig.4: Micro-hardness profile taken across the weld along three different paths.

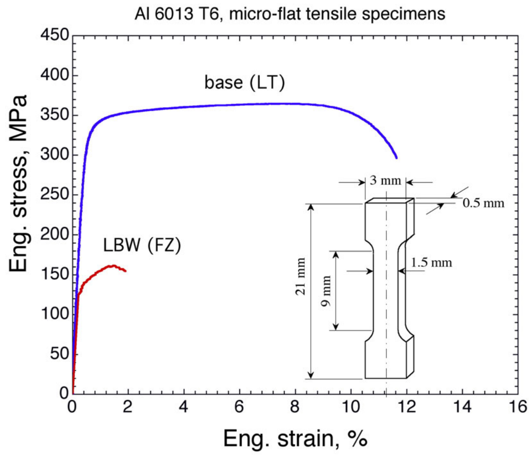

Fig.5: Engineering stress-strain curves obtained from micro-flat tensile specimens for base and fusion zone.

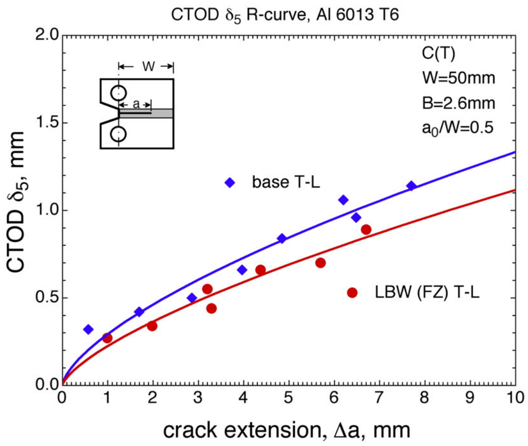

Fig.6: CTOD δ_5 R-curves of base and weld (LBW) materials obtained from C(T)50 specimens (multi specimens technique).

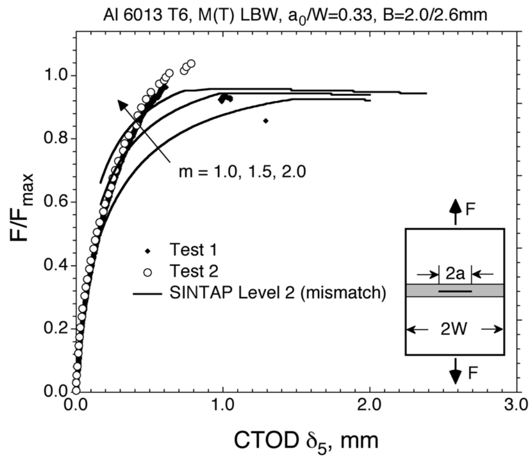

Fig.7: Comparison of the SINTAP prediction of the maximum load carrying capacity with the experimental results.