Effect of Plastic Deformation on Compliance Curve Based Crack Closure Measurement

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Abstract. Fatigue crack growth depends heavily on near tip stress-strain behavior controlled by many micromechanical and microstructural factors. Crack closure is widely used to rationalize crack growth behaviour under complex loading conditions. Reliable crack closure measurement is essential for enhanced damage tolerance design and remains a challenge to the industry. This paper focuses on the effect of plastic deformation ahead of a notch/crack on the non-linearity of compliance curves of 6082-T651 aluminium alloy specimens to highlight a potential issue in the conventional compliance curve based crack closure measurement technique. Experimental and numerical simulation results demonstrate that plastic deformation ahead of the notch will introduce non-linear stress-strain behavior in the absence of crack closure. It is proposed that the effect of crack tip plasticity on the non-linearity of the compliance curve be separated to obtain reliable crack closure measurement.

Introduction

It is generally accepted that crack growth driving force can be influenced by both intrinsic and extrinsic factors occurring around the crack tip. Intrinsic factors include deformation heterogeneity, crack tip plasticity in relation to grain size, secondary phase particle desperation and/or dislocation cell size. Extrinsic factor depends on crack tip shielding processes (e.g. crack closure) which may or may not depend on the microstructure [1]. Fatigue crack closure is the phenomenon which is widely considered to cause reduction in the fatigue crack growth driving force due to the premature contact of crack faces at positive load levels during cyclic loading. The concept of crack closure has been successfully used to rationalize various crack growth behaviours such as overload retardation, underload acceleration, and load sequence effect under variable amplitude loading [2-5]. It is evident that separation of the intrinsic and extrinsic behaviour in terms of isolating the crack closure effect from the crack tip plasticity effect can optimise the crack growth life prediction model. The challenge lies in the reliable measurement of crack closure as the closure process is continuous and dependent on many factors. Fig.1 illustrates a widely used method for crack closure measurement where the crack closure point is identified as the transition point of the linear part (solid line) representing a fully open crack and the non-linear part (dotted line) representing a gradually closed crack. It is however worth noting that reliable identification of the real crack closure point is challenging due to the complex process of crack closure. The non-linearity of the compliance curve can be attributed to other factors in addition to the crack closure. It is therefore not surprising that noticeable discrepancies in the results obtained using this method were reported [6-7]. This paper focuses on the effect of crack-tip plasticity on the non-linearity of compliance curves of 6082-T651 aluminium alloy specimens through experimental and numerical simulation studies. A potential

issue in the conventional compliance curve based crack closure measurement technique has been highlighted to improve future crack closure measurement.
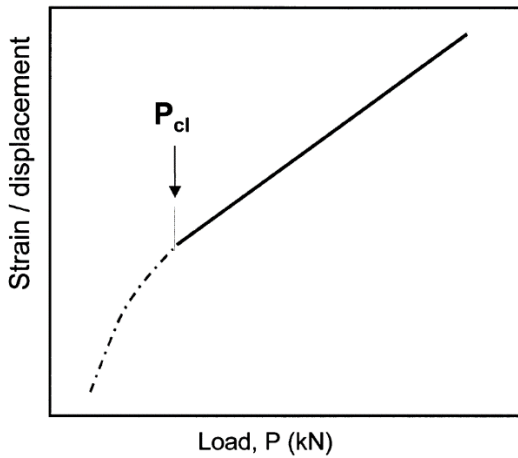

Fig.1   Schematic illustration of compliance curve based crack closure measurement.

Materials, Test Set-up, and Finite Element Mesh

Table 1 shows the chemical compositions of the aluminium alloy (6082A-T651) used for this study. Table 2 shows the mechanical properties of the alloy.

Alloy	Al	Si	Fe	Cu	Mn	Cr	Mg	Zn	Ti
6082A-T651	Bal	0.7-1.3	0.50 max	0.10 max	0.40-1.00	0.25 max	0.06-0.120	0.20 max	0.10 max

Table 1 Chemical compositions of Al 6082A-T651.

Alloy	Young's modulus (GPa)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
6082A-T651	70	295	255	8

Table 2 Mechanical properties of Al 6082A-T651.

(a)   (b)
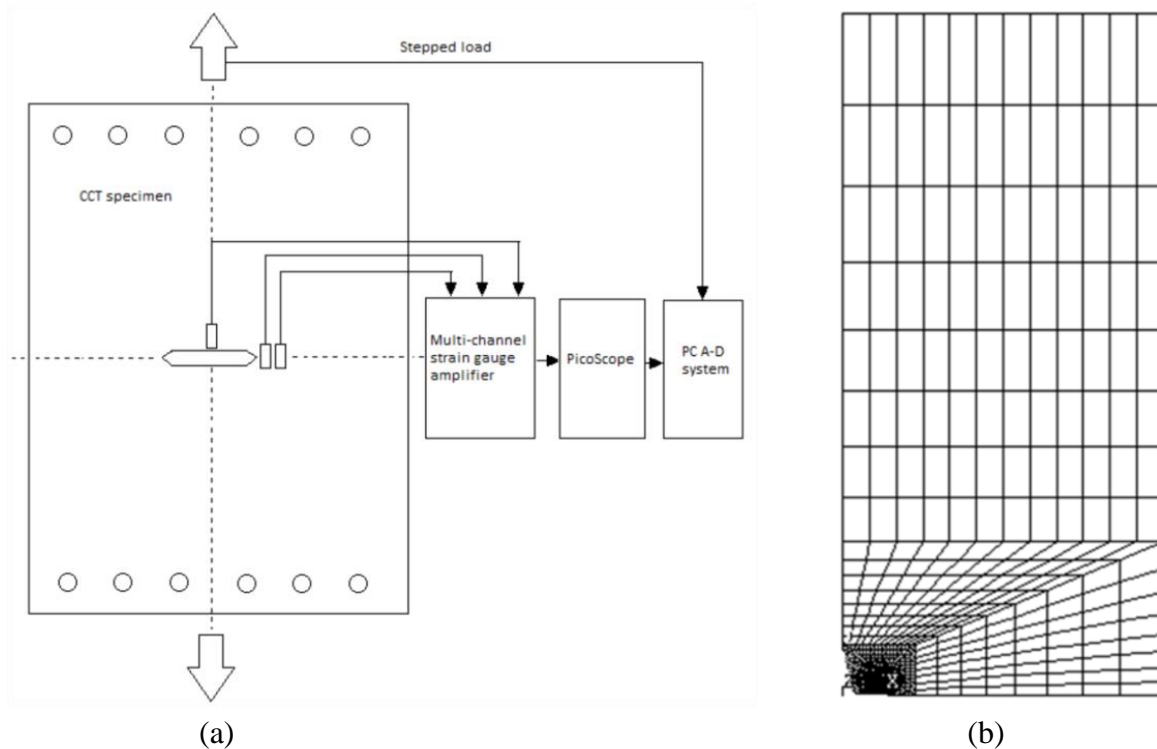
Fig.2   (a) Schematic view of the test set-up, (b) Mesh of the FE model of the quarter specimen.

Fig.2(a) shows the test set-up. Specimens of 150mm width, 400mm gauge length and 1.6mm

thickness were loaded slowly from 0 to 26kN to obtain the compliance curve for a central slot with sharp notches at its ends. Three strain gauges were used to obtain the compliance curves with gauge G1 located 2mm ahead of the notch, G2 located 8mm ahead of the notch, and G3 located right in the middle and above the slot. No fatigue loading was applied to the specimen to ensure that no plastic deformation was left behind the notch. As such, the compliance curve obtained from the three strain gauges shouldn't have the effect of crack closure. Fig.2(b) shows the mesh of the quarter specimen where a dense mesh was used near the notch and coarse mesh is used away from the notch. Mesh density study was carried out and the element size around the notch was selected as 24μm which fulfils the criterion of less than one-tenth of the plastic zone size at the notch as recommended in literature [8-9].

Results and Discussion

Out of the three strain gauges, G1 is the closest one to the notch and chosen to demonstrate the effect of near tip plasticity on compliance curve. Fig.3(a) shows the compliance curve obtained from strain gauge G1 when the specimen is loaded step-by-step from 0 to 26kN. The compliance curve looks straight and is difficult to detect whether there is any non-linearity. The compliance curve in Fig.3(a) is further processed using an offset technique to identify possible transition point [10]. A linear fit was applied to the data of the upper part of the curve. Fig.3(b) shows the offset compliance curve replotted after the original compliance curve data are offset from the straight line from the linear fit. A clear transition point is shown in Fig.3(b) after the potential non-linearity has been amplified using the offset technique, demonstrating the existence of the non-linearity of the compliance curve. The 'transition point' is found at around $6kN$ which could be identified as the closure load using the conventional compliance curve based crack closure measurement method.
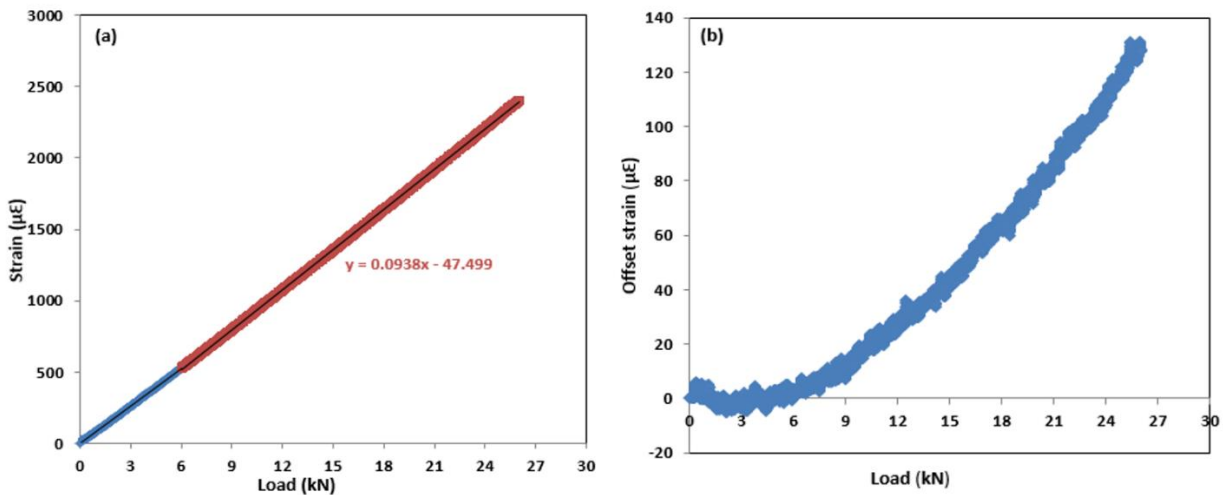

Fig.3   (a) compliance curve from G1 (2mm ahead of the notch), (b) offset compliance curve from G1.

Fig.4 shows the finite element simulation results of the compliance curve obtained from a node 2mm ahead of the notch when the specimen was loaded from 0kN to 19.2kN. Similar to the experimental results from the strain gauge, Fig.4(a) is the original compliance curve difficult to detect the transition point. Fig.4(b) is the offset compliance curve processed in the same way as for Fig.3(b). A transition point can be seen clearly at around 6kN in Fig.4(b), which is consistent with the experimental result in Fig.3(b). Similar observations have been made for other strain gauges and nodal positions. The results closer to the notch, however, show stronger non-linearity of the compliance curve.

It is clear non-linearity exists on the compliance curves obtained through strain gauge measurement and finite element simulation. It is however worth noting that no plastic deformation has been left behind the notch in the current study. As such, the non-linearity is not related to the plasticity-induced crack closure. It is directly linked to the plastic deformation ahead of the notch or crack tip for a fatigue crack. The conventional compliance based crack closure measurement method could therefore identify a false crack closure, causing problems in crack growth life prediction.
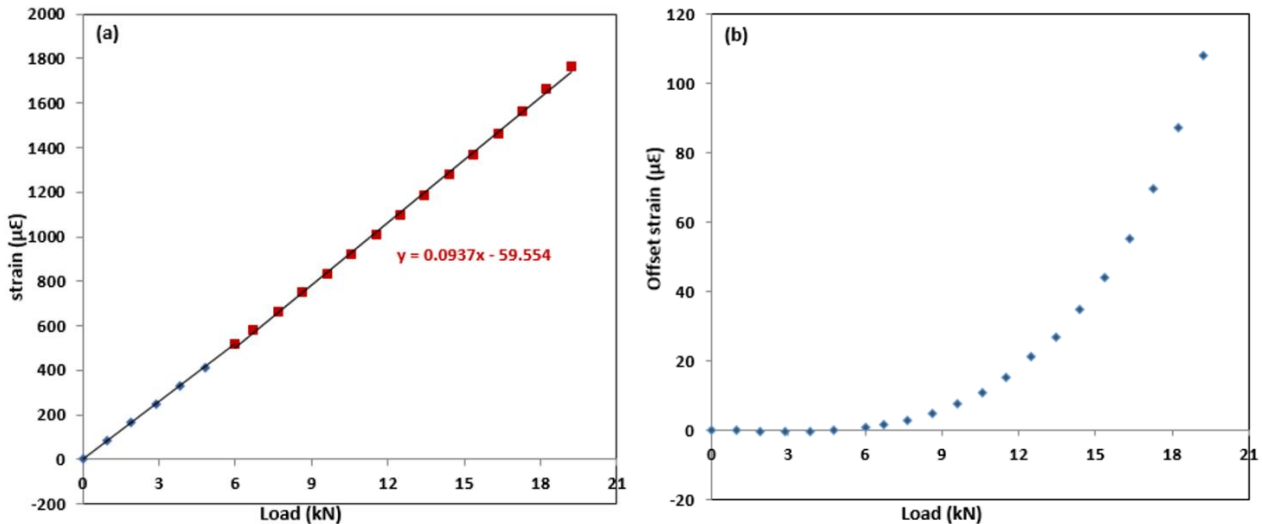

Fig.4 (a) compliance curve from the node 2mm ahead of the notch, (b) offset compliance curve from the node 2mm ahead of the notch.

Conclusions

Both the experimental and finite element simulation results demonstrate that the plastic deformation ahead of the notch will introduce non-linearity of the compliance curve, which may lead to the identification of a false crack closure when the popular conventional compliance curve based crack closure measurement method is used. The effect of crack tip plasticity on the non-linearity of the compliance curve should be separated from that of crack closure to obtain reliable crack closure measurement.

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