Through-Thickness Fracture Analysis of a Ductile Steel by Observing 3D Surface Displacements with Consideration of Constraint Effects

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Abstract: The development of a fracture resistance (J–R) curve requires the accurate measurement of J-integral as a function of crack extension (Δa). This can be achieved by following different procedures like unloading compliance (UC), normalization method (NM) and direct-current potential drop (DCPD) described in ASTM E1820, ISO12135 for the determination of crack length and fracture toughness. However, these procedures require standard specimens, displacement clip gauges, and electrical circuits to infer crack lengths. This study investigates the effect of constraint on crack tunnelling and the signature it leaves on the specimen surface. The relationship between crack front shape and out-of-plane displacements δ_z on the specimen surface is explored. The experiments were conducted in displacement control at 0.5mm/min on compact tension (CT) and single-edge notch bend (SENB) specimens made from 304L steel with a/W ratios varying between 0.3 and 0.6 and thicknesses ranging between 2 to 25mm, recorded using 3D digital imaging correlation (DIC) at 1Hz. The normalisation method was applied to determine the J-R curve for comparison purposes. The results have shown that out-of-plane displacements are sensitive to changes in both in-plane and out-of-plane constraints. The out-of-plane displacements ahead of the crack tip on the surface are the footprint of the internal crack front shape, and they switch from negative to positive at a particular ligament length, which indicates the magnitude of constraint and plastic zone expansion. Another way to determine the fracture initiation could be to observe the slope and location of maximum inward contraction. The rate of inward contraction ($d\delta_z/d_J$) suddenly changes at the moment when the physical crack starts to tear, and the maximum δ_z location begins to translate forward in the x-direction.

Introduction: The flaws and cracks within a material and structure play a critical role in characterizing their strength and integrity. Fracture toughness is a fundamental material property that quantifies a material's resistance to crack initiation and propagation. The accurate computation of fracture toughness is critical in predicting failure [1]. The constraint level refers to the influence of surrounding material on the deformation and stress at the crack tip, which affects the fracture toughness values. The plastic constraint is divided into in-plane and out-of-plane directions, and usually, each of them would be treated separately. This separate treatment of constraints adds significant complexity to the engineering structural integrity analyses. J. Yang et. al. [2] demonstrated that the out-of-plane constraint effect is related to the in-plane constraint effect and there exists an interaction between them. Their combined effect alters the stress state at the crack-tip and make the crack tunnel when it advances. So, it is better to deal with them collectively by developing a unified constraint parameter which is sensitive to both of them simultaneously. Currently, the standards for the determination of fracture toughness of ductile metals primarily deal with the calculation of fracture parameters based only on in-plane displacements of the tested specimens [3]. Actually, fracture is a three-dimensional problem, and with the advancement of DIC technology, the 3D displacement measurement is available.

In a couple of studies [3,4] conducted previously, the surface displacements have already been used to determine fracture initiation points of ductile materials, but the crack extension and CTOD-R curves were determined using a normalisation method. The UC, NM and DCPD methods [5,6] infer the average crack length rather than gauging the actual curved crack front of the specimens. In this study, we looked at the crack front shape and constraint effect on fracture toughness variation by observing the surface displacement trends, especially the δ_z which acts as a surface footprint of the internal constraint changes. The experimental testing with DIC and numerical simulations using ABAQUS are used to perform a parametric study to observe and quantify these relationships.

Methodology: The CT and SENB specimens were wire eroded on EDM from a 304L steel plate, such that the crack propagation direction was kept perpendicular to the rolling direction in all the specimens. The specimens with different thicknesses were then fatigue pre-cracked to different a/W ratios. The specimens were tested in monotonic loading, and the mechanical tests were recorded from both front and back to make sure we have data from both surfaces in case an uneven crack front is observed on some thinner specimens. Fig. 1 shows the experimental setup and one fractured CT specimen (ID: S1I1) with B=25mm and a/W=0.611.

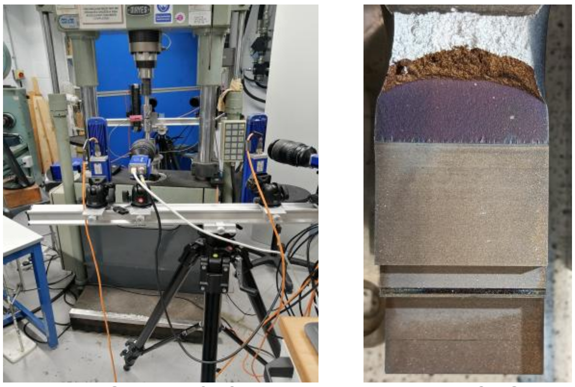

Fig. 1: Experimental Setup (left) & Heat Tinted Fractured CT Specimen (right)

The applied load (P) and the load-line displacement (LLD) were discretely monitored jointly with the 3D surface displacements of the lateral surface of the specimens tested, obtaining a set of load–displacement data for each recording stage. The load-displacement data, along with the initial and final crack length measurements obtained from fractured specimens after heat tinting, were used to get J-R curves from the normalisation method.

Results & Discussion: The J-R curve from the normalisation method is shown in Fig. 2, which gives the initiation toughness of 832 kJm^2. The initiation toughness (J_Q) decreased with an increase in specimen thickness and a/W ratio. The max. $\boldsymbol{\delta_z}$ near the crack tip, also followed the same trend as J_Q, which represents the $\boldsymbol{\delta_z}$ is sensitive to both in-plane and out-of-plane constraints and potentially can act as a unified constraint parameter (UCP) for the large-scale yielding (LSY) condition. The curved crack front shape, because of different constraint levels at the surface and mid-section of the specimen, was correlated to the $\boldsymbol{\delta_z}$ distribution ahead of the crack-tip and was observed to show quite a linear relationship, as shown in Fig. 2.

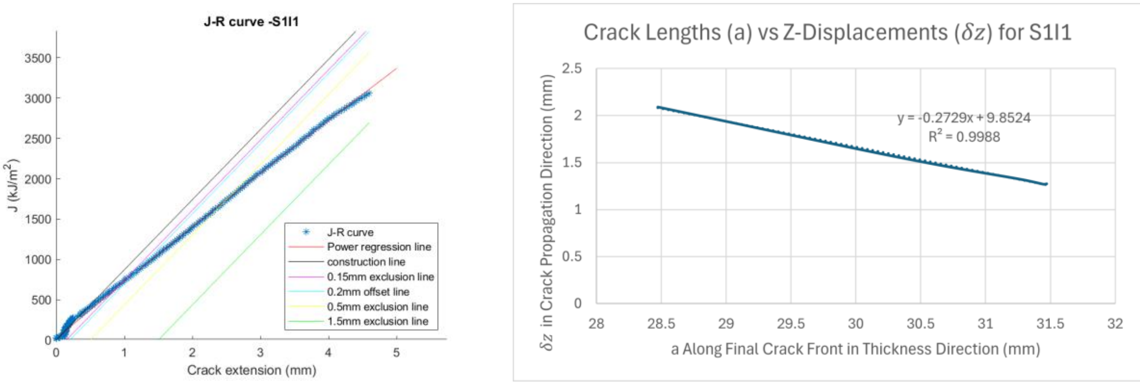

Fig. 2: J-R Curve of CT Specimen (left) & Crack Front Shape and δ_z Correlation (right)

Conclusions & Future Work: The results indicate that the z-displacement distribution can reveal a lot of information about the fracture process. Especially, it can be used to directly determine the crack front shape and consequently the crack lengths and constraint level within the same specimen and across various specimens with different B and a/W. Further analysis will be done to explore the possibility of developing a UCP, plastic zone size (PZS) estimation and development of J-R curve based on $\boldsymbol{\delta_z}$ trends.

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