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Ductile Fracture Simulation of Aluminum 6061-T6 Thin Sheet

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Abstract— Fracture toughness of thin aluminum sheet is of great intense in numerous areas of industrial fields especially in aerospace industry. Thus, this work aims to simulate the ductile fracture of aluminum 6061-T6 thin sheets which are widely used in many industrial and aerospace applications. Finite element analysis technique is implemented to simulate compact tension test specimen to reveal the fracture properties of thin sheets aluminum alloy 6061-T6. The finite element model carried out for compact tension specimen of thin sheets aluminum alloy 6061-T6 of 1 and 1.6 mm thickness to measure energy release rate (GIC). The test is applied at room temperature. The model measured the energy release rate (GIC) successfully and was acceptable considerably. The model showed that thickness effect is small as the specimen is a plan stress state.

Index Terms— Finite element, alloy, mesh, energy release rate.

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1. INTRODUCTION

Thin aluminum sheets are very important for a many of applications such as application in aerospace, aircraft, marine and shipbuilding industry [1]. The fracture toughness of thin aluminum sheet is higher than those of thicker thickness in (mode I), therefore it has a great variety of applications. Fracture toughness of thin aluminum sheets are difficult to measure because the specimen ends tend to buckle and wrinkling during the test. Whereas, the large size sheet distinguished by large deformation zone near crack tip.

Shinde et al. [1] measured fracture toughness of aluminum alloy 6061-T6 of different thickness. They used a modified compact tension test specimen with different un cracked ligament of 1 and 1.6 mm thickness. A numeral finite element simulation was performed using (ANSYS) to simulate the compact tension test specimen. It is established that the fracture toughness or surfaced release energy (G_{IC}) effect is small with thickness when un-cracked ligament. The calculated J- integral using finite element is compared with the experimental measured surfaces release energy and the results were in good agreement and acceptable.

Mohammed [2] measured energy release rate of thin aluminum sheet of 1.2 mm using essential work of fracture method (EWF). It was also a trial to extract a numerical model to predict the EWF properties of ductile fracture using finite element analysis. This study focused on measuring the two energies for a material of strain hardening using plan stress state for the problems. It is concluded that it is possible to measure the surface release energy using the separation energy method (EWF) and the extracted model implemented acceptable results.

Pardon et al [3, 4] investigated thickness effect on fracture toughness of ductile fracture of thin aluminum sheet of different thickness. It is concluded that fracture toughness measured based on plan stress state over double edge notch is independent on thickness.

Derpenski and Seweryn [5] studied the ductile fracture criteria in aluminum alloy, numerically. They investigated the stress and strain of varying crack tip radii and carried out the calculation using finite element method. They validated their model using their work in [6]. Many works [7-12] studied numerically and experimentally the fracture toughness in ductile material to describe deeply the state of fracture and effect of thickness of thin strips.

The main goal of the present study is to measure numerically the fracture toughness of ductile fracture in thin aluminum sheet. Moreover, this work investigates the effect of sheet thickness on the fracture toughness which is very important and dominant fracture property. Also, it is aimed to relate the linear elastic j-integral with plastic fracture process zone.

2. FINITE ELEMENT ANALYSIS

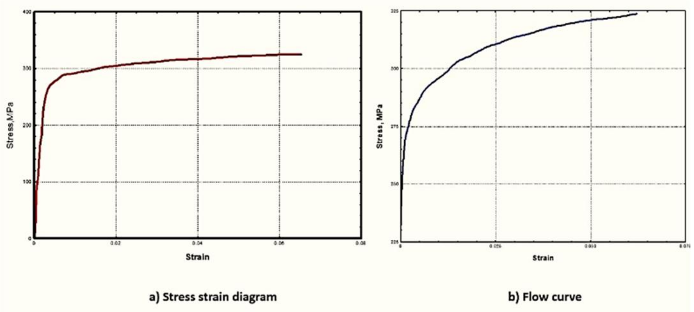
Finite element method used elastic-plastic deformation model for a material of strain hardening. Fig. (1-a) shows stress strain curve of aluminum alloy 6061-T6 obtained from simple tension test of standard tensile test specimen [1]. Fig. (2-b) illustrates flow curve extracted from stress strain curve of Fig. (1-a). The constitutive equations of the proposed model are based on hook law for elastic region and Hollomon's equation. 3-D parts state problems is selected using elastic plastic solid. Thus, the complete model of that solid which subject to compressive uniaxial loading is the following [13]

$$\varepsilon = \varepsilon_e + \varepsilon_p \tag{1}$$

$$\varepsilon_e = {}^{\sigma}/_{E} \tag{2}$$

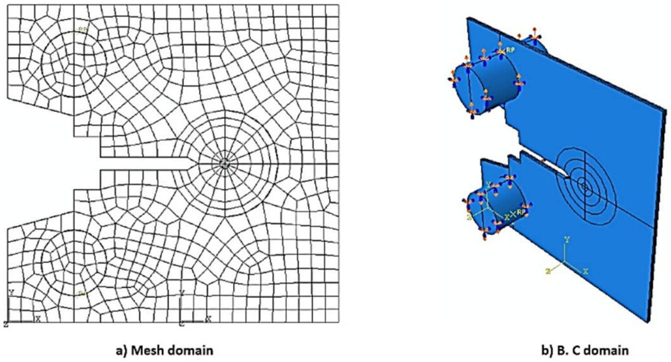
$$\varepsilon_p = \langle \frac{\sigma}{K_y} \rangle^n \tag{3}$$

where (n) is, the material hardening coefficient, K_y shear yield stress. The finite element model is build up using 1036 elements of 3-D stress plan strain of C3D8R types, this type is preferred because it provides accurate results for the meshes and it can handles complicated and irregular shapes accurately [13]. The mesh domain is shown in Fig. 2 b. The crack tip region are divided to make a dense of refinement mesh using swept meshing technique [14, 15]. This type of element has stress stiffening, large strain capabilities, creep, plasticity and large deflection. The model applies the load as controlled displacement over the loading pin as shown in the boundary condition domain in Fig. (2-b). It gives displacement in (Y) direction but displacement is fixed in the other two direction. The value of given displacement is selected as 0.8 mm according to the load line displacement curve in reference [1]. Friction at the interfaces of load pins and specimen was defined as a pair of contact body of constant friction coefficient equal to 0.1 with rough contact as shown in the interaction domain in Fig. (3-a). The crack is implemented into the model as seam crack. A seam is a face that is originally closed but can be opened during the analysis. This model is constructed for FEM to estimate the J-integral (J_{IC}), total external, and internal energies. The crack tip singularity is implemented through the model to $1/\sqrt{r}$ of 0.25 with crack direction as shown in crack domain in Fig. (3b). The J-integral is requested for 5 contours over calculation. The J-integral approach model proposed firstly by Rice [16]. Cherepanov [17] confirmed that the approach is independent of path around a crack tip. The J-integral method in fracture mechanics theorem was extracted to include difficulties in evaluation stresses near crack tip in a nonlinear elastic or elastic-plastic solid or material. Rice [16] confirmed that if monotonic loading was considered without unloading, then the J-integral could be used to evaluate the energy release rate of a plastic material the critical value of J-integral J_{IC} in mode I loading can be define at the large scale plastic yielding during crack propagation [18]. The force matrix consists of numerical values of loads and reactions. The unknown is the displacement matrix. It is used to calculate the displacement at the node points. These displacements are subsequently used to calculate stresses and strains at different locations in the model. FEM results can be evaluated using many different methods the stresses or strains at node can be used to obtained contour plots therefore, the distributions can be visualized simply. Understanding the process mechanism can be animated using FE dynamics system.



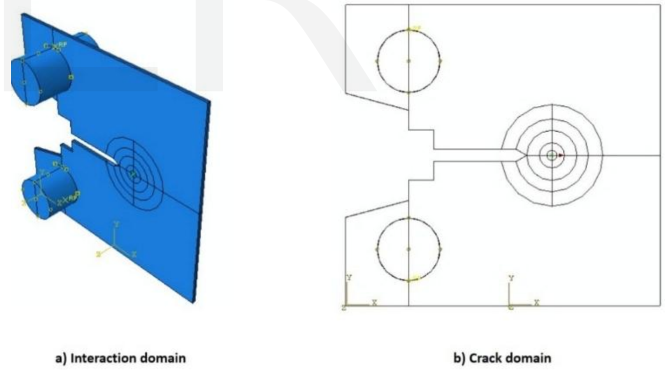
a) Stress strain diagram b) Flow curve

Fig. 1 stress strain relation of aluminum alloy [1]



a) Mesh domain b) B. C domain

Fig. 2 Finite element domain a) mesh, b) boundary conditions



a) Interaction domain b) Crack domain

Fig. 3 Finite element domain a) interaction b) seam crack

3. RESULT AND DISCUSSION;

For aluminum 6061-T6 thin sheet, Fig. 4 shows the predicted release energy G_{IC} for mode I of failure using finite element model. It is observed that for that types of specimen of plan strain state the thickness changes slightly. These results are the same as that obtained in reference [1]. This can be attributed to triaxiality vanished through thickness of the sheet [3, 4, 19, 20]. This curve is average of 5 contours integral, the value was very close to that measured experimentally and ranged around 140 N/m [1]. In plan strain, growth initiates at $K_R = K_{Ic}$, which gives a sufficiently sharp precrack. Even modestly tough materials display some crack growth resistance such that the stress intensity required to advance the crack which increases when steady-state resistance is attained [21]. The Mises stress contour is observed in Fig. 5 for both thicknesses

1 and 1.6 mm. It is clearly shown that there is stress riser near crack tip due to singularities of sharp crack tip. The buckling of the specimen is clearly observed and gives a stress riser, this can be attributed to the formation of material wrinkling in these regions and compressed over lab. Shinde et al [1] modified the compact tension specimen to avoid this buckling which makes increasing in the measured value. Therefore, the proposed model gives higher values than the reported results in reference [1]. Fig. 6 gives a prediction for load line displacement relation for the studied thicknesses. It is observed that there is an increasing difference due to the changing of the subjected area. The elastic plastic behavior of the material gives long and large displacement over strain hardening and consequently the bending moment develops high stress concentration at the crack tip but at the same time high compression stresses are usually generated in the region far away from the crack tip. These compressive stresses may cause the buckling of the thin specimen which should not be allowed so as to facilitate two-dimensional analysis of the specimen. However, the tensile load suppresses the compressive stresses. The predicted displacement contours for tested specimen are shown in Fig. 7, it is clearly observed that flow line of displacement is directly to the loading direction while it is shown in the region of crack tip that the displacement contour is highly high but does not reach maximum values as the material separation makes relive of displacement in that region. The reset of specimen at the back edge is evidence to the occurrence of buckling and wrinkling of the material as the displacement flow though the specimen is not homogeneous because at the back-end contour of the displacement is minimum.

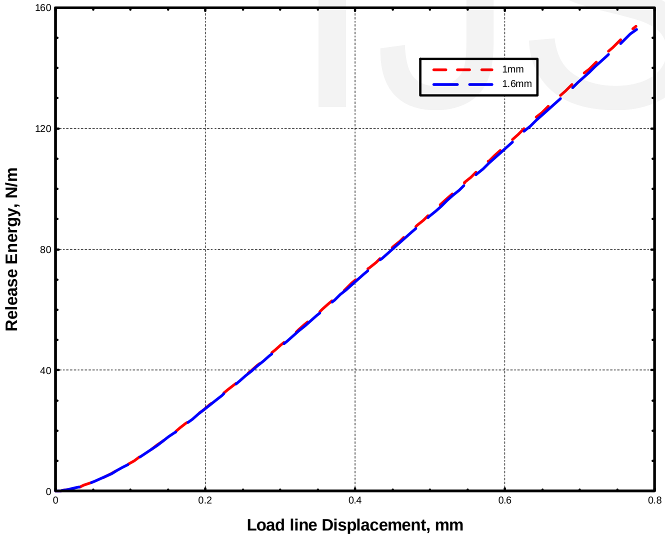
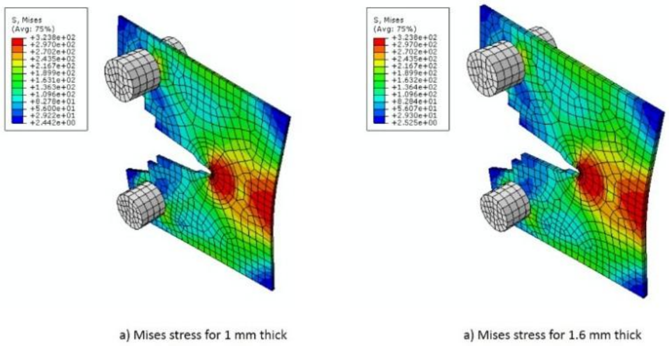


Fig. 4 Predicted J-integral curve using finite element model



a) Mises stress for 1 mm thick a) Mises stress for 1.6 mm thick

Fig. 5 Mises stress contours for aluminum alloy has thickness of a)1 and b) 1.6 mm

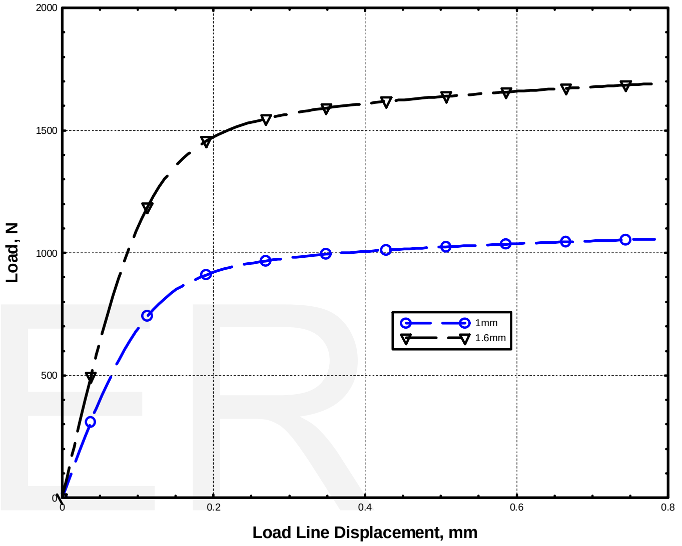
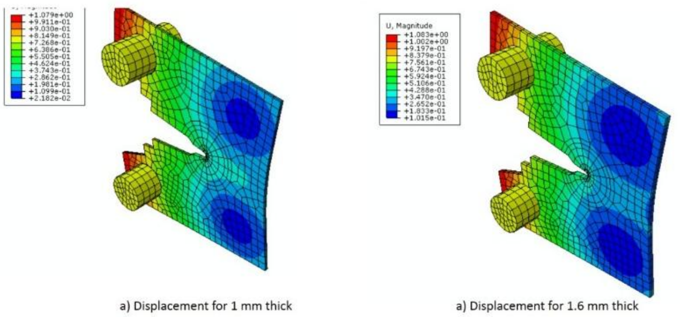


Fig. 6 Predicted relation between load and load line displacement



a) Displacement for 1 mm thick a) Displacement for 1.6 mm thick

Fig. 7 Predicted displacement contours for aluminum alloy has thickness of a)1 and b) 1.6 mm.

4. CONCLUSION;

The linear and nonlinear finite element models are capable to simulate the ductile fracture mechanics. Using J-integral approach model based on seam crack and then implemented into ABAQUS package is a successful tool to achieve the simulation of ductile fracture. The obtained results showed that the fracture toughness of thin aluminum alloy 6061-T6 is predicted well with the proposed finite element model. It is confirmed that for plan strain state, surface release energy is independent on the specimen thickness. In other words, the effect of aluminum sheet thickness on the surface release energy is small.

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