INVESTIGATING THE INFLUENCE OF COMBINED STRESSES ON DYNAMIC CRACK PROPAGATION IN THIN PLATE

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Abstract

This paper presents the influence of cycling impact loading and temperature on dynamic crack propagation in thin plates for two types of aluminum plates (7075, 6061) with aspect ratio (1.5, 2) and plate boundary conditions (CSCS & SFSF). Using analytical solution and numerical analysis, crack lengths have (3, 5) mm and crack angle (45°).

Analytical solution using program (MATLAB-16), the purpose of analytical solution to get the mechanical and thermal stress with time at crack tip in thin aluminum plate, then calculate the dynamic crack propagation under the effect of these stresses.

Numerical analysis using program (ANSYS-18 APDL) based on finite element method, the purpose of numerical analysis to obtain mechanical and thermal stress respect with time at the tip of the crack in thin aluminum plate, then calculate the dynamic crack propagation under the mechanical and thermal stresses effect. The results showed that the dynamic crack propagation increased as the crack length increased, and also found that the dynamic crack propagation decreased as the aspect ratio of the plate increased.

Keywords: Stress, dynamic crack propagation, crack tip, analysis, plate.

I. Introduction

To strengthen the design against fracture it is very important to study the dynamic crack propagation within structures. Certain cycling thermal loading applications occur in automobiles, aircraft wings, boilers and machine structures. During the continued development of crack propagation, the strength of the structure decreases until it becomes low that the service loads cannot be carried any more, Gdoutos, 2005. Temperature changes cause structures to expand or contract, leading to thermal stress. When the plate is heated, each material part undergoes thermal stresses in all directions. Ordinary structural materials expand when heated, hence the...
temperature increase produces a thermal stress, James, 2004. Throughout this work the mechanical and thermal stresses were measured with respect to time at crack tip throughout thin plate and the crack propagation values were determined with respect to time.

There are several researchers researching the stresses of propagation of cracks and cracks under temperature influence. Hoai, and Catherine, 2010. The cyclic temperature evolution on the plate surface induces a cyclic temperature gradient between the outside and the inside of the plate. Mahmut et al., part 1, 2014. In this study, thermal and displacement-controlled loads were subjected to finite-thickness surface cracks. Katarina et al., 2016. Detailed analysis was performed on plates with different length of surface crack geometries and different thermal load. And Shiwei et al., 2017. Proposed thermal stress of a continuous rigid frame bridge, based on bridge temperature gradient was investigated.

The aim of this work is to get the mechanical and thermal stresses with respect to time at crack tip in thin aluminum plate, then measure the dynamic crack propagation under mechanical and thermal stresses effect. Build up a model defined the stresses induced at crack tip in thin plate and crack propagation under cyclic impact loads and temperature effect. The ANSYS18-APDL package will be used to build the model and evaluate the stresses and measure the values of crack propagation in time.

II. Analytical Solution

This study will focus on analyzing thermal stresses with regard to time and impact loading with cycling stresses with respect to time and compute the velocity of crack propagation, using the analytical method, the MATLAB program was used to obtain the analytical solution results.

IIi. Assumptions

A plate is a two-dimensional structural element, one of the dimensions (the plate thickness h) is small relative to the length and width of the dimensions in the plane. The load applied to the plate is perpendicular to the center plane of the plate. This research has some assumptions for getting the equations to solve the plate theory as follows. Varadan and Bhaskar, 1999.

1. The plate material is linear elastic, and it follows the law of Hooke.
2. The plate material is homogeneous and isotropic.
3. The impact load is applied in a perpendicular direction to the center plane of the plate.
4. The plate is stationary.
5. The plate has an effect under different temperatures.

By using a generalized Hertz law, Arace, 2005. Get impacts loading as a function of time:

\[ F(t_i) = \frac{n^2}{5} \left( \frac{\nu^2}{4M} \right)^{3/5} \left[ \sin \frac{\pi t_i \nu}{2946} \right]^{3/2} \]  

(1)
Where:
\[ n = \frac{4\sqrt{R}}{3\pi(K_1 + K_2)}, \quad K_1 = \frac{1 - \nu_1^2}{\pi E_1} \quad \text{and} \quad K_2 = \frac{1 - \nu_2^2}{\pi E_2} \]

\[ M = \frac{1}{m_1} + \frac{1}{m_2} \quad , \quad V = V_1 + V_2 \quad \text{and} \quad \delta_1 = \left( \frac{5V^2}{4Mn} \right)^{2/5} \]

The governing equation of the plate subjected to impact load, \textit{Loke, 2005}.

\[
\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{F(x,y,t)}{D} \quad (2)
\]

Where: \[ D = \frac{E_2 h^3}{12(1 - \nu^2)} \]

Total solution for deflection \[ W = W_h + W_p \]

Levy's solution:

\[ W_h = \sum_{m=1}^{\infty} \left[ C_1 \sinh \alpha_m y + C_2 \cosh \alpha_m y + C_3 \sin \alpha_m y \right] * \sin \alpha_m x \]

Where:
\[ C_1 = C_2 = 0 \quad \text{(symmetric plate)} \]

And

\[ W_p = \frac{F(t_i)A^4}{\pi^4 m^4 D} * \sin \alpha_m x \]

\[ W = \sum_{m=1}^{\infty} \left[ \frac{F(t_i)A^4}{\pi^4 m^4 D} + C_2 \cos \alpha_m y + C_3 \sin \alpha_m y \right] * \sin \alpha_m x \]

Where: \[ \alpha_m = \frac{m\pi}{A} \]

\[
\frac{\partial^2 w}{\partial x^2} = -\sum_{m=1}^{\infty} \left[ \frac{F(t_i)A^4}{\pi^4 m^4 D} + C_2 \cos \alpha_m y + C_3 \sin \alpha_m y \right] * \alpha_m^2 \sin \alpha_m x \quad (3)
\]
\[
\frac{\partial^2 w}{\partial y^2} = \sum_m \left[ a_m^2 C_2 \cosh \alpha_m y + C_3 (\alpha_m^2 y \sinh \alpha_m y + 2 \alpha_m^2 \cosh \alpha_m y) \right] \sin \alpha_m x
\]  
(4)

\[
\frac{\partial^2 w}{\partial x \partial y} = \sum_m \left[ a_m (C_2 \sinh \alpha_m y) + C_3 (\alpha_m^2 y \cosh \alpha_m y + \alpha_m \sinh \alpha_m y) \right] \alpha_m \cos \alpha_m x
\]  
(5)

Boundary Conditions:

1) Consider a plate was clamped edges, \( y=0 \) and \( y=B \), and simply supported opposite edges, \( x=0 \) and \( x=A \)

\[
C_2 = -\frac{F(t_i)A^4}{\pi^4 m^4 D} \cdot \frac{1}{\beta_m \csc \beta_m + \cosh \beta_m}
\]

\[
C_3 = \frac{F(t_i)A^4}{\pi^4 m^4 D} \cdot \frac{1}{\beta_m \csc \beta_m + \cosh \beta_m}
\]

Where: \( \beta_m = \frac{m \pi B}{2A} \)

2) Consider a plate was simply supported, \( x=0 \) and \( x=A \), and free opposite edges, \( y=0 \) and \( y=B \)

\[
C_2 = -\frac{F(t_i)A^4}{\pi^4 m^4 D} \cdot \frac{\beta_m \sinh \beta_m + 3 \cosh \beta_m}{3 \cosh^2 \beta_m - \sinh^2 \beta_m}
\]  
&

\[
C_3 = \frac{F(t_i)A^4}{\pi^4 m^4 D} \cdot \frac{\beta_m \cosh \beta_m + \sinh \beta_m}{3 \beta_m \cosh^2 \beta_m - \beta_m \sinh^2 \beta_m}
\]

The cycling temperature depends on the time, assuming that the temperature rises from room temperature \( 25^\circ C \) to \( 200^\circ C \) and stays at that temperature until a certain stable temperature period returns to room temperature after that, as shown in Fig.1

\[
T_{t_{ch}} = \frac{1}{L} \int_{-L}^{L} \frac{T dt}{2} + \sum_{n=1}^{N} \left[ \frac{1}{L} \int_{-L}^{L} T \cos \left( \frac{n \pi t}{L} \right) dt \cos \left( \frac{n \pi t}{L} \right) \right] + \frac{1}{L} \int_{-L}^{L} T \sin \left( \frac{n \pi t}{L} \right) dt \sin \left( \frac{n \pi t}{L} \right)
\]  
(6)

Thermal stress on the plate in relation to time:

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Bassam Ali Ahmed et al
\[
\sigma_{th} = \frac{E_2a}{1-v} \left[ \frac{1}{2} \int_{-L}^{L} T \, dt \left( \frac{n\pi t}{L} \right) \right] + \sum_{n=1}^{N} \frac{1}{L} \int_{-L}^{L} T \cos \left( \frac{n\pi t}{L} \right) \, dt \cos \left( \frac{n\pi t}{L} \right) + \\
\frac{1}{L} \int_{-L}^{L} T \sin \left( \frac{n\pi t}{L} \right) \, dt \sin \left( \frac{n\pi t}{L} \right) \right] \]

Stresses occurring in the plate:

\[
\sigma_{xx} = \frac{Z_2 E_2}{(1-v)} \left[ \frac{\partial^2 w}{\partial x^2} + v \frac{\partial^2 w}{\partial y^2} \right] - \frac{E_2 a T_{th}}{(1-v)} \]

\[
\sigma_{yy} = \frac{Z_2 E_2}{(1-v)} \left[ \frac{\partial^2 w}{\partial y^2} + v \frac{\partial^2 w}{\partial x^2} \right] - \frac{E_2 a T_{th}}{(1-v)} \]

\[
\tau_{xy1} = \frac{Z_2 E_2}{(1+v)} \frac{\partial^2 w}{\partial x \partial y} \]

The principal stresses components are, Srinath, 2009.

\[
\sigma_1, \sigma_2 = \frac{\sigma_{xx} + \sigma_{yy}}{2} \pm \sqrt{\left( \frac{\sigma_{xx} - \sigma_{yy}}{2} \right)^2 + \tau_{xy1}^2} \]

\[
\theta_p = \frac{1}{2} \arctan \frac{2\tau_{xy1}}{\sigma_{xx} - \sigma_{yy}} \]

The structural components with an efficient cracking stress on crack propagation and dynamic factor of stress intensity are the main natural and tangential stress facing cracks. Gosz, and Moram, 1998.

\[
\sigma_{1n} = \sigma_{\text{impact}}(x, y, t_i) = \sigma_1 \cos^2 \theta_p + \sigma_2 \sin \theta_p \cos \theta_p \]

\[
\sigma_{2t} = \tau_{\text{impact}}(x, y, t_i) = \sigma_2 \cos^2 \theta_p - \sigma_1 \sin \theta_p \cos \theta_p \]

The factor of stress intensity \((K_I, K_{II})\) for crack infinite plate subject to impact loading. Faulkner, 2005.

\[
K_{I\text{impact}} = C_f \sigma_{\text{impact}} \sqrt{\pi a} \quad \text{&} \quad K_{II\text{impact}} = C_f \tau_{\text{impact}} \sqrt{\pi a} \]

By superposition theory, get total stress intensity factor:

\[
K_{I\text{total}} = K_{I\text{impact}} + K_{I\text{cyclic}} + K_{I\text{thermal}} \]

Where:

\[
K_{I\text{cyclic}} = C_f \sigma_a \sin wt \sqrt{\pi a}, \quad \text{&} \quad K_{I\text{thermal}} = C_f \sigma_{th} \sqrt{\pi a} \]

Combined stresses at the crack tip in the plate, Zaei, 2000.

\[
\sigma_x(t) = \frac{K_{I\text{total}}}{\sqrt{2\pi t}} \cos \left( \frac{\theta}{2} \right) \left( 1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \]

\[
- \frac{K_{II\text{impact}}}{\sqrt{2\pi t}} \sin \left( \frac{\theta}{2} \right) \left( 2 + \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \right) \]

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Bassam Ali Ahmed et al
\[ \sigma_y(t) = \frac{K_{I \text{total}}}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left( 1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) + \frac{K_{II \text{impact}}}{\sqrt{2\pi r}} \sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \]  
(19)

\[ \tau_{xy}(t) = \frac{K_{I \text{total}}}{\sqrt{2\pi r}} \sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2} + \frac{K_{II \text{impact}}}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left( 1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \]  
(20)

The principal stresses on a crack:

\[ \sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \]  
(21)

Normal stress on a crack respect to time:

\[ \dot{\sigma}_{\text{normal}} = \frac{d}{dt} \left( \sigma_1 \cos^2 \theta_p + \sigma_2 \cos \theta_p \sin \theta_p \right) \]

\[ \therefore \dot{\sigma}_{\text{normal}} = -2\sigma_1 \cos \theta_p \sin \theta_p + \sigma_2 \left( \cos^2 \theta_p - \sin^2 \theta_p \right) \]  
(22)

\[ r_p = \frac{1}{6\pi} \left( \frac{K_{I \text{total}}}{\sigma_{\text{ys}}} \right)^2, \quad a_c = a + r_p \]  
(23)

Dynamic crack propagation velocity:

\[ \dot{a} = \sqrt{\frac{\pi}{K} \frac{E}{\rho} \left( 1 - \frac{a}{a_c} \right) \dot{\sigma}_{\text{normal}}} \]  
(24)

### III. Numerical Analysis

The results of the numerical analysis were obtained using ANSYS tools. Several numeric methods for simulating fracture mechanics have been developed, Madenci et al., 2015. The finite-element approach used was computerized methods to predict the reactions of the real object to force, heat, and vibration. Similiar methods were used to determine work piece, machinery, and structures actions for various loading conditions. Entire structural analysis was found by examining the individual elements simultaneously, taking due account of their individual locations within the mesh. Stolarski et al., 2006.

The stresses to respect time were analyzed by applying the cycling impact loading on the crack in the center of the plate under the temperature effect via an impactor arm and calculating the crack propagation in time.

### III.i. Selection of Element

Coupled filed solid item SOLID226 had twenty nodes with a maximum of five degrees of freedom per node. The structural capabilities include elasticity,
plasticity, viscoelasticity, visco-plasticity, creep, pressure, tension, thermal expansion and structural-thermal capabilities. ANSYS Release 18.0 Documentation.

SURF152 can be used for different applications of load and surface effects. It can overlay any 3-D thermal element on an area face. Four to ten nodes described the product, and the properties of the material. For effects of convection or radiation an extra node (away from the base element) may be used. Documentation to ANSYS Release 18.0. Three-dimensional representation of a cracked plate as shown in Fig.2.

III.ii. Load and Boundary Conditions

Establish the surface area of interaction between impactor and plate. The plate was defined as the contact surface, while impactor identified the target as being treated as rigid with the pilot node for the displacement to apply. The pilot node aligned with the impactor was also used during the simulation to obtain the structural force. All touch surfaces were TARGE170 modelled for target surfaces and CONTA174 elements for interface elements. The plate was clamp-clamped from two ends, with the other edges clearly simply supported (CSCS) Fig.3., and simply-supported from two ends, with the other edges clearly free (SFSF) Fig.4.

IV. Results and Discussion

The results showed substantial convergence with numerical analysis in the analytical solution, and illustrated the effect of thermal and mechanical stress on cracked plate dynamic crack propagation.

IV.i. Analytical Solution

IV.i.a. Analytical Solution of Crack Lengths Effect on Dynamic Crack Propagation.

The dynamic crack propagation analytical solution is dependent on the value of the combined stresses according to equations (18, 19, and 20). By the equation (24), for crack lengths (3, 5) mm, crack angles (45°), the effect of crack length on dynamic crack propagation was demonstrated in Fig. 5 to 12. The displacement in the plate was directed proportionally with applied stresses which means the increase in the length of the crack which leads to an increase in the stress values and thus to an increase in the propagation of the crack, so note from the figures that the propagation of the crack growth for the length of 5 mm is higher than the growth of the crack of 3mm for the same conditions. The crack's mechanical behavior shows the gradual growth and spread of the crack over time and the increase of the stresses caused by the crack, leading to a clear increase in the crack's growth, especially after 2700 seconds, where growth accelerates, to reach its maximum at 7200 seconds. That there are some limiting values that strain hardening will influence the performance, so that the rate of curve slope will be small until almost 2700 seconds, then the rate of curve slope will rise high. It can be seen that the dynamic crack propagation rate in Al-6061 is very high when compared to Al-7075, it is seen that the dynamic crack propagation depends on the elasticity of the materials.
IV.i.b. Aspect Ratios Effect on Dynamic Crack Propagation

With the rise of the aspect ratio plate for aluminum 6061 alloy and aluminum 7075 alloy the stresses decreased. The bending would be lower with an increase in the aspect ratio, which contributes to a reduction in the deflection, while the stress depends on the deflection according to equations (3, 4, 5), as a result that the dynamic distribution of the crack decreases with the high aspect ratio plate. Via outcomes as shown in Fig. 5 to 12 that the crack growth values for the aspect ratio 1.5 are high compared to those aspect ratio values of 2 for the same conditions. The propagation of crack growth varies from material to material where the propagation of crack growth in ductile materials such as aluminum 6061 is greater than in hard materials such as aluminum 7075, since the propagation of crack growth depends on the elasticity modulus and material density.

IV.i.c. Boundary Conditions Effect on Dynamic Crack Propagation

The clamped simply supported - clamped simply supported (CSCS) condition, having the moment and linear deflection at the two ends of the simply supported plate is equal to zero, and at the other ends of the clamped plate, the linear and angular deflection equal to zero, while simply supported free – simply supported free (SFSF) condition, at the two ends of the free plate having the moment and the shear force is equal to zero, and at the other ends of the simply supported plate, the moment and linear deflection is zero. Through the results in the Fig.5 to 12, noted that the values of the crack propagation in the plate fixed by CSCS were less than the values of the crack propagation in the plate fixed by SFSF that mean CSCS is safer than SFSF.

IV.ii. Numerical Analysis (ANSYS Program)

IV.ii.a. Crack Lengths Effect on Dynamic Crack Propagation

The effect of the numerical crack lengths and crack angles on the dynamic crack propagation is illustrated in Fig. 13 to 20 by the number of impactor strikes (cycling impact loading) and cycling thermal stresses with a total time of 7200 seconds. The maximum percentage of error (9.7 per cent) between analytical solution and numerical analysis when comparing the results.

IV.ii.b. Aspect Ratios Effect on Dynamic Crack Propagation

The effect of numerical aspect ratios on dynamic crack propagation under the number of impactor strikes (cycling impact loading) and cycling thermal stresses with a total period of 7200 seconds is demonstrated in Fig. 13 to 20.

IV.ii.c. Boundary Conditions Effect on Dynamic Crack Propagation

As shown in the Fig. 13 to 20, the results showed that the dynamic crack propagation values at free-free with simply supported on the other edges the boundary condition (SFSF) is higher than the clamped-clamped with the other sides of the boundary condition simply supported. (CSCS), it is because the deflection value at free with simply supported at the other edges is higher than the clamped-
clamped value with simply supported at the other edges, which contributes to higher crack propagation values.

V. Conclusions

1. It was observed that the crack growth propagation rate with a length of 3 mm was fewer than the rate of crack propagation for the length of 5mm at the same angle and same boundary conditions.

2. It was found that the greater aspect ratio of plate, the less stresses would have been, and thus the rate of crack growth was fewer, there for the crack propagation have been greater for the smaller aspect ratio.

3. The clamped-clamped with simply supported at the other edges boundary condition was better (safe design) for dynamic crack propagation than free-free with simply supported at the other edges.

4. It has been found that the crack growth rate for the Al-6061 alloy was greater than Al-7075 alloy for the same crack length and conditions.

5. It was found that the thermal stresses resulting from applied temperatures with time lead to increase in the dynamic crack propagation.

Nomenclature

A- Plate width, m.

a- Half crack length, m.

\(a_c\) - Half-length of crack after the propagation, m.

\(\dot{a}\) - Velocity of crack propagation, m/s.

B- Plate Length, m.

D- Flexural rigidity of plate, Pa.m³.

\(E_1, E_2\) - Modulus of elasticity of impactor and plate respectively, Pa.

\(F(t_i)\) - Impact load, N/m.

\(K_{I}, K_{II}\) - Stress intensity factor for mode I&II respectively, MPa\(\sqrt{m}\).

\(m_1, m_2\) - Impactor and plate mass, Kg.

R- Radius of Impactor, m.

\(r_p\) - Radius of plastic zone, m.

\(T_{th}\) - Temperature respect to time, C°.

\(V_1, V_2\) - Velocity of impactor and plate respectively, m/s.

W- The total deflection in the plate, m.

\(\sigma_{th}\) - Thermal stress, N/m².

\(\sigma_{xx}, \sigma_{yy}, \tau_{xy}\) - Stresses induced in plate, N/m².

\(\sigma_x, \sigma_y, \tau_{xy}\) - Stresses at crack- tip region, N/m².

\(\sigma_1, \sigma_2\) - Principal stress, N/m².
Fig. 1: Cycling temperature with time

Fig. 2: 3D model cracked plate

Fig. 3: Load and boundary conditions of the cracked plate (CSCS)
Fig. 4: Load and boundary conditions of the cracked plate (SFSF)

Fig. 5: Crack propagation with time (A.R=1.5, CSCS, β=45, Lc=3mm)

Fig. 6: Crack propagation with time (A.R=2, CSCS, β=45, Lc=3mm)
Fig. 7: Crack propagation with time (A.R=1.5, CSCS, β=45, Lc=5mm)

Fig. 8: Crack propagation with time (A.R=2, CSCS, β=45, Lc=5mm)

Fig. 9: Crack propagation with time (A.R=1.5, SFSF, β=45, Lc=3mm)
Fig. 10: Crack propagation with time (A.R=2, SFSF, β=45, Lc=3mm)

Fig. 11: Crack propagation with time (A.R=1.5, SFSF, β=45, Lc=5mm)

Fig. 12: Crack propagation with time (A.R=2, SFSF, β=45, Lc=5mm)
**Fig. 13:** Crack propagation with time (A.R=1.5, CSCS, $\beta=45$, Lc=3mm)

**Fig. 14:** Crack propagation with time (A.R=2, CSCS, $\beta=45$, Lc=3mm)

**Fig. 15:** Crack propagation with time (A.R=1.5, CSCS, $\beta=45$, Lc=5mm)
Fig. 16: Crack propagation with time (A.R=2, CSCS, β=45, Lc=5mm)

Fig. 17: Crack propagation with time (A.R=1.5, SFSF, β=45, Lc=3mm)

Fig. 18: Crack propagation with time (A.R=2, SFSF, β=45, Lc=3mm)
Fig. 19: Crack propagation with time (A.R=1.5, SFSF, β=45, Lc=5mm)

Fig. 20: Crack propagation with time (A.R=2, SFSF, β=45, Lc=5mm)

Table 1: The specifications of aluminum 7075

| Property                  | Value    |
|---------------------------|----------|
| Young modulus (E) Gpa     | 81.5     |
| Yield Tensile Strength (σy) Mpa | 503     |
| Ultimate tensile strength (σult.) Mpa | 570     |
| Poisson's ratio (ν)       | 0.33     |
| Density (ρ) Kg/m³         | 2780     |

Table 2: The specifications of aluminum 6061

| Property                  | Value    |
|---------------------------|----------|
| Young modulus (E) Gpa     | 79       |
| Yield Tensile Strength (σy) Mpa | 275     |
| Ultimate tensile strength (σult.) Mpa | 310     |
| Poisson's ratio (ν)       | 0.33     |
| Density (ρ) Kg/m³         | 2700     |

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Bassam Ali Ahmed et al

522
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