MODIFIED METHOD FOR STUDYING THE EFFECT OF LASER SHOT PEENING IN THIN PLATE ON DYNAMIC CRACK PROPAGATION UNDER CYCLING THERMAL EFFECT

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Abstract

In this research, for studying dynamic crack propagation behavior in thin plate, a modified method has adopted, when solidification with laser shot peening with cycling thermal effect have done. Since anew a technique is based on an accumulating two types of energies and employments, these together or alone by [Griffith] approach are used to emulate what happen in fuselage with specific conditions in order to study crack velocity and stress intensity factor. The two energies are coming from laser ray and cycling thermal. Analytical model has built with two scenarios for comparing between them. The first one (oven state) when cycling temperatures range for one cycle is from 30 to 150°C and the second (plane path state) when temperature range decreases from 30 to -30 °C . In addition, the functions (cycling thermal) are functions of duration. Therefore, Fourier series method for periodic functions has built for cycling during path of flight. Oven state for a specific function has assumed with specific shape. Accordingly, simply support condition is adopted for all plates' edges. Laser ray influence has applied according to (P. Peyer & R. Fabbro) equations. For plane path state (cooling), it has been observed that the dynamic crack propagation clearly decreases when the energy of laser was influenced and cycling thermal has increased retardation of crack extension. While for oven state (heating), cycling thermal leads to reducing retardation of crack extension. Also, when comparing between two energies, a high benefit energy is produced from laser (positive effect), and thermal effect depends on state of system if heating or cooling and type of boundary conditions. The values are as well depended on thickness, crack ratio and properties of material

Keyword : dynamic crack propagation, stress intensity factor, laser energy, thermal energy

Abbreviations :

\(U_T\) = Total energy (N.m)
\(U_{th1}\) = Thermal energy (N.m)
\(U_{th}\) = Thermal energy for unit thickness

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\( U_{re} \) = Laser energy for unit thickness  
\( U_{re1} \) = Laser energy (N.m)  
( \( a_0 \) ) = Initial length of crack (m)  
( \( a_i \) ) = Length of crack after extension (m)  
( \( h \) ) = Thickness of plate (m)  
( \( h1 \) ) = Laser deep (m)  
( \( w \) ) = Width of plate (m)  
(V1) = Poisson’s ratio for cylindrical steel  
(V2) = Poisson’s ratio for plate  
(E2) = Young’s modulus for plate (G Pa)  
(M) = Equivalent mass (1/Kg)  
( \( m_1 \) ) = Mass of impactor (Kg)  
( \( z_1 \) ) = Impedance for water or coating, \( \left( \frac{g}{cm^2s^{-1}} \right) \)  
( \( z_2 \) ) = Impedance for material, \( \left( \frac{g}{cm^2s^{-1}} \right) \)  
( \( \rho_2 \) & \( \rho_1 \) ) = Density for water and material (Kg/m3)  
( D1) = Shock velocity (m/s)  
( \( m_2 \) ) = Mass of plate (kg)  
( \( t_a \) ) = Impact time (s)  
( \( n \) ) = Variable depends on material properties for both impactor and plate  
( \( a_{o2} \), \( an \) , \( bn \) ) = Periodic function  
( \( a_{io} \) ) = Decay factor = 0.2 (Mario1980)  
(I) = Stress intensity factor (MPa/\( \sqrt{m} \))  
( n, m ) = Coefficients deflection equation  
(T) = Time of one periodic (s)  
( t ) = Time fluctuating (s)  
( \( \mu, \lambda \) ) = Lame’s elasticity constant (Mpa)  
(HEL) = Stress elastic limit in direction of shock wave, Hugoniot Elastic Limit (Gpa)  
( I_0 ) = Power density ( Gw/cm² )  
( \( a_2 \) ) = Efficiency of interaction or (correction factor corresponding to the fraction of internal energy, value about (0.25), by [Berthe])  
( \( z \) ) = Effective acoustic impedance, \( \left( \frac{g}{cm^2s^{-1}} \right) \)  

I. Introduction

The integration of materials components are representing a high challenge in the field of aerospace applications and planes manufacturing to upgrade and develop it to the limit. It can be achieved that by increasing materials resistance against external conditions and enhancement life of aging of airplanes in the case of extension fatigue life and reduced mitigation and retardation propagation of dynamic

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crack. [IV] Have suitable tools to complete that, since one of them is energy release rate. It depends on the amount of energy will release during unstable crack stage. Moreover, it can be implemented that in energy balance approach. Subsequently, material components can be enhanced through choosing the best method for solidification external surface with laser shot peening technique. It is one of the positive energies, which contributed to achieve a target of enhancement the outer surface of material component. Laser shot-peening method produces compressive residual stress to retard extension of cracks by change of external mechanical properties of materials [XII]. So, there are many researches are adopted that. In [IX], AL2024 and 4340 steel were used with same extension of crack length. It needs 20000 cycles for the unpeened case, while it needs 60000 cycles to reach to the failure, and the crack growth is reduced from 2 to 4 times for same cycle and type of material. The authors of [VI], has produced (-175 to-375) Mpa compressive stress and depth (0-275) mm on AL-7050-T7451with energy 2 (\(\eta w/cm^2\)). In addition, in [III], AL7475- T735 plate was used with thickness 20mm, so as to monitor crack growth with and without using laser shot peening. It was observed an extension of crack length when without using shot peening with 1400\(\mu m\) through 200000 cycles, while the crack length was 200 \(\mu m\) only for 450000 cycles.

Thermal cycle effects on change temperature range above or underground degree. Since energy of thermal loading is one of external coefficient that effects on the behavior of materials components due to compressive stress at high temperature and tensile stress under zero temperature with respect to simply support condition. It stands for negative or positive energy depending on specific conditions. Effect of high temperature (heating space) is noted that leads to increase or decrease in crack growth [V]. It has noticed a crack growth increase when temperature increases with respect condition. Super alloy DZ125 with high temperature range (900-1000) °C, by using experimental method was showed at 1000 °C thermal fatigue for 15 cycles and crack length of 0.45mm, while in (900) °C, it was 0.35mm during 225 cycles as well as for cooling space (plane state) noticed. In [X], the authors have clarified crack growth for aluminum alloy with 2624-T351 type, plate dimension (400 x 140x 5mm\(^3\)) reinforced by layer Glare fiber under effect of temperature fluctuating from 70 to -60 °C and room temperature. It is noticed the fatigue life under temperature value (- 60 °C ) is longer than at temperature (70c). The authors of [I], noticed for Aluminum type 7075-T651 with respect pressure and humidity, the reduction in fatigue behavior largely saturates below -50 °C.

II. Theoretical Analytical:

Creating a new modified equation for dynamic crack propagation as follows:

II.i. Theory of Energy balance

To create a new equation for governing progress of dynamic crack propagation when the plate imposed to (laser, thermal) loadings, it was adopted energy balance approach [Griffith]. The principle of this method was approved and confirmed by Mott and Hahn. So, according to this theory at unstable stage when crack initiation, stands for an extension for pure energy to be converted to kinetic energy.

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Here, \( U_T = U_K \)
When \( (U_T) \) total excess energy is (laser, or thermal energy) which represents simulation for environmental altitude conditions. It includes effect of energy cycling thermal and energy of laser ray. So, the total energy will be a state of temperatures under or above zero degree. Consequently, add plus or minus for compression or tension effect \([XI]\), bending as tension, laser as compression or negative case :
\[
U_T = \pm U_{th1} - U_{rel1} \quad \ldots \ldots \quad (1)
\]
So, according to modified energy approach, the total energy balance become
\[
\pm U_{th1} - U_{rel1} = U_K \quad \ldots \ldots \quad (2)
\]

### II.ii. Thermal energy \((U_{th})\) and thermal stress scenarios

For first scenario, assume summation for cycling temperature through aircraft flying during take off, the temperature will be decreased linearly with time from ground temperature until minus zero. After that, passing through stable duration at specific altitude for a long time, an increasing linearly from minus zero to ground temperature during landing is observed.

For 2nd scenario, because of difficulty to achieve stability state under zero temperature as a practicly, we will apply heating scenario, for increasing above zero and compare the different cases between them.

For investigation of above two scenarios, mathematical model was adopt using Fourier series method in order to represent periodic functions with special shape (it has stable duration) by using (Dirichlet theorem) [III].

\[
T(t) = \frac{a_0}{2} + \sum_{n=1}^{N} \left( a_n \cos \left( \frac{n\pi t}{l} \right) + b_n \sin \left( \frac{n\pi t}{l} \right) \right) \ldots \ldots \quad (1)
\]

over \([-l, l]\], when
\[
a_{02} = \frac{1}{l} \int_{-l}^{l} f(t) \, dt, \quad a_n = \frac{1}{l} \int_{-l}^{l} f(t) \cos \left( \frac{n\pi t}{l} \right) \, dt, \quad b_n = \frac{1}{l} \int_{-l}^{l} f(t) \sin \left( \frac{n\pi t}{l} \right) \, dt
\]

For first scenario actual simulation for aircraft temperature assume change is linear as in Figure (1).

Function is built with linear temperature change with respect time \(T(t)\) as Figure (1)

The cycling temperature \(T(t)\) =
\[
\begin{cases}
\left( \frac{T_2-T_1}{t_1} \right) (t - t_1) + T_1 & 0 < t < t_1 \\
T_2 & t_1 < t < t_2 \\
\left( \frac{T_2-T_1}{t_2-t} \right) (t - T) + T_1 & t_2 < t < T
\end{cases}
\]

\[
(2)
\]
For second scenario, assume from 30°C room temperature ground temperature until T=150°C and stay at this temperature until particular time and retain back as in Figure (2)

Temperatures cycling with time above zero degree for one period is:

\[
T(t) = \begin{cases} 
\left( \frac{T2-T1}{t1} \right) t + T1 & 0 < t < t1 \\
T2 & t1 < t < t2 \\
\left( \frac{T2-T}{t2-T1} \right) (t - T) + T2 & t2 < t < T 
\end{cases}
\]  

(3)

Thermal stress \( (\sigma_{th}) = E. \alpha. T(t) \)

By sub T (t) to get \( (\sigma_{th}) \)

\[ U_{th} = \int_0^\varepsilon \sigma_{th} \, de \quad \text{for unit thickness} \]

By doing integration, we will obtain.

\[ U_{th1} = \frac{1}{2E} (\sigma_{th})^2 \quad \text{sub thermal stress we get for unit thickness} \]
\[ U_{th} = \frac{1}{2E} \left( E \alpha \frac{1}{l} \int_{-l}^{l} T(t) dt \right) + \sum_{n=1}^{N} \left( \frac{1}{l} \int_{-l}^{l} T(t) \cos \left( \frac{n\pi t}{l} \right) dt \cos \left( \frac{n\pi t}{l} \right) \right) + \]
\[ \frac{1}{l} \int_{-l}^{l} T(t) \sin \left( \frac{n\pi t}{l} \right) dt \sin \left( \frac{n\pi t}{l} \right) )^2 \]

For crack, area will be

\[ U_{th1} = \pi * U_{th} * h * (a_i - a_o)^2 \]

(Energy with respect crack area)

\[ U_{th1} = \pi * \frac{1}{2E} \left( E \alpha \frac{1}{l} \int_{-l}^{l} T(t) dt \right) + \sum_{n=1}^{N} \left( \frac{1}{l} \int_{-l}^{l} T(t) \cos \left( \frac{n\pi t}{l} \right) dt \cos \left( \frac{n\pi t}{l} \right) \right) + \]
\[ \frac{1}{l} \int_{-l}^{l} T(t) \sin \left( \frac{n\pi t}{l} \right) dt \sin \left( \frac{n\pi t}{l} \right) )^2 * h * (a_i - a_o)^2 \]

For laser energy and residual stress \( U_{re} \), laser energy will produce compressive residual stress according to procedure that has followed by [VII, VIII].

\[ U_{re} = \frac{1}{2E} (\sigma_{re})^2 \ldots (10) \]

Energy for unit thickness

since \( \sigma_{re} = \sigma_o - \left[ \mu e_p \frac{1+v}{1-v} + \sigma_o \right] \cdot \left[ 1 - \frac{4\pi}{\pi} (1 + v) \frac{l}{r_0/\sqrt{\pi}} \right] \]

\[ \epsilon_p = \frac{2HEL}{3\lambda + \mu} \left( \frac{p}{HEL} - 1 \right) \]

\[ HEL = \left( 1 + \frac{\lambda}{2\mu} \right) (\sigma_y - \sigma_o) \]

based on yield stress \( (\sigma_y) \)

\[ p = 0.01 \sqrt{\frac{a_2}{2a_2+3}} * \sqrt{Z} * \sqrt{l_0} \]

\[ \sigma_{re} = - \left[ \frac{2}{Z} \left( \frac{1}{Z_1} + \frac{1}{Z_2} \right) \right] \times \left( \frac{2}{Z} = \left( \frac{1}{\rho_1D1} + \frac{1}{\rho_2D1} \right) \right] \]

\[ l = \frac{c_e c_p}{c_e-c_p} \left( \frac{p-HEL}{2HEL} \right) \]

Plastified depth \ldots (13), \( c_e = \frac{\lambda+2\mu}{\rho} \ldots \), \( c_p = \sqrt{\frac{\lambda+2\mu}{\rho}} \)

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Since:

\[
lame\text{se elastic}(\lambda) = \frac{Eu}{(1+\nu)(1-2\nu)}
\]

\[
lame\text{se elastic}(\mu) = \frac{\lambda(1-2\nu)}{2\nu}
\]

Sub equation in residual stress to get \((U_{re1})\).

\[
U_{re} = \frac{1}{2E} \left[ \frac{2 \left( 1 + \frac{\lambda}{2\mu} \right) (\sigma_y - \sigma_o) \left( 0.01 \sqrt{\frac{a^2}{2a_2+3}} * \sqrt{I_o} \right)}{\lambda \left( \frac{1}{\lambda} \left( \sigma_y - \sigma_o \right) - 1 \right) \left( 1 - \frac{\lambda}{2\mu} \left( \sigma_y - \sigma_o \right) \right) - 1} \right] \left[ 1 - \frac{\pi}{\mu} \right] (1 + \nu) \left( \sigma_y - \sigma_o \right) \left( 0.01 \sqrt{\frac{a^2}{2a_2+3}} * \sqrt{I_o} \right) ^2 * \left( 1 + \nu \right) \left( \sigma_y - \sigma_o \right) \left( 0.01 \sqrt{\frac{a^2}{2a_2+3}} * \sqrt{I_o} \right) ^2
\]

With respect to crack area, equation will be:

\[
U_{re1} = \pi * U_{re} * h1 * (a_i - a_o) ^2 \quad \text{(17)}
\]

Since \((h1)\) is laser thickness deep, sub \((U_{re1})\) from equation 14 to be

\[
U_{re1} = \pi * \frac{1}{2E} \left[ \frac{2 \left( 1 + \frac{\lambda}{2\mu} \right) (\sigma_y - \sigma_o) \left( 0.01 \sqrt{\frac{a^2}{2a_2+3}} * \sqrt{I_o} \right)}{\lambda \left( \frac{1}{\lambda} \left( \sigma_y - \sigma_o \right) - 1 \right) \left( 1 - \frac{\lambda}{2\mu} \left( \sigma_y - \sigma_o \right) \right) - 1} \right] \left[ 1 - \frac{\pi}{\mu} \right] (1 + \nu) \left( \sigma_y - \sigma_o \right) \left( 0.01 \sqrt{\frac{a^2}{2a_2+3}} * \sqrt{I_o} \right) ^2 * \left( 1 + \nu \right) \left( \sigma_y - \sigma_o \right) \left( 0.01 \sqrt{\frac{a^2}{2a_2+3}} * \sqrt{I_o} \right) ^2
\]

For Kinetic energy \(U_K\) and based on vertical distance, we can consider \([I]\):

\[
\frac{2a}{E} \sqrt{a^2 - x^2}
\]

Where \((x)\) is a function of \((\alpha)\) and can be written as:

\[
x = c \cdot a \quad \text{for} \quad 0 \leq c \leq 1 \quad \text{then,} \quad c_1 = 2 \sqrt{1 - c^2} \quad v = \frac{c_1 \cdot a}{E}/
\]

When the crack is propagated, the vertical displacement \((\theta)\) will be variable with time. Therefore the rate of change is \((\frac{\partial}{\partial t})\) with

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\[ v' = \frac{\partial}{\partial t} \left( c_1 \sigma_T \frac{d}{E'} \right) \]  \hspace{1cm} (17)

Total stress represents effect of bending, thermal and laser stress:
\[ \sigma_T = \sigma_{re} + \sigma_{th} + \]  \hspace{1cm} (18)

since derivative of \((\sigma_{re})\) = zero (constant with time) and sub in equation (20), we get:
\[ v' = \left( \frac{c_1 + \sigma_{th}}{E'} \right) \]  \hspace{1cm} (19)

Residual stress is constant, so only thermal and bending stress will be derivative
\[ \sigma_{th} = \frac{\partial}{\partial t} \left( E \cdot \alpha \cdot \frac{1}{2} \int_{-i}^{i} (t) dt \right) + \sum_{n=1}^{N} \left\{ \frac{1}{i} \int_{-i}^{i} T(t) \cos\left( \frac{n \pi t}{i} \right) \cos\left( \frac{n \pi t}{i} \right) + \frac{1}{i} \int_{-i}^{i} T(t) \sin\left( \frac{n \pi t}{i} \right) \sin\left( \frac{n \pi t}{i} \right) \right\} \]  \hspace{1cm} (20)

Then, it is derivative as:
\[ \sigma'_{th} = E \alpha \sum_{n=1}^{N} \left( -an \cdot \omega_n \cdot \sin \omega_n t + bn \cdot \omega_n \cdot \cos \omega_n t \right) \]  \hspace{1cm} (21)

Kinetic energy when the material in crack edges will move with speed\(v'\), so it will be:
\[ U_K = \frac{1}{2} M. v' \ldots \ldots (25), \] \hspace{1cm} with density of material for specific thickness becomes.
\[ U_K = \frac{1}{2} \rho. A. h. \left( \frac{C_1 \sigma_T + a + a \sigma_T}{E'} \right)^2 \]  \hspace{1cm} (22)

with integration when \((A = dx dy)\)
\[ U_K = \frac{\rho}{2} * h * \left( \frac{(\sigma_T + a + a \sigma_T)}{E'} \right)^2 \int_{0}^{a_i} \int_{0}^{a_i} c_i^2 dx dy \]  \hspace{1cm} (23)

Finally, \(U_K\) will be:
\[ U_K = \frac{1}{2} \frac{\rho a_i^2}{E'} (\sigma_T + a + a \sigma_T)^2 \]  \hspace{1cm} (24)

For total energy balance,
\[ U_{th1} + U_{re1} = U_K, \]

sub all energies, we will get

\[ U_{th1} \pm U_{re1} = U_K, \]
\[ \pi \ast (\pm h \ast U_{th} - h1 \ast U_{re}) \ast (a_i - a_o)^2 = \frac{1}{2} \frac{\rho k a_i^2}{E^2} (\sigma_T \ast \dot{a} + a \ast \sigma_T)^2 \] (25)

\[ a^o = \text{abs} \left( \frac{\sqrt{2} \ast \pi \ast E^2 \ast \rho \ast (\pm h \ast U_{th} - h1 \ast U_{re}) \ast (a_i - a_o)^2}{\rho k a_i^2} \ast \frac{a_i (\pm \sigma_{th})}{(\pm \sigma_{th} - \sigma_{re})} \right) \] (26)

It can be rearranged as:

\[ a^o = \text{abs} \left( \frac{\sqrt{2} \ast \frac{\pi}{k} \ast \frac{E^2}{\rho} \ast \left(1 - \frac{a_2}{a_1}\right) \ast \sqrt{\left(\pm (h \ast U_{th}) - (h1 \ast U_{re})\right) - a_i \ast (\pm \sigma_{th})}}{(\pm \sigma_{th} - \sigma_{re})} \right) \] (27)

To calculate crack extension length after particular time based on principle of velocity:

\[ \frac{da}{dt} = \frac{a_i - a_o}{t_i - t_o} \] (28)

The extension in crack with original length is:

\[ a_t = a^o (t_i - t_o) + a_o \] (29)

Since \( t_d \) represents time of extension

\[ a_t = a^o \ast t_d + a_o \] (30)

III. Result and discussion

We have adopted two scenarios with linear behavior of thermal cycling to create thermal energy effect. One like oven state and second as simulation to airplane flight and land path. They are compared and we have chosen fourth type of isotropic aluminum alloy (6061, 2024, 7050, 7049) with three different thicknesses (1, 1.5, 2) mm suitable to fuselage material types

For multi cycles with multi thermal loading and constant time for every cycle, Figures (3) to (4) have appeared values of dynamic crack behavior with a cycle for oven state and plane path state under effects of laser and thermal energy. For simple support condition, temperature change effects as tension compressive thermal stresses, and dynamic crack propagation increases with thickness and different types of material

Figures (5) to (6) have depicted dynamic crack behavior for plane state since temperature range effects as compressive thermal stress. So, the values of dynamic crack range is less than oven state due to combined stress through plane state, while it is subtracted for oven state. The percentage between oven and plane state with respect to type and thickness of material was 79%
Figure (7) to (10) have clarified values of dynamic crack propagation for oven and plane state when thermal energy effects only with a role of removing laser compressive stress. The values increase with acceleration for oven state and increase with slow down plane state. Different percentages when compared with removed laser effect with respect to type and thickness of material were 69% and 94% for oven and for plane.

Figure (3): AL7049, dynamic crack/cycle with thermal and laser effect, constant time every cycle, and oven state

Figure (4): AL2024, dynamic crack/cycle, with thermal and laser energy, oven state, and constant time
Figure (5): AL7049, dynamic crack/cycle, with thermal and laser, plane state, and constant time

Figure (6): AL2024, dynamic crack/cycle with thermal and laser plane state, and constant time

Figure (7): AL2024, dynamic crack/cycle with oven state and thermal effect only
Figure (8): AL2024, dynamic crack/cycle with thermal effect and plane path state

Figure (9): AL7049, dynamic crack/cycle with thermal effect and oven state

Figure (10): AL7049, dynamic crack/cycle, with thermal effect and plane state

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