Effect of Foreign Object Damage at Different Impact Parts for TC4 Titanium Alloy Blades

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Abstract. The effect of foreign object damage at different impact parts of TC4 Titanium Alloy blades is studied in this paper and impact damage from common foreign objects at different parts of the inlet side of the blade has been simulated in the process of aircraft skidding using the ANSYS/LS-DYNA software based on the Kinematic hardening plastic constitutive model. The results show that the damage depth of the sandstone increases linearly with the increase of relative kinetic energy when the same foreign object strikes different parts, but there is a critical relative kinetic energy of 2.54J and 2.50J for the steel ball and screw, respectively. When the relative kinetic energy is less than the critical value, the damage depth increases continuously with the relative kinetic energy, and when the relative kinetic energy is greater than the critical value, the damage depth decreases continuously with the relative kinetic energy.

1. Introduction

It is of great significance to study the foreign object impact damage referred to as FOD on blades to ensure the reliability of aircraft engines and flight safety. Especially when the aircraft takes off and lands, the elements such as sand particles, steel balls, screws, etc. are often drawn into the engine and hit the engine blades synchronously. If it hits the first stag rotor blade of compressor, it will damage the blades and seriously affect the performance of the engine and endanger flight safety. The notch stress concentration, residual stress and micro-structure damage caused by FOD severely can weaken the high cyclic fatigue resistance of the blade and make the blade in high-frequency vibration state facing the significant risk of premature failure during the engine design life. The impact mechanism, residual, failure and impact response are discussed in the literature [1-7].

Therefore, this paper takes the rotor of a certain type of Aero engine titanium alloy as the research object, using the large nonlinear ANSYS/LS-DYNA finite element program based on the Kinematic hardening plastic constitutive model to study the damage from steel balls, sandstones, and screws on blades at different distances from the root of the blades, which is beneficial to engine maintenance and on-site damage identification in the field [8-16].

2. Materials and methods

The process of solving method is calculated by explicit-implicit sequence solving, using the implicit solver to get the model's initial stress (preload)firstly, then adds the initial stress to the structure before the explicit dynamic analysis is performed. The interrelated function between the influence of initial
stress and the influence the dynamic response of the structure is analyzed in explicit calculation [17, 18].

The plasticized hardening constitutive equation is:

\[
\sigma_y = \left[ 1 + \left( \frac{\varepsilon}{C} \right)^p \right] \left( \sigma_0 + \beta E_p \varepsilon^{eff}_p \right)
\]  \hspace{1cm} (1)

\[
\varepsilon^{eff}_p = \int_0^t \left( \frac{2}{3} \dot{\varepsilon}_p \dot{\varepsilon}_p \right)^{1/2} \mathrm{d}t, \quad \dot{\varepsilon}_p = \dot{\varepsilon}_p - \dot{\varepsilon}_p^e, \quad E_p = \frac{E E_0}{E - E_0} \text{ and } \varepsilon^{eff}_p \text{ are equivalent plastic strain; } \dot{\varepsilon}\text{ is strain rate; } E_p \text{ is hardened. The plasticity hardening model consists of two parts. The first half describes the effect of the strain rate on the dynamic yield stress. The latter part describes the effect of the plastic hardening process on the dynamic flow stress. The model determines the failure of the material by defining the failure plastic strain } \varepsilon_f, \text{ if the equivalent plastic strain, is } \varepsilon^{eff}_p > \varepsilon_f, \text{ so the material will fail. The } \beta (0 \leq \beta \leq 1) \text{ is hardening parameters, used to reflect the material isotropic hardening with the hardening and mixing hardening, when } \beta = 0 \text{ or } \beta = 1 \text{ which expressed hardening and isotropic hardening, respectively.}

Table 1: Calculated parameters and materials parameters

| Parameter | \(E(10^8)\) | \(E'(10^9)\) | \(\rho\) | \(\nu\) | \(\sigma_0(10^9)\) | \(\beta\) | \(C\) | \(P\) | \(\varepsilon_f\) |
|-----------|-------------|-------------|------|-----|-------------|-----|----|-----|------|
| Ti alloy  | 112.5       | 1.139       | 4500 | 0.33| 0.95        | 0   | 0  | 0   | 0.200 |
| Steel ball| 210.0       | 2           | 7800 | 0.30| 1.62        | 0   | 0  | 0   | 0.0600 |
| Sand      | 40          | 4           | 2800 | 0.20| 1.2         | 0   | 0  | 0   | 0.0135 |

Table 1 is calculated parameters and material parameters. Data listed in the table, \(E(10^8), \sigma_0(10^9), \nu, \varepsilon_f\) are from the literature [19]. Among which, the \(\rho\) is the mass density; \(\nu\) is the Poisson's ratio; \(\varepsilon_f\) is the contact stiffness factor in the Table 1. The simulation results are in good agreement with the experimental data and then parameters in the table 1 is obtained by methods of inversion calculations.

3. Blade damage simulation

The blade material of an aero-engine compressor rotor is a titanium alloy and the geometry and size of the blade is showed in the Fig.1 [19]. Make the \(x\)-axis coincide with the engine axis. The \(x\)-axis positive direction is the airflow direction and also is the direction of the foreign object movement. Before the strike occurs, the foreign object moves along the positive \(x\)-axis at a speed of \(v_1\), the blades move with the aircraft along the \(x\)-axis at a speed of \(v_2\), and also moves around the \(x\)-axis at an angular speed of \(\omega\). Assume that the position of the collision point is \(y\), the strike \(V_x, V_z\) and the angle \(\theta\) between the strike direction and the \(x\)-axis in the blade reference system are calibrated as follows:

\[
V_x = v_1 + v_2 V_z = \omega y \quad \theta = \tan^{-1} \frac{V_z}{V_x}
\]  \hspace{1cm} (2)
Figure 1. Blade reference system and coordinate system (modified by Zhu et al, 2017)

The model is shown in Figure 1, the length of the blade is 264.15 mm, the blade distance is 182.5 mm from the central axis, and the angular velocity of the blade is 1036 rad/s. The impact points is 210.35 mm from the root of the blade, 392.85 mm from the center points, and the relative velocity of the tangential direction is multiplied by the distance between the impact point and the central axis by 407 m/s, and the velocity of the blade along the x-axis with the plane is 77.8 m/s. The ball and sand are along x axis forward speed \( v_1 \). According to Hs \( v = \frac{9800Hs}{m} \cdot 4.3 = \frac{m}{1935} \left[ v_s - v_i + 180 \ln \frac{180 - v_i}{180 - v_s} \right] \) calculated by Zhang [16], so the sand relative to the aircraft in the X direction of the speed is \( V_s = v_1 + 77.8 \) m/s.

And the axial velocity of the impacted blade is consistent with the velocity of the airflow. The relative velocity of the blades is \( v_r = \sqrt{v_x^2 + v_z^2} \) selecting the blades as the reference system.

Taking the sphere with diameter of 2 mm and the cylinders with diameter of 1.2 mm and length of 4 mm as striking objects (steel, and et al) in this paper to study the damage situation of different material spheres and striking the inlet edge of the blade. The 8 strikes points are selected on the inlet side of the blade at a spacing distance of 30 mm calculated from the root of the blade. The relative axial velocity of foreign objects is: steel ball is 198.7 m/s, sandstone 237.5 m/s, steel nail is 158.6 m/s, respectively. The circumferential speeds at different height of blade are obtained by multiplying the angular velocity of the blade rotation at 1036 rad/s by the by the distance between the strike point and the engine shaft. The maximum operating state of the engine is used as the initial state in this study and \( h \) is the distance from the striking points to the root, with unit mm, the angle \( \theta \) between the impact direction and the x-axis is calculated according to equation (2).

4. Results and discussion

The impacting damage and the notch depth, width and impacting duration are showed in Figure 2, and among which \( \xi \) is distance from striking points to engine axis (unit mm), and D is notch depth includes two data of 3.1 mm and 3.4 mm, while the 3.1 mm is notch depth at the end of shock and 3.4 mm is the sum of the notch depth at the end of shock and the subsequent notch extension depth, namely, the final notch depth or total notch depth.
The extension increases firstly and then decrease in stress shock wave and the rotating centrifugal stress, impacting angle and blade twist angle. The changing range and rules of impacting angle $\theta$ of steel ball, gravel and steel nails with impacting height $h$ are:

$43.58^\circ \leq \theta_g \leq 63.98^\circ \quad \Delta \theta_g = 20.4^\circ$

$\theta_g = -0.000228 h^2 + 0.144h + 43.72 \quad (3)$

$38.53^\circ \leq \theta_s \leq 59.73^\circ \quad \Delta \theta_s = 21.2^\circ$

$\theta_s = -0.000209 h^2 + 0.144h + 38.63 \quad (4)$

$50.01^\circ \leq \theta_d \leq 68.71^\circ \quad \Delta \theta_d = 18.7^\circ$

$\theta_d = -0.000237 h^2 + 0.137h + 50.18 \quad (5)$

And the corresponding curve is shown in Figure 6 which shows the impacting angles are different due to different materials although foreign objects have the same size or impacting height. There are little difference and the change rules of angle with impacting height is a quadratic function with parallel curve. As the impact position increases, the impact angle increases; when the position is the same, the impact angle $\theta$ of the screw is the largest and the sandstone is the smallest.

The impacting angle varies with the impacting height of the foreign objects by reason that the impacting varies with the axial and circumferential relative speeds lies in that the axial speed is a function of the size, shape, and material of the foreign object and the relative speed is a function of the impacting height according to equations (3), (4) and (5).

In order to describe the relationship clearly and quantitatively between impacting velocity and blade damage, the concept of "relative kinetic energy" is defined as that the kinetic energy of foreign objects shock the blades at the relative velocity in the blade reference system and the energy refers to the volume, mass and flow velocity which is defined as

$$E_s = \frac{1}{2} m V_s^2$$  \hspace{1cm} (6)
The changing rule of relative kinetic energy \( E \) of steel ball, gravel and steel nails with impact height \( h \) are:

\[
E_s = 1.746 \times 10^{-5} h^2 + 0.00623 h + 1.209
\]

\[
E_g = 6.296 \times 10^{-6} h^2 + 0.00225 h + 0.531
\]

\[
E_d = 1.898 \times 10^{-5} h^2 + 0.00674 h + 1.06
\]

(7) \hspace{1cm} (8) \hspace{1cm} (9)

And the corresponding curve is shown in Figure 7 that shows the three curves are all quadratic functions. As the impacting height increases, relative kinetic energy of the foreign object increases as the increase of the circumferential velocity of the blade. When the height is the same, the relative kinetic energy of the sand is the smallest and the relative kinetic energy of the steel ball is the largest.

The changing rule of damage depth \( D \) of steel ball, gravel and steel nails with impacting height \( h \) are:

\[
D_s = 0.874 e \left( \frac{h-152.2}{21.49} \right)^2 + 3.639 e \left( \frac{h-186.4}{214.8} \right)^2
\]

\[
D_g = 0.00786 h + 0.375
\]

\[
D_d = 6.291 e \left( \frac{h-160.7}{141.1} \right)^2 - 0.929 e \left( \frac{h-99.89}{279} \right)^2
\]

(10) \hspace{1cm} (11) \hspace{1cm} (12)

And the corresponding curve is shown in Figure 8 which shows the damage depth of sandstone increases linearly with the increase of the impacting height, but there is a critical height of 150mm for steel balls and nails. When the impacting height is less than 150mm, the depth of damage increases as the height \( h \) increase that Impacting points from blade root. However, when the impacting height is higher than 150 mm, the depth of damage decreases. The changing rule of damage depth \( D \) of steel ball, gravel and steel nails with the relative kinetic energy \( E_r \) and the impacting height \( h \) are:

\[
D = 0.727 e \left( \frac{E_r-2.558}{0.0723} \right)^2 + 3.808 e \left( \frac{E_r-2.825}{1.844} \right)^2
\]

\[
D = 2.195 E_r - 0.701
\]

\[
D = 0.61 e \left( \frac{E_r-2.575}{0.176} \right)^2 + 6.079 e \left( \frac{E_r-2.825}{1.672} \right)^2
\]

(13) \hspace{1cm} (14) \hspace{1cm} (15)

The corresponding curve is shown in Figure 9 and it indicates that as the increase of relative kinetic energy, the damage depth of sandstone increases linearly, but there is a critical relative kinetic energy of 2.54J and 2.50J respectively for steel ball and nails. When the relative kinetic energy is less than the critical value, the depth of damage increases with the relative kinetic energy; and when the relative kinetic energy is greater than the critical value, the depth of damage decreases with the relative kinetic energy.
5. Conclusion
The effect of different foreign objects impacting TC4 Titanium alloy blades in different positions of blade damage such as steel ball, sand stone and steel screws has been investigated in this paper. The rules of impacting angel, relative kinetic energy, damage depth with impact position and the interrelation of damage depth and relative kinetic energy are also discussed in this paper. The simulation results help the enhancement of understanding of foreign objects on the damage law of the titanium alloy blade in the future.

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References
[1] J. van der Geer, J.A.J. Hanraads, R. A. Lupton, The art of writing a scientific article, J. Sci. Commun. 163 (2000) 51 - 59.
[2] Sun Z, Lu Q. INVESTIGATION ON SIMULATION OF FOREIGN OBJECT IMPACT DAMAGETO COMPRESSOR BLADE [J]. Journal of Aerospace Power, 1989.
[3] Duó P, Pianka C, Golowin A, et al. Simulated Foreign Object Damage on Blade Aerofoils: Real Damage Investigation [M]// ASME Turbo Expo 2008: Power for Land, Sea, and Air. 2008:169 - 176.
[4] Kim H S, Kim B C, Lim T S, et al. Foreign objects impact damage characteristics of aluminum/composite hybrid drive shaft[J]. Composite Structures, 2004, 66 (1–4): 377 - 389.
[5] Bansal N P, Lamon J. 14. Foreign Object Damage in Ceramic Matrix Composites [M]// CeramicMatrix Composites: Materials, Modeling and Technology. John Wiley & Sons, Inc. 2014: 405 - 429.
[6] Choi S R. Foreign Object Damage Phenomenon by Steel Ball Projectiles in a SiC/SiC Ceramic Matrix Composite at Ambient and Elevated Temperatures [J]. Journal of the American Ceramic Society, 2008, 91 (9): 2963 – 2968.
[7] Choi S R, Alexander D J, Faucett D C. Comparison in Foreign Object Damage between SiC/SiC and Oxide/Oxide Ceramic Matrix Composites[M]// Mechanical Properties and Performance of Engineering Ceramics and Composites IV. 2009: 177 - 187.
[8] Sun Z, Zhao S, Wei X, et al. Preparation of palladium/polymeric yrole-multiwall carbon annotates/titanium electrode for hydrodechlorination of pentachlorophenol [J]. Fresenius Environmental Bulletin, 2016, 25 (1): 275 - 283.
[9] Hamrick J L I. Effects of foreign object damage from small hard particles on the high-cycle fatigue life of titanium-(6)aluminum-(4)vanadium [J]. 1999.
[10] Pollak R D. Analysis of methods for determining high cycle fatigue strength of a material with investigation of titanium-aluminum-vanadium gigacycle fatigue behavior [J], 2005.
[11] Kang J. Impact Energy Equivalent Method for Simulation of Foreign Object Damage to Compressor Blades [J]. Journal of Nanjing University of Aeronautics & Astronautics, 1998.
[12] Qiao C, Li J, Yang B, et al. Effects of foreign object shape on the aero-engine compressor blade impacted damage [J]. Chinese Journal of Applied Mechanics, 2014.
[13] Yin D M, Qian L F, Ya-Dong X U, et al. Simulation and Analysis of Blades Damaged by Sandstone [J]. Journal of Nanjing University of Science & Technology, 2008.
[14] Hou L, Yin X. An Analysis of Fracture-Damage Process of Sandstone by Brazilian Disc Numerical Simulation Test [J]. Journal of Xian University of Technology, 2012.
[15] Chen G, Chen Z F, Tao J L, et al. Study on Plastic Constitutive Relationship Parameters of TC4 Titanium [J]. Journal of Experimental Mechanics, 2005, 20 (4): 605 - 609.
[16] Xing Z K, Tang E J, Duan R, et al. Research on Structure and Properties of Micro-Arc Anodic Oxidation Film on TC4 Titanium Alloy [J]. Materials Protection, 2005.
[17] Zhang, Z. P., Zhang, J., Chai, Q., Li, C. W. and Wu, X. L. (2015) Velocity Estimation for the Impact of Foreign Object against the Aero-engine Blade. Journal of Air Force Engineering University (Natural Science Edition). 16, 7-10.

[18] Hallquist J O. LS-dyna Theoretical Manual [C]// 1991.

[19] Zhu G. F, Zhang Z.P, Gao P. P, et al. Comparison of damage mechanism for TC4 Blade of steel ball and sand shock [J]. Fresenius Environmental Bulletin, 2017, 26 (12): 8078 - 8083.