The use of laser shock processing for extension of service life of critical units of aircraft engines after the foreign object damage

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Abstract. The authors study the change of the rate of growth of fatigue cracks that occur due to the damage of surface of an engine blade made of the alloy Ti-6Al-4V, previously processed by laser shockwaves, by foreign objects. The numerical study of the model of damaged laser-processed blade was performed by finite element method. The model developed took into consideration the residual stress fields that occurred due to the foreign object damage as well as the effect of the crack closure under compressive residual stresses. To cause the growth of fatigue cracks, the blade was stressed using real operation modes, including low- and high-cycle fatigue and the combination thereof. The residual stresses, previously inserted into laser shock processing blade surface, complicate the origin and growth of fatigue cracks after the foreign object damage, extending the service life of the blade and the entire engine.

1. Introduction
The open elements of aircraft, such as wings, aircraft engine turbine blades, subject to foreign object damage during the aircraft motion. Such objects, even smaller than 3 mm, are able to reduce the fatigue design life of the most critical and highly stressed aircraft elements by more than 50 % [1]. The damages are characterized by the lost material weight, the dent depth, shock angle and redistribution of residual stresses around the dent perimeter. The foreign object damage (FOD) is one of the main factors reducing service life of aircraft engine blades and wings.

The FOD effect on aircraft structural elements made of titanium alloy Ti-6Al-4V has been previously studied; the studies established that the maximum fatigue hardness reduction up to 50 % occurs in the event of angle hit of the element surface, and the object should be of cubic shape [2].

Laser shock processing (LSP) of Ti-6Al-4V alloy creates the compression residual stresses (CRS) in the upper layer of the material, moreover, they are much deeper than the traditional types of processing, such as shot peening. Such residual stresses reduce the average stress in the cycles, thereby reducing the crack propagation rate [3].

The assessment of the effect of residual stresses from CRS and LSP on stress-strain state (SSS) at the top of the crack and the crack propagation rate is the objective of this work.

2. Study materials and methods
To assess the residual stress distribution, the authors created a 3D finite element model of the front part of the blade (FPB). SSS analysis included two steps: during the first one, FOD in FPB was
modelled to assess the residual stress distribution using finite element packages ABAQUS/Standard and ABAQUS/Explicit; during the second one, the stress-intensity factor, accounting for the residual stress fields and the crack closure due to low-cycle fatigue (LCF) CRS, high-cycle fatigue (HCF) CRS and their combined stress (figure 1) was determined. After that the relation between the effective stress-intensity factors and the rate of fatigue cracks growth is established.

![Figure 1. Blade stress operating unit. Combined stress consists of thousand HCF cycles, included into one LCF cycle.](image)

The study material is the titanium alloy Ti-6Al-4V with the same properties: ultimate tensile strength \( \sigma_u = 980 \) MPa; flow stress \( \sigma_{0.2} = 860 \) MPa, Poisson’s ratio \( \nu = 0.3 \); elastic modulus \( E = 116 \) GPa [4].

FOD is modelled by the hit of a steel cube 50–60 HRC hard, side length 3 mm, on FPB, at the speed of 250 m/s at the angle of 45° and 200 m/s at the angle of 0° (figure 2).

![Figure 2. The diagram of FOD of FPB: a – FOD at the angle of 45°, b – FOD at the angle of 0°.](image)

During blade LSP, the optimal ratio between its geometry distortion and the induced residual stresses was observed. The main processing parameters: processed surface area: \( 66 \times 6 \) mm\(^2\); pulse duration: 27 ns; overlapping degree – 50%; laser spot area: \( 3 \times 3 \) mm\(^2\); laser power density is 10 GW/cm\(^2\).

Johnson–Cook model was used for SSS calculation [5]:

\[
\sigma = \left( A + B\bar{e}^n \right) \left( 1 + C\dot{\bar{e}}^\gamma \right) \left[ 1 - (T^* - T_0)^m \right],
\]

where \( \sigma \) – a von Mises equivalent stress; \( \bar{e} \) – an equivalent plastic deformation; \( \dot{\bar{e}} = \dot{\bar{e}}/\bar{e}_0 \) – a dimensionless equivalent strain rate (\( \bar{e}_0=1.0 \) s\(^{-1}\)); \( T^* \) – a homological temperature, which relationship with the absolute temperature \( T \) is determined as follows:

\[
T^* = (T - T_0)/(T_m - T_0),
\]

where \( T_0 \) – is the ambient temperature; \( T_m \) – is the sample material melting temperature, \( A \) – is the static limit of yield point; \( B \) – is the strain hardening modulus; \( n \) – is the exponent in strain hardening law; \( C \) – is the strain rate coefficient; \( m \) – is the exponent in thermal softening law.

Strain in material spall is determined using the Johnson–Cook model dynamic fracture model:
\[ \varepsilon_f = [d_1 + d_2 \exp \left( \frac{d_3 P}{q} \right) \left[ 1 + d_4 \ln \frac{T}{T_0} \right]} \left( 1 + d_5 \frac{T - T_0}{T_m - T_0} \right) \]  

where \( d_1 - d_5 \) are Johnson–Cook fracture (spall) parameters, taken at ambient temperature \( T_0 \).

The values of effective stress intensity factors are determined by the following sequence: first \( J \)-integrals values are determined at the maximal stress and crack opening stress, after that the crack opening stress in calculated in the units along the crack front, further, the stress intensity factor (SIF) values are calculated at maximal stress and crack opening stress \( K_{\text{max}}, K_{\text{op}} \) correspondingly by the average values of the corresponding \( J \)-integrals, and, finally, the range of effective stress intensity factors is determined in the peals of cracks \( \Delta K_{\text{eff}} \) :

\[ \Delta K_{\text{eff}} = K_{\text{max}} - K_{\text{op}}. \]  

3. Results and discussion

The determined values of residual stress distribution have shown the coincidence of the calculated modelling parameters and the experiment (figure 3a, b).

![Figure 3. Residual stress distribution coefficient depending on the distance to FPB. The diagram of FOD direction in FPB: a – after blade LSP, (the line) shows the finite element calculation (FEC), (o) experimental data from [6], 1 – stresses, perpendicular to crack growth plane \( \sigma_{xx} \), 2 – stresses along the crack growth \( \sigma_{zz} \); b – after FOD at 0°, 1 – \( \sigma_{xx} \) experimental data from [6], 2 – \( \sigma_{xx} \) FEC, 3 – \( \sigma_{yy} \) FEC, 4 – \( \sigma_{zz} \) FEC.](image)

The calculated depth of dent due to FOD at 0° is 1.29 mm, the experimental one is 1.43 mm.

The comparison of residual stresses before and after FOD shows their redistribution, RCS after LSP on the surface were –600 MPa, after FOD they decreased to –200 MPa.

FOD at the angle of 45° produces 0.77 mm deep V-dent.

The values of residual stresses perpendicular to crack growth plane \( \sigma_{xx} \) are of primary importance for origin and growth of fatigue cracks (figure 4a, b).

In figure 4a the points A and B show the potential sites of occurrence of fatigue cracks after FOD at 0°, because the tensile residual stresses (TRS) are concentrated in them, whereas CRS pre-dominate in the inner part of the blade, they will oppose to the formation of new cracks.

During the FOD at 45°, RCS are concentrated at point A (figure 4b), and RTS are concentrated at point B in a small area, they are the most dangerous. However, after generation at point B the crack will run into CRS field that will slow down its further development.

The analysis of regularities of the rates of growth of fatigue cracks and the resulting stress intensity factor \( \Delta K_R \) has shown that at the small crack length in OCS field there is no correlation between the analyzed values. The introduction of the crack closure effect into analysis made it possible to determine that the fatigue crack growth is possible at small values. The fatigue cracks growth rates depending on various stress intensity coefficients are provided in figure 5a, b, c.
Figure 4. The curves of residual stresses perpendicular to crack growth plane: \textbf{a} – after FOD at 0°, \textbf{b} – after FOD at 45°.

Figure 5. Dependence of fatigue cracks growth rates on various stress intensity factors and stress mode: \textbf{a} – LCF, \textbf{b} – HCF, \textbf{c} – Combined. □ – ΔK; Δ – ΔK_R; ○ – ΔK_{eff}.

The maximal effect of residual stresses on the crack growth rate is observed at combined stress (figure 5c). All the dependencies converge in the upper part of the curves, which certifies the correct-ness of the selected task solution approaches.

The analysis has shown that only the consideration of residual stresses and the crack closure effect can provide the correct analysis of fatigue cracks growth.

4. Conclusions

The authors have studied the growth of fatigue cracks that occur from FOD in FPB of titanium alloy Ti-6Al-4V, previously processed by LSP at various operating stress modes. The residual stresses, previously inserted into blade surface and LSP greatly affect the origin and growth of fatigue cracks and,
therefore, the service life of the entire engine. Blade LSP makes it possible to reduce stresses in the dangerous points which delays the origin and development of fatigue cracks. FOD at 45° is more dangerous than at 0°. Hit modelling using Johnson–Cook model provides the results well correlating with the experiment. To obtain the real correlation of fatigue cracks rates correlation with the range of effective stress intensity factors, it is necessary to consider the residual stresses and the crack closure effect. RCS significantly affects the fatigue crack growth, especially at combined stress.

The increase in the fatigue characteristics of the material is associated with the rise in microhardness and the creation of high compressive stresses that prevent the generation and propagation of cracks in the surface layers of the material.

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