Estimation on stress concentration factor of remanufacturing notch for TC4 titanium alloy

Mingchao Ding¹, Yuanliang Zhang¹* and Hongwei Xian¹

¹ School of Mechanical Engineering, Dalian University of Technology, Dalian, Liaoning, 116024, China

*Corresponding author’s e-mail: zylgzh@dlut.edu.cn

Abstract. Remanufacturing notch would be produced after crack polishing in remanufacturing pre-treatment. In the present study, stress concentration of remanufacturing notch was investigated by a series of semi-elliptical notch models using finite element analysis. Comparing with notch width, notch depth has a critical effect on stress concentration. An equation to estimate stress concentration factor (SCF) has been modified to be suitable for remanufacturing notch. Based on the pre-estimation of stress concentration for remanufacturing notch, references on crack polishing plan can be provided in the remanufacturing field.

1. Introduction

The remanufacturing of damaged blades is an effective way to make full use of remaining parts, with great advantages of sustainable development. Abandoning the blades with surface defects such as cracks can result in terms of both energy consumption and financial expenditure. Remanufacturing of the blades with various defects is highly demeaned for the aerospace enterprises considering sustainable development[1-2]. Remanufacturing is a technique that can give a new service cycle to the damaged blades.

Under the severe service environment such as high centrifugal force and variable aerodynamic load, there is great possibility to fatigue crack. Aero-compressor blades with surface defect such as crack cannot be directly applied to remanufacturing engineering. The pre-treatment of surface defect is a primary step in current remanufacturing engineering to match with the subsequent processes such as detection and laser cladding technology[3]. For cracked blade, crack polishing is widely used to provide a regular and neat interface. After crack polishing, a notch with length would be produced on the surface of blade, which defined as remanufacturing notch in this paper. The local stress field of remanufacturing notch must be known in order to fatigue life prediction of structure, which can provide references in remanufacturability judgment[4-5].

Remanufacturing notch possesses the characteristics of a smooth transition after crack polishing. A single semi-elliptical can be used to describe the section shape. The elastic stress concentration factor (SCF), $K_t$, is widely used to express the local stress filed. However, few lectures or models are prosed to calculate SCF of remanufacturing notch. Cerit[6-7] concluded that semi-elliptical corrosion pit aspect ratio ($a/2c$) is the main parameter affecting stress concentration factor (SCF). To facilitate engineering application, a simple equation to estimate SCF depending on the characteristic of pit parameters was proposed. It should be pointed out that the coefficients of SCF equation for semi-elliptical pit maybe not suitable for remanufacturing notch considering the difference in geometric characteristics.
In this paper, the stress concentration of remanufacturing notch with a single semi-elliptical was investigated. A series of finite element models with various notch depth and width were calculated under uniaxial loading. An SCF equation was modified for remanufacturing notch based on finite element analysis results.

2. Finite element analysis

The material used in this paper is TC4 titanium alloy. TC4 is an α-β titanium alloy which is widely used in the aeronautical blade due to outstanding mechanical features such as low density, high-temperature specific strength, creep, oxidation and corrosion[8]. Density, Modulus of elasticity and Poisson's ratio of TC4 titanium alloy are given as 4.44g/cm$^3$, 107GPa and 0.34, respectively.

![Figure 1](image)

Figure 1. (a) The dimension of notch model, (b) Profile of section A-A

Figure 1 (a) shows the dimension of remanufacturing notch. After crack polishing, the bottom of the notch is circular transition in order to avoid additional stress concentration on the surface of blade. Therefore, the section shape of notch model was designed as a single semi-elliptical as shown in figure 1(b). $W$ is referred to notch width and $D$ is referred to notch depth. The determination of notch depth depends on crack depth, varying from 0.5mm to 2mm. Based on crack polishing in engendering practice, notch widths range from 4mm to 12mm. Subsequently, the ratio of depth and width varies from 0.042 to 0.5. The length of notch was designed as 10mm, assuming crack with 10mm in length.
Figure 2. Quarter finite element model of a notch

The commercial software Hypermesh and ANSYS version 19.2 were utilized to establish the finite element model and solve the stress distribution, respectively.

The notch owns the geometric characteristics of quarter symmetry as shown in Figure 2. Only a quarter of the model was given in figure 2. In terms of meshing, the entity notch was refined with 8-node hexahedral element as shown in figure 2. To ensure the accuracy of calculation results, the element size was selected as 0.1mm for the critical location of notch as shown in figure 2(b). However, for the areas that have little effect on notch stress distribution, the element size was selected as 1mm to reduce the calculating time of finite element calculation.

Structure has symmetry with respect to the loading and geometry. Axial loading with 400MPa is applied to one side and full constraints are applied to the other side of the model as shown in figure 2(a).

3. SCF equation for remanufacturing notch

Figure 3 shows the stress distribution of two notches with 0.5 mm in depth and 4 mm in width and 1.4 mm in depth and 8 mm in width. It can be seen that stress concentration happened at the bottom center of the notch. Corresponding the maximum principal stress is 602MPa and 733 MPa, respectively. Notches in other sizes possess the same location of maximum principal stress. Four sides of notch may have no obvious effect on the stress distribution of the bottom center of the notch.

In this paper, the elastic stress concentration factor $K_t$ is defined as the ratio of the local maximum principal stress to the gross nominal stress. So, SCF of the notch in figure 3 is 1.505 and 1.832.
As can be seen in figure 4(a), for a given notch depth, $K_t$ tends to decrease with the increasing of notch width. For notch with 0.5mm in depth, $K_t$ vary from 1.208 to 1.505 only as notch width increasing by 8mm. However, for notch depth notch with 2mm in depth, range of $K_t$ can reach to 1 under the same width range. It can be concluded that the effect of notch width on $K_t$ may depend on notch depth.

For a given crack depth, increasing polishing width can reduce stress concentration as expected. What is more, $K_t$ inclines to become stable when notch width exceeds 10mm. Consequently, it can be inferred that excessive polishing width may have little effect on reducing stress concentration distance. Polishing width of 10mm may be a critical value roughly.

What is more, once notch depth increases by 0.3mm, the whole curve of $K_t$ will move upward parallel. Therefore, comparing with notch width, notch depth exerts a significant influence on $K_t$. So, facing with parts with deep crack, the decision of crack polishing plan should be careful to make.

The basic model reflecting the relationship between $D/W$ and $K_t$ from Cerit for pit with semi-elliptical is given as equation (1).

$$K_t = \frac{1 + a (D/W)}{1 + b (D/W)}$$

(1)

where $a$ and $b$ are material constant, which related to notch shape and material.

For remanufacturing notch, notch shape can be assumed as single semi-elliptical. Stress distribution mainly affected by notch size and stress amplitude. The relationship between $D/W$ and $K_t$ is given in figure 4(b). It is possible to conclude that there is a reasonable correlation between $D/W$ and $K_t$ for remanufacturing notch. That is agreement with Cerit’ research.

Based on the results of finite element analysis, an estimation of $K_t$ for remanufacturing notch is modified according to Cerit’ model.
\[ K_t = \frac{1+5.74(D/W)}{1+0.5241(D/W)} \]  

The coefficient of determination \( R^2 \) by using equation (1) is 0.9844.

Once fatigue crack from blade surface is detected, the polishing depth can be determined as constant \( D \). In terms of the polishing width \( W \), the value can be chosen from 4mm to more according to man-made decision. The different combination of \( D \) and \( W \) can lead to various stress concentration. With the assistance of equation (2), \( K_t \) of various remanufacturing notch can be pre-estimated.

\( K_t \) can be a significant parameter in fatigue life prediction of the component with notch. Equation (2) provides a convenient method to obtain the essential \( K_t \), making a contribution to fatigue life prediction of remanufacturing notch. Basic parameters \( K_t \) for fatigue life prediction and subsequent remanufacturability judgment of cracked blade can be provided by equation (2).

4. Conclusions
In this paper, stress concentration of remanufacturing notch with semi-elliptical shape was studied by finite element models. Depending on the finite element analysis, the maximum stress occurs at the bottom center of notch. Comparing with notch width, notch depth exerts a significant influence on \( K_t \). When the notch width exceeds 10 mm, the effect of notch width on \( K_t \) gradually decreases and tends to be stable. It is confirmed that for remanufacturing notch SCF is also predominantly influenced by the aspect ratio \( (D/W) \). Based on Cerit’s model, an equation to estimate SCF for remanufacturing notch is modified.

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