

Fatigue Life Prediction of an Impeller Based on Fracture Mechanics

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Abstract—Welding structure is widely used in impellers fitted on the large centrifugal compressor and the crack propagation life prediction is studied based on the fracture mechanics. First the finite element structure strength analysis is carried on the three-dimensional entity model of the impeller, and the dangerous area of the structure is determined. Then based on the mechanical similarity and geometric similarity principles, a simplified two-dimensional model of the dangerous area is established. According to the simplified model, the stress intensity factors of two typical kinds of the center crack and the edge crack are calculated and functions of the stress intensity factor changed with the crack length are obtained. Finally, using the mixed mode crack propagation model, the fatigue crack propagation life of the edge crack is estimated by iterative method. The fatigue life prediction method and calculation procedure of the impeller structure is summed up based on the fracture mechanics.

Keywords—impeller; life prediction; equivalent model; stress intensity factor; crack propagation

I. INTRODUCTION

The impeller is the core component of the high-speed centrifugal compressor rotor. Due to the complexity of the work environment and the structure of the impeller, the fatigue damage often happens. With the increase of diameter and exit width of the impeller, the cracks initiate more easily and gradually extended to fracture, which seriously affect the safe operation of the compressor set. In this paper, the crack propagation life prediction of the first ternary closed impeller for a centrifugal compressor is studied based on the fracture mechanics.

II. FINITE ELEMENT STRUCTURE STRENGTH ANALYSIS

A. Structure of the Impeller

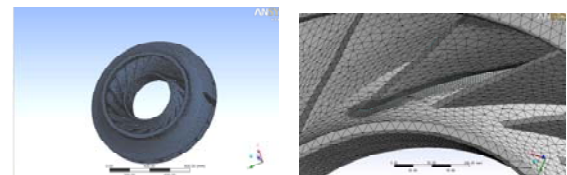
The ternary closed impeller is widely used in impellers fitted on the large centrifugal compressor, which the disk, blade and shroud were welded to. The blade is composed by 19 slices which structure is spatial curved surface, and the diameter of the impeller is 1390mm, as shown in Figure 1.

B. Material and Meshing

The material of the impeller is FV520B which Elastic modulus, Poisson's ratio, Density and Yield strength are 210GPa, 0.3, 7860kg/m³ and 1100MPa respectively. Solid 187



FIGURE I. MODEL OF THE IMPELLER



(A) THE WHOLE GRID (B) LOCAL GRID REFINEMENT

FIGURE II. MESHING OF THE IMPELLER

unit is used in meshing, as shown in Figure 2, which consists of 390564 elements and 614542 nodes.

C. Loading and Constraint

Fixed displacement is restrained on the shaft hole. The rotate speed is 459.07rad/s, and the pressure field of fluid-solid coupling form which obtained by aerodynamic analysis is applied on the shroud, disk and blade, as shown in Figure 3.

D. Analysis Results

The stress distribution of the impeller was shown in Figure 4. It can be seen that the distribution of stress is axisymmetric, and the maximum stress is located in the connection between the blade and the wheel, as shown in Figure 4b.

III. ESTABLISHMENT OF AN EQUIVALENT MODEL OF THE DANGEROUS AREA

Based on the mechanical similarity and geometric similarity principles, an equivalent model of the dangerous area is established, as shown in Figure 5. The maximum error of the node stress nearby the dangerous area between the equivalent and original models is less than 1.6 percent.

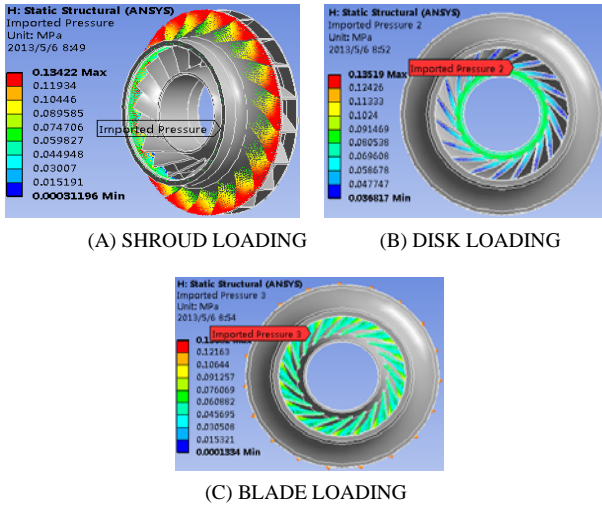


FIGURE III. AERODYNAMIC LOADING

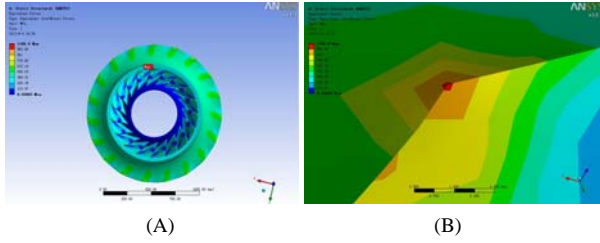


FIGURE IV. STRESS DISTRIBUTION

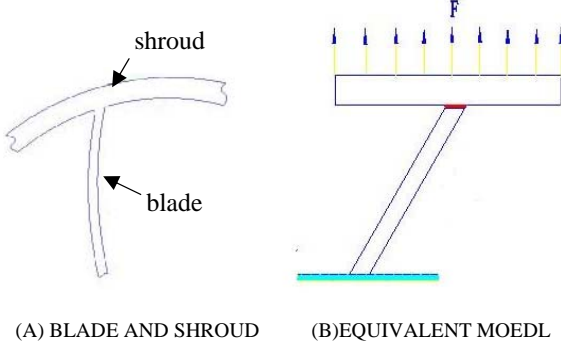


FIGURE V. EQUIVALENT MOEDL OF THE DANGEROUS AREA

IV. DETERMINATION OF STRESS INTENSITY FACTORS

Cracks initiation would be easy to occur where the position welded due to the stress concentration, process defects and material defects. The most common forms of crack include the centre crack, edge crack and surface crack, in which the surface cracks are easily found and remedied in the manufacturing process, so the growth behaviors of the centre crack and edge crack were analyzed here.

The stress intensity factor is an important parameter in the analysis of crack propagation, which can determine the stress, strain and displacement near crack tip point. The stress intensity factor must be calculated before estimating the fatigue crack propagation life. In this paper, the stress intensity factor

of the dangerous point is calculated by finite element method using the equivalent model.

A. Crack Modeling

Private welding rod for FV520B is used, and the material around the weld joint is distinguished to the weld zone and thermal response zone as shown in Figure 6.

Then the element type is set to PLANE183, and the crack tip singular elements are created, for example, the center crack is established as shown in Figure 7.

B. Results and Analysis

Set the crack length, define the crack path, and solve. Then K_I and K_{II} are obtained under the state of plane stress. The stress intensity factors of the center crack and the edge crack are shown in Table 2 and Table 3 respectively.

Taking the edge crack for example, the fitting curves of the stress intensity factor K_I and K_{II} can be obtained by fitting data in Table 2, which were shown in Formula (1) and (2), Figure 8 and Figure 9.

$$y = 249.0249 + 2.0591t + 0.1477t^2 \quad (1)$$

$$y = 86.6066 + 21.2528t - 2.5694t^2 \quad (2)$$

It can be seen that I-II mixed mode crack grows in the early time of the crack propagation. With the increase of the crack length K_I is increased and K_{II} is tend to a fixed value, which lead to the increased ratio of K_I and the crack turn to open type. It was also found that in the condition of the same crack length the stress intensity factor of edge crack is much higher than the center crack.

V. PREDICTION OF FATIGUE CRACK PROPAGATION LIFE

A. Cracking Direction and Criterion of Mixed Crack

For the mixed mode crack, the crack initiation angle is determined by the criterion of maximum stress in tangential direction. The formula is as follow:

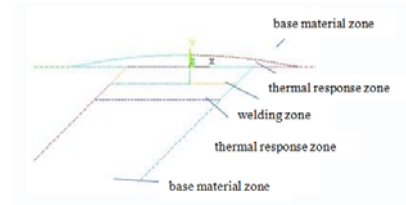


FIGURE VI. MATERIAL AROUND THE WELD JOINT

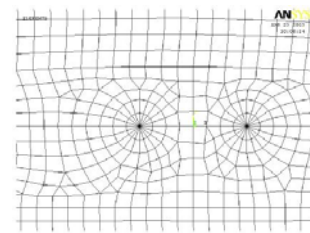


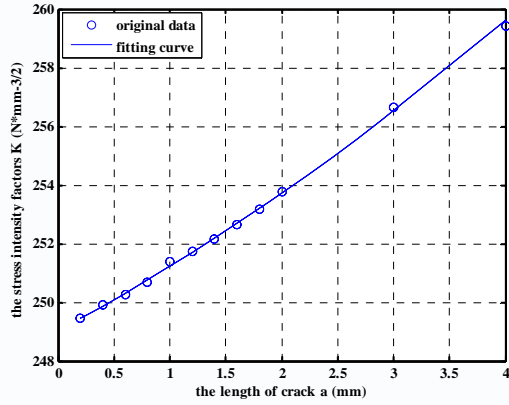
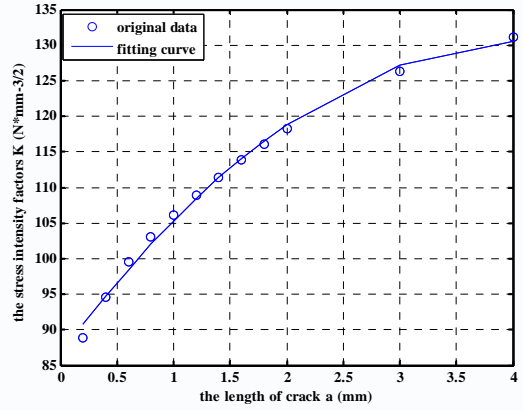
FIGURE VII. MESH OF CRACK TIP

TABLE I. RESULTS OF THE CENTER-CRACK STRESS INTENSITY FACTORS

No.	The length of crack a(mm)	The crack tip A		The crack tip B	
		K_I ($N \cdot mm^{3/2}$)	K_{II} ($N \cdot mm^{3/2}$)	K_I ($N \cdot mm^{3/2}$)	K_{II} ($N \cdot mm^{3/2}$)
1	0.2	30.517	14.850	29.903	14.392
2	0.4	43.018	20.794	42.640	20.511
3	0.6	52.597	25.372	52.493	24.996
4	0.8	60.492	29.243	57.465	26.440
5	1.0	67.652	32.978	67.027	31.839
6	1.2	73.842	36.164	72.969	34.696
7	1.4	79.491	39.067	78.323	37.268
8	1.6	84.703	41.753	83.205	39.608
9	1.8	89.568	44.257	87.656	41.762
10	2.0	94.181	46.632	91.800	43.787

TABLE II. RESULTS OF THE EDGE-CRACK STRESS INTENSITY FACTORS

No.	The length of crack a(mm)	K_I ($N \cdot mm^{3/2}$)	K_{II} ($N \cdot mm^{3/2}$)
1	0.2	249.443	88.905
2	0.4	249.901	94.540
3	0.6	250.260	99.493
4	0.8	250.680	103.040
5	1.0	251.390	106.150
6	1.2	251.740	108.890
7	1.4	252.160	111.442
8	1.6	252.649	113.815
9	1.8	253.180	116.080
10	2.0	253.783	118.232
11	3.0	256.638	126.291
12	4.0	259.432	131.147

FIGURE VIII. FITTING CURVE OF K_I FIGURE IX. FITTING CURVE OF K_{II}

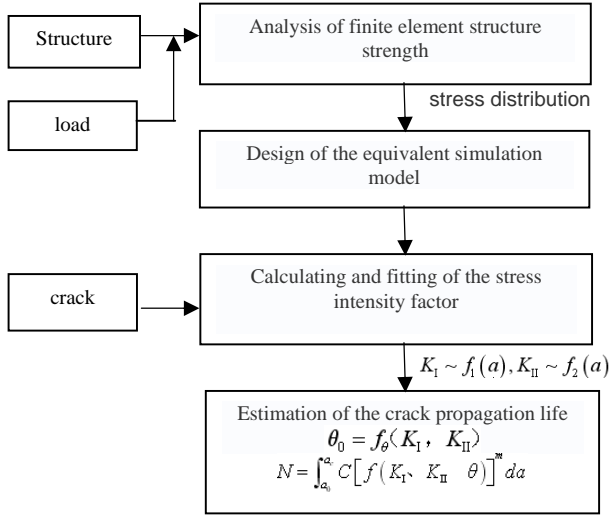


FIGURE X. PREDICTION OF FATIGUE CRACK PROPAGATION LIFE

$$\theta_0 = \arccos \frac{3K_{II}^2 + \sqrt{K_I^4 + 8K_I^2 K_{II}^2}}{K_I^2 + 9K_{II}^2} \quad (3)$$

The material failure criterion of the mixed mode crack propagation, namely crack unstable propagation condition, is shown in Formula (4):

$$\frac{1}{2} [K_I (1 + \cos \theta_0) - 3K_{II} \sin \theta_0] \cos \frac{\theta_0}{2} = K_{Ic} \quad (4)$$

where, K_{Ic} is Fracture toughness of type I crack; K_I and K_{II} are the stress intensity factors of type I and II crack respectively; θ_0 is the crack initiation angle.

B. Life Prediction Model of the Mixed Mode Fatigue Crack

Based on the Paris formula (5), in which the combined stress intensity factor ΔK^* showed in Formula (6) is substituted, the life prediction formula (7) was obtained.

$$\frac{da}{dN} = C (\Delta K^*)^m \quad (5)$$

$$\Delta K^* = \frac{1}{2} (1 + \cos \theta_0) \sqrt{\Delta K_I^2 - \frac{4 \sin \theta_0}{(1 + \cos \theta_0)} \Delta K_I \Delta K_{II} + \frac{(5 - 3 \cos \theta_0)}{(1 + \cos \theta_0)} \Delta K_{II}^2} \quad (6)$$

$$N = \int_{a_0}^{a_c} \left\{ C \left[\frac{1}{2} (1 + \cos \theta_0) \sqrt{\Delta K_I^2 - \frac{4 \sin \theta_0}{(1 + \cos \theta_0)} \Delta K_I \Delta K_{II} + \frac{(5 - 3 \cos \theta_0)}{(1 + \cos \theta_0)} \Delta K_{II}^2} \right]^m \right\} da \quad (7)$$

where, a_0 is the initial crack length; a_c is the termination crack length; ΔK_I and ΔK_{II} are the amplitudes of stress intensity factor. θ_0 is the crack initiation angle; C and m are the material constants.

C. Prediction of the Fatigue Crack Propagation Life

Finally, the crack propagation life of the edge crack is calculated. Take $a_0 = 0.02\text{mm}$, $a_c = 4\text{mm}$,

$$\Delta K_I = 249.0249 + 2.0591a + 0.1477a^2,$$

$$\Delta K_{II} = 86.6066 + 21.2528a - 2.5694a^2 \quad \text{and}$$

$$\theta_0 = \arccos \frac{3\Delta K_{II}^2 + \sqrt{\Delta K_I^4 + 8\Delta K_I^2 \Delta K_{II}^2}}{\Delta K_I^2 + 9\Delta K_{II}^2}$$

into Formula (7), and take 0.01 for the integral iteration step distance, it can be obtained that $N=36736$ times.

D. Steps for Predicting Fatigue Crack Propagation Life

The steps of predicting fatigue crack propagation life of the impeller is shown in Figure 10.

VI. CONCLUSIONS

(1) The structural strength of the impeller is analyzed under the steady-state loading condition. The stress distribution of the welding area between the blades and the wheel are obtained, which is considered as the most dangerous position. It provides the basis for the simplified model.

(2) According to the mechanical and geometry similarity principle, a simplified two-dimensional model of the impeller with the welding area is established, which provided feasible solution for simulating the stress intensity factors.

(3) Combined with fracture mechanics, the stress intensity factors of two typical kinds of the center crack and the edge crack are calculated and functions of the stress intensity factor changed with the crack length are obtained by curve fitting. The simulating results are very valuable to the prediction of crack propagation life.

(4) Using the mixed mode crack propagation model, the fatigue crack propagation life of the impeller is estimated. The fatigue life prediction method and calculation procedure of the impeller structure is summed up based on the fracture mechanics, which are advantageous to the fatigue life prediction of similar structure.

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