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DESIGN METHOD FOR THE FATIGUE-SIMULATING SPECIMEN OF TWIN-WEB TURBINE DISK

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Abstract

A new design criterion as well as design method for the fatigue-simulating specimen of Twin-web turbine disk was proposed, and the simulated specimen for twin-web turbine disk throat was designed. Results showed that the maximum Von-Mises stress, stress gradient and equivalent detrimental volume were similar between the specimen and the turbine disk, with the maximum difference between the stress gradients being 2.48%, while for the maximum Von-mises stresses the difference was merely 0.2%, and their probabilistic fatigue lives were basically the same, which indicated that the fatigue-simulating specimen designed could effectively represent the fatigue characteristics of Twin-web turbine disk throat.

Keywords: Twin-web turbine disk; Fatigue-simulating specimen; Fatigue damage; Stress gradient; Probabilistic fatigue life

1. General Introduction

Twin-web turbine disk is a new type of aero-engine turbine disk, which has the advantages of comparatively uniform stress, light weight and excellent performance [1-2]. While at the same time, it has more critical regions than traditional turbine disks, such as the inner cavity, the cooling hole and so on [3], which brings great challenges to accurately predict the fatigue life of Twin-web turbine disk. In engineering, numerical simulation and experimental evaluation are mainly used to analyze the probabilistic fatigue lives of turbine disks. The commonly used fatigue life reliability analysis method can only consider a few main factors, and the accuracy of numerical simulation results must be verified by experiments [4]. However, the cost of Twin-web turbine disk is very expensive, and the fatigue test always takes a long time, hence the test data is quite few. Considering that fatigue life has certain dispersion, in order to obtain more accurate probabilistic fatigue life, it is necessary to carry out large sub-sample experimental researches [5-6]. The simulated specimen has the advantages of simple structure, small size, and can represent the fatigue characteristics of the critical part of the turbine disk to a certain extent, which makes it possible to carry out larger samples of fatigue test. Therefore, in practical engineering, the fatigue reliability of turbine disk is studied by using the test results of many sub-samples of simulated specimens and a few real turbine disk fatigue tests [7].

The commonly used method for simulated specimens includes one-dimensional method and two-dimensional method. Since the design of three-dimensional simulated specimens is quite difficult, the related application has not been found in open reference. The one-dimensional simulated specimen, also known as the "accompanying bar specimen", mainly applies the stress or strain of the critical region of the component directly to the standard smooth bar, and can only simulate the simple uniaxial tensile condition, while ignoring the effects of stress gradient and detrimental volume. The two-dimensional simulated specimen is a plate with hole in most cases, and the stress concentration of the hole can reflect the influence of stress gradient. Therefore, the two-dimensional simulated specimens are more commonly used to simulate the critical components of the turbine disk in engineering [7-10]. Ruiz [11] studied the design method of specimen for fretting damage of dovetail groove, which simulated the actual working condition as well as connection on the real turbine disk by loading in horizontal and vertical direction. Zhao [7] gives a variety of typical styles of simulated specimens, explains the design criterion of two-dimensional simulated specimens according to the basic fatigue mechanism, and puts forward the design method of simulated specimens with the same strain range $\Delta\varepsilon_m$ and mean stress σ_m at the maximum stress point. In order to solve the problem of low cycle fatigue, a design method is proposed by Li [12] to ensure that the equivalent plastic strain and equivalent total strain of the simulated specimen at the maximum strain point keep the same as those of the real structure. Li [13] put forward a simulated specimen design method for high cycle fatigue, in which the ratio of six stress components at the maximum stress point of the simulated specimen is consistent with that of the real structure. Liu [14] designed the simulated specimen of a compressor disk tenon groove by making the maximum principle stress and stress gradient of the simulated specimen the same as the critical part of the compressor under elastic conditions. On the basis of Liu, Lu [15] put forward a simulated specimen design method suitable for arbitrary first principal stress gradient path. What’s more, some scholars [16] have designed the simulated specimens by ensuring that the first principal stress range and the first principal strain range are similar between the simulated specimen and the real structure in engineering detectable crack length.

It can be seen that the design of simulated specimens is mainly under elastic loading conditions, while the redistribution of stress after entering plasticity in critical parts has not been considered yet. Meanwhile, the similarity of stress gradient between simulated specimen and real structure is commonly used in practice to account for the influence of stress concentration, however the influence of different geometric size on fatigue life has not been considered as well. Considering that the fatigue life of turbine disk is affected by many factors, such as loading condition, stress concentration, mean stress effect, size effect and so on, this paper takes the similarity of maximum Von-Mises stress and stress gradient near the critical point as design criterion to ensure the similarity of the stress field in the critical region of twin-web turbine disk, combining with the similarity of fatigue damage to account for the influence of geometry size on fatigue life, thus proposes a design method for elastoplastic fatigue-simulating specimen based on maximum Von-Mises stress, stress gradient and fatigue damage. Finally, the fatigue-simulating specimen which can effectively represent the fatigue characteristics of the Twin-web turbine disk throat is designed.

2. Design Method for the Fatigue-Simulating Specimen

2.1 Criterion for Fatigue-Simulating Specimen Design

Fatigue cracks generally occur on the surface or subsurface (for defects, inclusions, etc. cases) in the critical region of turbine disk. In finite element analysis, it is generally assumed that the surface of turbine disk is smooth, and there are no defects inside, thus, cracks are more likely to occur at the maximum Von-Mises stress point, so the maximum Von-Mises stress point of the finite element analysis results is taken as the critical point. Based on the theory of fatigue mechanics, it can be known that crack will propagate along the direction of the smallest strain energy density factor at the crack tip, and the normal stress at the crack tip will have an important influence on the crack growth rate. Obviously, the Von-Mises stress at the critical point, the strain energy density factor and the normal stress at the crack tip are all highly related to the stress distribution in the critical region of turbine disk. However, considering that there will be some differences in geometric shape, size and load condition between the simulated specimen and the real turbine disk component, especially under complex stress conditions, therefore, the maximum Von-Mises stress gradient near the critical point is considered as the comprehensive characterization parameter of the stress field, that is, when the maximum Von-Mises stress and stress gradient of the simulated specimen and the real turbine disk component are similar or the same, it can be considered that the stress distribution near the critical point is also approximately the same.

In addition, considering that the detrimental volume also has an important influence on the fatigue life, it is necessary to consider the influence of size effect in the design of the simulated specimen. However, in most cases, the difference of the geometric size between the real turbine disk component and the simulated specimen is so big that it is difficult to ensure the geometric volume of the critical region to be exactly the same. Therefore, this paper proposes a method to ensure the equivalent volume [17] of the critical region of the turbine disk and the simulated specimen to keep the same under loading and unloading conditions. The "equivalent volume" here refers to the same damage contained in different geometric volumes, which can be calculated by Equation (1). Obviously, it can be known that the equivalent volume not only relates to the real detrimental volume of the component, but also closely related to the loading and unloading state. Figure 1 shows the relationships among the fatigue life (N_{f}), equivalent volume (V_{eff}) and stress ratio (R) for the standard smooth bar of FGH96 material at 550℃, while the σ_{t} and R_{t} are target stress and target stress ratio [17]. It can be seen that the influence of detrimental volume on fatigue life can be equivalently reflected by changing the unloading load while keeping the loading load unchanged, which can compensate for the geometric volume difference between the simulated specimen and real turbine disk component.

$$V_{\mathrm{eff}} = \frac{V_0}{\mathrm{In2}}\left[\frac{N_{\mathrm{f,t}}(\sigma_t,R_t)/N_f(V_{\mathrm{ref}},P_{f=50\%})-\gamma}{\eta}\right]^{\beta} \tag{1}$$

while, V_0 is the geometric volume of the detrimental region, $N_{\mathrm{f,t}}$ is the target fatigue life, V_{ref} is reference volume which can be obtained by standard smooth bar at σ_{t} and R_{t}, $P_{f=50\%}$ represents the failure probability of 50%, γ, η and β are the location parameter, size parameter and shape parameter of Weibull distribution, respectively.

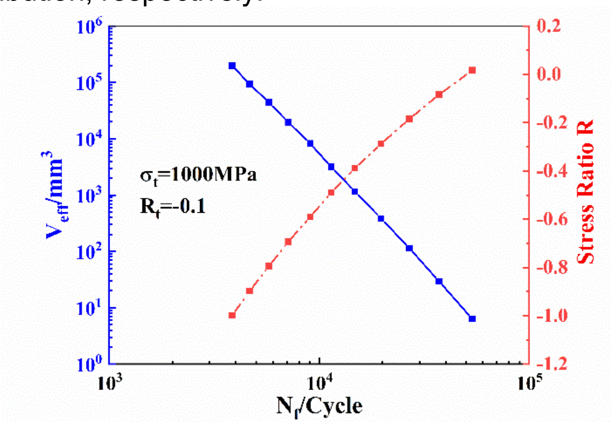


Figure 1-The relationship among equivalent volume, stress ratio and fatigue life for FGH96 standard smooth bar

Based on the above, the similarity criterion for fatigue-simulating specimen design of twin-web turbine disk under elastoplastic condition is put forward:

(1) the maximum Von-Mises stresses at the critical point are equal;

(2) the maximum Von-Mises stress gradients near the critical point are basically the same;

(3) the equivalent volume containing fatigue damage in the critical region are basically the same.

When the basic design criterion of the simulated specimen[7] and the above three design criterion are satisfied at the same time, it can be considered that the fatigue life and fatigue characteristics of the simulated specimen and turbine disk component are basically the same.

2.2 Extraction of Von-Mises Stress Gradient

The Von-Mises stress gradient is the direction in which the equivalent stress decays fastest in the crack propagation path. Thus, through the maximum stress and stress distribution near the critical region, the crack propagation path and according propagation plane can be determined, in which the critical point is taken as the center of the circle and Δr is used as the radius step to make a series of circular arcs, then the Von-Mises stress gradient can be obtained through connecting the minimum stress points on each arc, as shown in Figure 2. It is obvious that the smaller the Δr is, the closer the stress gradient will be to the reality.

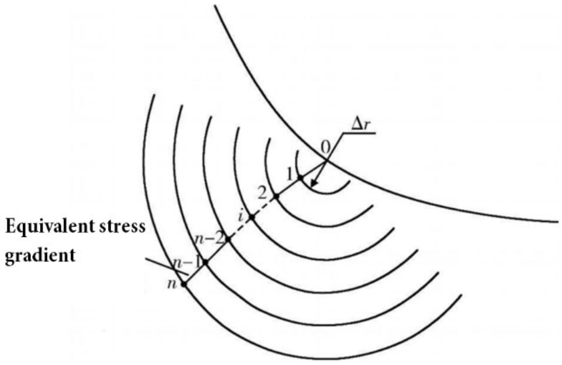


Figure 2-The schematic diagram of maximum stress gradient path extraction

Take $\sigma_{\mathrm{M},0}$ to represent the maximum Von-Mises stress at the critical point, as is the stress for point 0 in Figure 2. Then, the stresses in the Von-Mises stress gradient path can be expressed by:

$$\sigma_{\mathrm{M}} = [\sigma_{\mathrm{M},0}, \sigma_{\mathrm{M},1}, \cdots, \sigma_{\mathrm{M},i}, \cdots, \sigma_{M,n-1}, \sigma_{\mathrm{M},n}] \tag{2}$$

in which $\sigma_{\mathrm{M},i}$ is the Von-Mises stress for point *i* in Figure 2, and Equation (2) is the stress vector for the Von-Mises stress gradient. Obviously, if the stress vector for the simulated specimen and the turbine disk component are basically the same, then the Von-Mises stress gradient near the critical points are similar, as is shown in Equation (3).

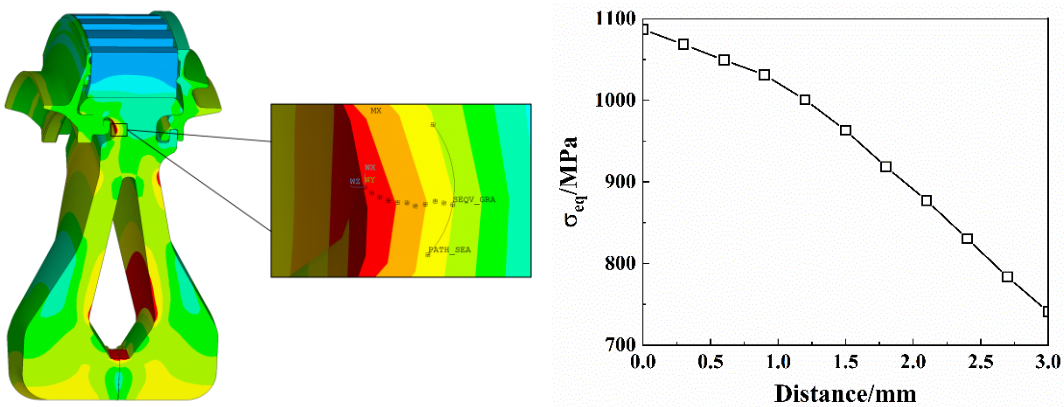
$$\begin{aligned} \|\sigma_{\mathrm{M,res}}\|_1 &= \|\sigma_{\mathrm{M,d}} - \sigma_{\mathrm{M,s}}\|_1 \\ &= |\sigma_{\mathrm{M,d},0} - \sigma_{\mathrm{M,s},0}| + |\sigma_{\mathrm{M,d},1} - \sigma_{\mathrm{M,s},1}| + \cdots + |\sigma_{\mathrm{M,d},i} - \sigma_{\mathrm{M,s},i}| + \cdots \\ &\quad + |\sigma_{\mathrm{M,d},n-1} - \sigma_{\mathrm{M,s},n-1}| + |\sigma_{\mathrm{M,d},n} - \sigma_{\mathrm{M,s},n}| \end{aligned} \tag{3}$$

In Equation (3),$\sigma_{\mathrm{M,d}}$ is the stress vector of Von-Mises stress gradient for turbine disk component, while $\sigma_{\mathrm{M,s}}$ for the simulated specimen, and $\sigma_{\mathrm{M,res}}$ is the stress residual vector. When the minimum value for 1-norm of vector $\sigma_{\mathrm{M,res}}$ is obtained, it can be considered that the Von-Mises stress gradients are basically the same.

3. Design of Simulated Specimen for Twin-web Turbine Disk

3.1 Initial Model for Twin-web Turbine Disk Simulated Specimen

The elastoplastic finite element analysis result of the twin-web turbine disk by ANSYS is shown in Figure 3, in which rotating speed is 19150rpm, and the working temperature is 550℃. It can be seen that Von-Mises stress in the throat region under the rim of turbine disk appears to be quite large, which is one of the critical regions for the Twin-web turbine disk. The throat is approximately a triangular notch with chamfer. Based on the geometric similarity principle of critical region in the simulated specimen design [7], the critical region of simulated specimens should also have corresponding geometric shape. In addition, by changing the position and size of the slot between the clamping section of the specimen and the cavity, the force transmission path in the simulated specimen can be changed accordingly, and then the stress and stress gradient at the critical point of the cavity can be adjusted. In order to facilitate the optimization of the simulated specimen, it is necessary to establish the parametric model of the simulated specimen, as shown in Figure 4.



(a) Stress contour for twin-web turbine disk (b) The Von-Mises stress gradient

Figure 3- The FEA results for Twin-web turbine disk and its Von-Mises stress gradient

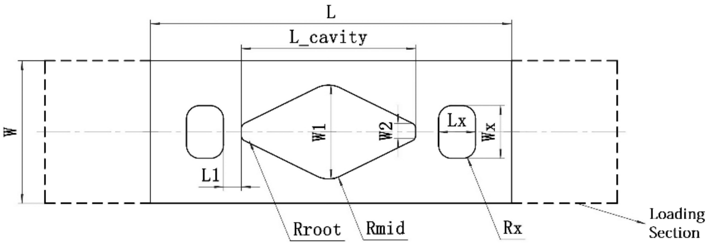


Figure 4- Parametric model of simulated specimen for Twin-web turbine disk throat

3.2 The FEA Model and Boundary Conditions for Simulated Specimen

Considering the symmetry of the simulated specimen, in order to reduce the amount of calculation, only 1/8 of the original model is established in the finite element parametric modelling. The simulated specimen is divided into 13575 elements and 58250 nodes by 20-node Solid186 element. According to the symmetry of the finite element model, the symmetry constrains are imposed on the XY plane, YZ plane and XZ plane of the model. In addition, the loading process is simplified by coupling the Y displacement of the end face for loading section and applying a certain Y displacement to simulate the load applied by the hydraulic fixture to the simulated specimen. The finite element model and loading position for the simulated specimen is shown in Figure 5.

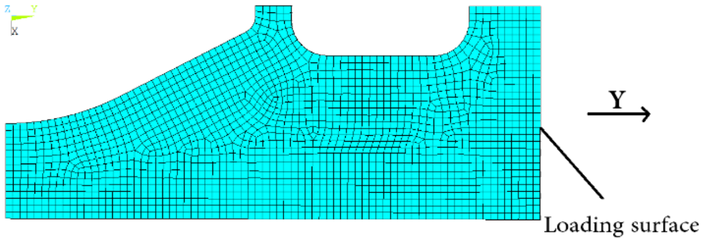


Figure 5- The finite element model for the original simulated specimen

Since the twin-web turbine disk is made of Nickel-based superalloy FGH96, the simulated specimen also uses this material. Thus, the cyclic stress-strain curve at 550℃ for the simulated specimen is show in Equation (4).

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \tag{4}$$

in which $K' = 1578MPa$, $n' = 0.06$[4].

3.3 The Optimization of Simulated Specimen

As can be seen in Figure 4, the parametric model of simulated specimen for twin-web turbine disk throat has many geometric parameters. Obviously, not all of these parameters have non-negligible influence on the maximum Von-Mises stress and stress gradient near the critical region. Therefore, sensitivity analysis was carried out to find out the parameters with obvious effect. Finally, it was found that W, L, L_cavity, W_1, R_{mid}, L_1, W_x, L_x, as well as the thickness H of the simulated specimen have obvious influence on the stress and stress distribution near the critical point. Therefore, these nine geometric parameters are selected as the design variables. In addition, elastoplastic simulated specimen design is needed because the throat of twin-web turbine disk has entered plasticity, thus the load became a very important parameter which can influence the stress redistribution after yielding. In this paper, the loading displacement U is used to characterize the load applied on simulated specimen. Therefore, a total of 10 parameters are selected as design variables for the simulated specimen design, and the initial values and optimization intervals are shown in Table 1.

It is considered that the closer the distance to the critical point, the more obvious the influence of stress on the initiation and propagation of cracks, and the farther the distance is, the smaller the influence will be. Therefore, the similarity of the stress gradient near the critical point should be as close as possible, and the similarity requirements for the distant region can be lowered moderately. Hence, the optimization intervals of the design state variables for the twin-web disk throat simulated specimen are arranged in Table 2, where $\sigma_{\mathrm{M,s},i}$ and $\sigma_{\mathrm{M,d},i}$ are the Von-Mises stress values for the point *i* of the simulated specimen and the twin-web disk throat, respectively. The Von-Mises stress of each point on the stress gradient path of the simulated specimen is obtained as shown in Figure

6.

Table 1 Initial value and optimization interval of design variables for simulated specimen

Design Variables	Initial Values	Optimization Intervals
W/mm	90.0	(75.0, 105.0)
L/mm	130.0	(110, 150)
W_1/mm	65.0	(60.0, 70.0)
L_1/mm	6.0	(4.0, 8.0)
W_x/mm	40.0	(30.0, 50.0)
L_x/mm	15.0	(10.0, 20.0)
L_cavity/mm	45.0	(35.0, 55.0)
R_{mid}/mm	15.0	(5.0, 30.0)
H/mm	5.0	(3.0, 15.0)
U/mm	0.6	(0.50, 0.70)

Table 2 Design state variables and optimization intervals for twin-web disk simulated specimen

Design State Variables	Lower value	Upper value
$1-\sigma_{\mathrm{M,s,0}}/\sigma_{\mathrm{M,d,0}}$	-0.5%	0.5%
$1-\sigma_{\mathrm{M,s,1}}/\sigma_{\mathrm{M,d,1}}$	-0.7%	0.7%
$1-\sigma_{\mathrm{M,s,2}}/\sigma_{\mathrm{M,d,2}}$	-0.9%	0.9%
$1-\sigma_{\mathrm{M,s,3}}/\sigma_{\mathrm{M,d,3}}$	-1.1%	1.1%
$1-\sigma_{\mathrm{M,s,4}}/\sigma_{\mathrm{M,d,4}}$	-1.3%	1.3%
$1-\sigma_{\mathrm{M,s,5}}/\sigma_{\mathrm{M,d,5}}$	-1.5%	1.5%
$1-\sigma_{\mathrm{M,s,6}}/\sigma_{\mathrm{M,d,6}}$	-1.7%	1.7%
$1-\sigma_{\mathrm{M,s,7}}/\sigma_{\mathrm{M,d,7}}$	-1.9%	1.9%
$1-\sigma_{\mathrm{M,s,8}}/\sigma_{\mathrm{M,d,8}}$	-2.1%	2.1%
$1-\sigma_{\mathrm{M,s,9}}/\sigma_{\mathrm{M,d,9}}$	-2.3%	2.3%
$1-\sigma_{\mathrm{M,s,10}}/\sigma_{\mathrm{M,d,10}}$	-2.5%	2.5%

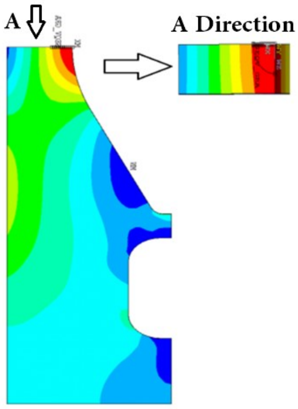


Figure 6- The Von-Mises stress gradient for simulated specimen

Obviously, the smaller of the stress residual vector $\sigma_{\mathrm{M,res}}$ between the simulated specimen and the turbine disk throat is, the closer of the Von-Mises stress and its distribution will be. Therefore, the stress residual vector $\|\sigma_{\mathrm{M,res}}\|_1$ is taken as the objective function in the design of the simulated specimen. Firstly, the zero-order optimization method is carried out for the simulated specimen design, which can perform multiple searches within a large range of solution sets to get acceptable results. After finding the solution set that satisfies the state variables, the first-order optimization method is continued to be used for detailed optimization. The results of zero-order optimization method and first-order optimization method of the stress gradient for the simulated specimen are compared with those of the twin-web turbine disk throat, as shown in Figure 7. It can be seen that both the simulated specimen and the twin-web turbine disk throat show yielding behavior near the critical point, and the first-order optimization method provides better results than the zero-order method. The stress difference between the simulated specimen and the twin-web turbine disk throat is only 0.2% at the critical point, while the maximum relative error on the stress gradient path near the critical point is 2.48%. It can be considered that the stress field of the simulated specimen is basically the same as that of the twin-web turbine disk throat, which meets the design requirements of the simulated specimen. The geometrical results for the optimized simulated specimen are shown in Table 3.

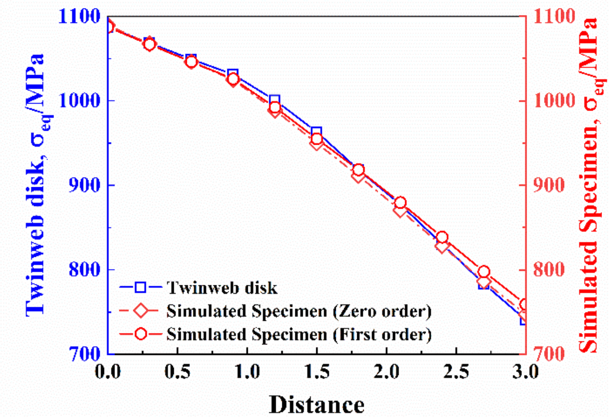


Figure 7- The comparison of Von-mises stress on the stress gradient path between the simulated specimen and the twin-web turbine disk

Table 3 Geometric results for optimized simulated specimen

Design Variables	Initial Values	Design Variables	Initial Values
W/mm	86.0	L/mm	120.0
W_1/mm	66.2	L_1/mm	5.0
W_x/mm	36.0	L_x/mm	12.0
L_cavity/mm	42.0	R_{mid}/mm	9.5
H/mm	10.0	U/mm	0.515

3.4 Determination of Equivalent Volume for Simulated Specimen

The geometric size of the simulated specimen designed in this paper is quite small compared with the twin-web turbine disk, therefore, its detrimental volume is obviously smaller than that of the twin-web turbine disk throat. So, it is necessary to optimize the similarity of fatigue damage between them to obtain better similarity of fatigue characteristics. The method used in this paper is to compensate the difference of detrimental volume through strengthening the influence of mean stress effect on the fatigue life of the simulated specimen. Thus, the stress and stress ratio at the maximum Von-Mises stress point of the twin-web turbine disk throat are taken as the target stress and target stress ratio [17] (σ_t=1086.9MPa, R_t=-0.148). The equivalent volume of the critical region for twin-web turbine disk throat can be obtained as 652.4mm^3. Under the condition of the same maximum load, the simulated specimen with different load ratios are analyzed, and the relation of the equivalent volume with the load ratio is obtained as shown in Figure 8. Through this diagram, it can be seen that when the equivalent volume of the simulated specimen is 651.3mm^3, the corresponding load ratio is R=-0.385. Furthermore, the optimized simulated specimen is analyzed under the load ratio, and the Von-Mises equivalent stress contour plot is shown in Figure 9.

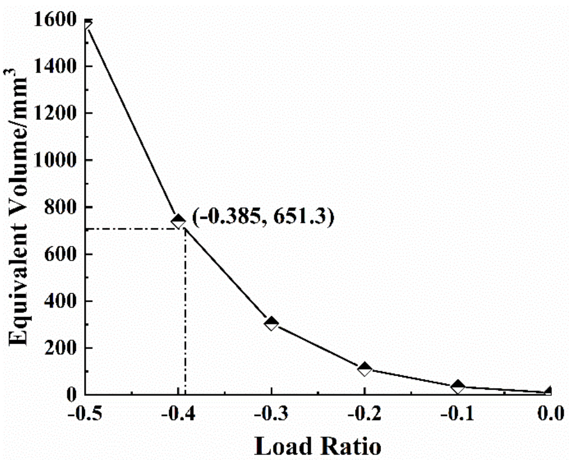
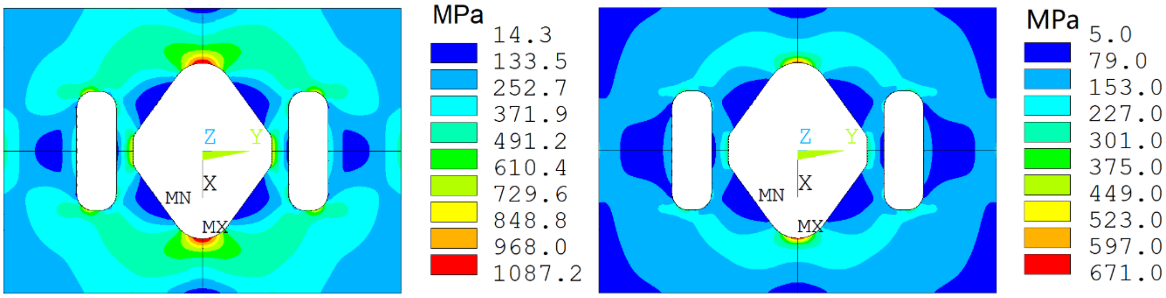


Figure 8- The equivalent volume versus various stress load for optimized simulated specimen



(a) Loading state (b) Unloading state

Figure 9- Von-Mises stress contour for loading and unloading state under stress ratio of *R*=-0.385 for optimized simulated specimen.

The calculated probabilistic fatigue lives of simulated specimen and twin-web turbine disk throat are compared in Table 4, in which the target stress and target stress ratio for the equivalent volume is based on the maximum Von-Mises stress at the twin-web turbine disk throat. It should be noted that although the load ratio of the simulated specimen is R_L=-0.385, since the critical region of the simulated specimen behaves yielding, resulting in reverse compression stress after unloading, thus the stress ratio for the critical point turned out to be R_S=-0.617. As can be seen, except for the difference of unloading stress, the maximum stress, equivalent volume and probabilistic fatigue lives at 50% and 99.87% reliability are all very close, which indicates that the simulated specimen designed can effectively represent the fatigue characteristics of twin-web turbine disk throat.

Table 4 Comparison of FEA results and probabilistic fatigue lives for simulated specimen and twin-web turbine disk throat

Component	Maximum stress σ_{max}/MPa	Stress ratio R	Equivalent volume V_{eff}/mm^3	Probabilistic fatigue life	
				$N_{f,50\%}$	$N_{f,99.87\%}$
Simulated specimen	1087.3	-0.617	651.3	19649	4951
Twin-web turbine disk	1086.9	-0.148	652.4	19658	4949

4. Conclusion

In this paper, the design criterion and method for elastoplastic fatigue-simulating specimen of twin-web turbine disk is studied, and the main work are as follows:

(1) Based on fatigue mechanism, the design criterion for elastoplastic fatigue-simulating specimen is proposed, which takes maximum Von-Mises stress, stress gradient and equivalent volume as fatigue characteristic similarity criterion;

(2) The method for elastoplastic fatigue-simulating specimen design is established, in which arbitrary Von-Mises stress gradient near the critical point can be extracted and the fatigue damage in various geometry size can be equivalently transformed;

(3) An elastoplastic fatigue-simulating specimen for the twin-web turbine disk throat is designed. The difference of probabilistic fatigue lives between the simulated specimen and twin-web turbine disk throat at 50% and 99.87% reliability are very small, which indicates that the simulated specimen designed can effectively represent the fatigue characteristics of twin-web turbine disk throat.

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6. Copyright Statement

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