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NUMERICAL STUDY ON FATIGUE LIFE OF NOTCHED SPECIMEN WITH SURFACE GRADIENT STRENGTHENING

Sichuan Jia
School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China.

Abstract: Using the improved Tanaka-Mura model, the equivalent conversion relationship between complex fatigue load and tension-compression fatigue load is determined, and the influence law of residual compressive stress is given. The fatigue life and crack origin location of samples were systematically analyzed numerically. The results show that: the fatigue nucleation life and position of the notched specimen are related to the thickness of the strengthening layer, the hardness ratio of the surface to the matrix and the residual stress; the change of the thickness of the strengthening layer will change the crack nucleation position; there is a critical thickness, when the thickness of the strengthening layer is less than the critical thickness, the crack nucleates at the interface between the strengthened layer and the matrix, otherwise, it nucleates at the strengthened subsurface or surface; the increase in the hardness ratio of the surface to the matrix will lead to an increase in the critical thickness; the residual compressive stress has little effect on the fatigue initiation life, while the residual Tensile stress significantly reduces the fatigue initiation life.
Keywords: Surface strengthening treatment; Fatigue life; Fatigue initiation; Stress concentration factor; Notch

1 INTRODUCTION

Surface strengthening treatment refers to the treatment method that uses mechanical, chemical and other methods to act on the surface of the material to improve the strength of the surface layer of the material. Common surface strengthening treatment methods include: shot peening, surface rolling, carburizing and nitriding, laser modification, surface quenching, etc. After surface strengthening treatment, the microstructure, mechanical properties, surface roughness and residual stress of the surface will all change, which will lead to the improvement of fatigue life and the change of fatigue nucleation position.

Surface strengthening treatment is an effective means to improve the fatigue performance of components [1], and is widely used in the manufacturing process of various aviation, vehicles and energy power.

Generally speaking, for samples that have undergone surface strengthening treatment, the surface to core. There will be obvious gradient changes in the microstructure of the part. The research on surface mechanical attrition treatment (SMAT) and surface mechanical grinding treatment (SMGT) [2-3] shows that the grain size of the surface layer of the sample has been significantly refined, and the surface layer is equal to Axonal nanocrystalline structure, and the grain size gradually increases with the increase of depth. For the surface quenched S38C axle steel, the research [4] shows that the tempered martensite structure gradually transitions to the normalized structure from the surface layer to the core. Due to the gradient change of the surface microstructure in the surface strengthening sample, the corresponding surface mechanical properties also present a gradient distribution feature. The shot peening treatment of nickel-based superalloy [5] shows that the surface hardness of the gradient layer reaches 4.5 GPa, which is 1.25 times higher than the hardness of the core part of 2 GPa, and the hardness distribution along the depth is basically linear., the thickness of the gradient layer can reach up to 660 μm. After carburizing or nitriding [6-8], the typical surface hardness of steel can be increased to more than 2 times that of the core, the depth of the carburized layer can reach 2 mm, and the nitrided layer can reach 500 μm.

Fatigue studies on samples with various surface strengthening treatments mentioned above show that the fatigue performance of the samples has been significantly improved. However, due to the gradient change of microstructure, mechanical properties and residual stress brought about by surface gradient strengthening, theoretical analysis is difficult, and fatigue research mainly relies on experimental methods. Especially for positions with large stress gradients such as gaps and corners of components, there is still a lack of effective theoretical evaluation methods.

The existence of the notch will bring local stress concentration, and in this stress concentration area, there is a distribution of stress gradient related to the size of the notch. Studies have shown that for homogeneous material samples, under the same notch stress concentration factor, the larger the notch size, the lower the fatigue strength.

Through the systematic research on this phenomenon, several different empirical expressions for determining the sensitivity coefficient of fatigue notch are given[9-10], but for samples with a gradient-enhanced treatment layer at the root of the notch, the above methods are difficult to carry out.

In this study, the improved energy balance model was used, combined with the empirical formula for determining the fatigue SN curve of materials by hardness, to systematically analyze the fatigue notch effect of surface gradient strengthened samples, so as to determine the thickness, hardness and residual stress of the surface strengthening layer. Effect of fatigue initiation life and initiation position on notched samples.

1.1 Fatigue Analysis Model and Method

The traditional fatigue analysis model is mainly for homogeneous materials. Generally, the fatigue SN curve of the material is firstly obtained through fatigue experiments, and the fatigue strength coefficient, fatigue strength index, fatigue ductility coefficient and fatigue ductility index in the Mason-Coffin formula or Basquin formula are obtained by analysis. etc.; Then, according to the specific service load, the complex load is equivalent to the equivalent load of simple tension and compression fatigue by using various equivalent stress methods; finally, the fatigue life is estimated. However, for samples with surface gradient strengthening, there are gradient changes in the microstructure, mechanical properties, and residual stress in the surface strengthening layer, which is no longer a homogeneous material sample, which brings new difficulties to theoretical analysis. It can be predicted that the fatigue parameters at different positions in the strengthened layer will have gradient changes with the distance from the surface, but the gradient distribution of fatigue parameters is difficult to measure experimentally, and there is usually a large residual compressive stress in the gradient layer, which makes It is difficult to carry out accurate analysis when adopting the traditional fatigue analysis model. In the previous work of the author [11], an improved energy balance model based on the Tan-aka-Mura model [12] was proposed. The basic idea of this model is that the sum of the accumulated dislocation energy and the elastic strain energy released during fatigue crack nucleation is equal to the surface energy required for crack nucleation when the resident slip surface increases with the fatigue loading cycle, crack initiation will occur. Due to the introduction of the elastic strain energy release term during crack nucleation, this model can be used for fatigue initiation life analysis under the condition of mean stress (including compressive mean stress) or multiaxial stress. For the analysis of the fatigue life in the strengthening layer after surface strengthening treatment, Zhao Sicong et al. [13] considered that the strength and hardness of the treated samples are usually very high, it can be assumed that the residual stress does not decay with the fatigue cycle during the fatigue process, so that the residual stress Stresses are considered as mean stresses. By using this model for the micro-areas at different depths from the surface, and substituting the material parameters, residual stress parameters and external loads in the micro-area into the model, the distribution diagram of fatigue initiation life with depth can be obtained, and then the life distribution Fig. 1 determines the fatigue initiation life and initiation location of the entire sample with gradient strengthening layer. Although the above analysis has given a theoretical analysis method for the fatigue of samples treated with gradient strengthening, since the dislocation slip reversibility factor P in the model cannot be accurately determined, and 1/6 of the hardness is simply used to estimate the fatigue limit of the micro-area, these All affect the accuracy of fatigue life analysis.

According to the improved energy balance model [11], a parameter λ reflecting the fatigue life is defined, and there is the following relationship for uniaxial fatigue where: P is the dislocation slip reversibility factor; Nf is the fatigue initiation life; σ UTS is the tensile strength; σ m is the average stress; σ a is the stress amplitude; fatigue limit. By formula (1).

It can be seen that the parameter λ is the combination of the external load and material parameters, and this combination corresponds to the fatigue life one by one.

For the case of stress ratio R = -1, it is obvious that

$$\lambda = 4PN_f = \frac{\sigma_{UTS}^2 - \sigma_{a,R=-1}^2}{(\sigma_{a,R=-1} - \sigma_e)^2} \quad (2)$$

Here $\sigma_{a,R=-1}$ is the stress amplitude under the condition of stress ratio R = -1.

According to formula (1) and formula (2), any loading condition including average stress can be transformed into the equivalent stress amplitude under the condition of stress ratio R = -1:

$$\sigma_{a,R=-1} = \frac{\lambda\sigma_e + \sqrt{(1+\lambda)\sigma_{UTS}^2 - \lambda\sigma_e^2}}{1+\lambda} \quad (3)$$

After this treatment, the fatigue life corresponding to the equivalent stress amplitude when R = -1 can be used to determine the fatigue life under complex loading conditions, thereby avoiding the influence of the uncertainty of the P factor.

In order to use formula (3) to carry out fatigue analysis of gradient strengthened samples, relevant empirical formulas [14-16] can be used to estimate the SN curves of micro-regions at different depths. Due to carburizing and nitriding, surface quenching

The hardness of the sample treated by such methods is very high, and it is usually used to work under high-cycle or even ultra-high-cycle loading conditions, so the hardness distribution can be used

The SN curves obtained at different depth positions are as follows:

$$\sigma_{a,R=-1} = 1.5\sigma_{UTS}(2N_f)^{-0.09} \quad (4)$$

The tensile strength of the material here can be estimated by 1/3 of the hardness value [17]. At the same time, according to formula (4), the fatigue limit σ_e corresponding to different depth positions in the metamorphic layer can also be obtained by substituting the fatigue life of 107 cycles. Therefore, for the fatigue numerical analysis of gradient strengthened samples, one can

Follow the steps below:

1) Measure the variation curve of hardness H and residual stress σ_r with depth in the metamorphic layer of the gradient-strengthened sample;

2) Obtain the variation curve of fatigue limit σ_e with depth from the hardness H distribution curve through formula (4);

3) Using finite element software to calculate the variation curves of stress amplitude and average stress with depth for gradient strengthened samples under the action of external nominal load;

4) According to formula (1), the fatigue life parameter λ at different depths is calculated from the stress amplitude, average stress, tensile strength and fatigue limit at different depths. Here the residual stress is equated to the mean stress;
5) Calculate the equivalent stress amplitude σ a at different depths according to formula (3), R = -1, and substitute into formula (4) to calculate the fatigue stress at different depths germination lifetime Nf ;
6) From the calculated distribution curve of fatigue initiation life Nf with depth, take its minimum value MIN(Nf) as the whole sample with gradient strengthening layer
The overall fatigue initiation life of, and the corresponding depth is the location of fatigue initiation.

2. CHARACTERIZATION OF MODEL AND PARAMETERS OF NOTCHED SAMPLE WITH GRADIENT STRENGTHENING LAYER

Referring to the work carried out by Zhao Sicong et al. [13] on notched samples with gradient strengthening layer, the new model is used to analyze the fatigue life of M50NiL carburized samples and carburized and nitrided samples.
As shown in Figure 1, the fatigue life analysis is carried out for the unilateral semicircular notched sample with gradient strengthening layer under tension and compression fatigue conditions, and the nominal stress concentration factor Kt = 3.

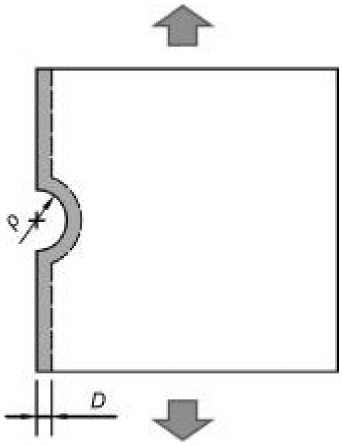

Fig. 1 Schematic cross-section of a semicircular notch sample with a gradient strengthening layer

According to the results of dimensional analysis, as shown in formula (5), the fatigue life Nf of the notched sample with gradient strengthening layer, the initiation position xi and the stress concentration factor Kt, the dimensionless thickness of the strengthening layer, the ratio of surface hardness to matrix hardness, Applied stress amplitude and residual stress are related.

$$Nf = f\left(\frac{x}{\rho}, Kt, \frac{D}{\rho}, \frac{H_s}{H_m}, \frac{\sigma_a}{H_m}, \frac{\sigma_{r,max}}{H_m}\right)$$

$$\frac{x_i}{\rho} = f\left(Kt, \frac{D}{\rho}, \frac{H_s}{H_m}, \frac{\sigma_a}{H_m}, \frac{\sigma_{r,max}}{H_m}\right) \qquad (5)$$

where: ρ is the radius of the notch; D is the thickness of the strengthening layer; Hs is the hardness of the surface of the strengthening layer; Hm is the hardness of the matrix; σ a is the nominal stress amplitude; In this work, the effects of dimensionless strengthening layer thickness, surface hardness to matrix hardness ratio, applied stress amplitude and residual stress peak value on fatigue initiation life and initiation location are mainly studied.
It should be noted that although the calculation is aimed at the case of M50NiL carburized and nitrided samples, the regularity results can also be used for fatigue analysis of components after various surface strengthening treatments of other materials. Of course, this numerical analysis method needs to be further verified in practice to determine the range of materials and processes applicable to the method. In addition, in order to simplify the problem in the simulation calculation, the influence of surface roughness, surface and internal inclusions is not considered, and these factors need to be corrected in the analysis of actual components.

2.1 Modeling of Hardness Distribution

According to the experimental test results, the surface hardness of M50NiL after carburizing can reach 11 GPa, and after carburizing and re-nitriding, the surface hardness can reach 14 GPa, while the matrix hardness is about 6.5 GPa, and the hardness gradually increases with the depth. From the surface hardness down to the matrix hardness. In order to simplify the calculation, the linear function relationship of formula (6) will be used in the analysis to characterize the change of hardness with depth.
curve.

$$H(x) = \begin{cases} H_m & x < D \\ \left[HRH - \frac{x}{D}(RH - 1)\right] \, m & x \geq D \end{cases} \qquad (6)$$

In the formula: x is the distance from the surface of the root of the notch; D is the depth of the strengthening layer; RH = Hs/Hm, which is the ratio of surface hardness to matrix hardness. In the analysis, in order to consider the impact of RH changes, the hardness Hm of the M50 NiL matrix will be kept constant, and the RH value of the carburized layer sample will be adjusted between 1 and 1.69. Specifically, five situations of RH = 1.69, 1.55, 1.42, 1.28, 1.14, and 1 will be analyzed.

2.2 Modeling of Residual Stress

For carburized samples, the residual stress is usually the residual compressive stress. In the gradient strengthening layer, the distribution curve of residual stress with depth can be modeled by the cosine function given by formula (7).

$$\sigma_r = \sigma_{r,max}\cos\left[\frac{\pi}{2}\cdot\left(\frac{x-x_c}{D-x_c}\right)\right] \quad x \le D \quad (7)$$

where: $\sigma_{r,max}$ is the peak value of residual stress; x_c is the depth corresponding to the peak value. According to literature [18], x_c can usually be taken as 1/4 of the depth D of the entire gradient enhancement layer.

According to the experimental results, the peak value of the residual stress can reach above -1000 MPa. In order to fully reflect the influence of residual stress on fatigue nucleation life, the numerical analysis will not only be limited to the case of residual compressive stress, but will take

$\sigma_{r,max}$ = 0, ± 200 MPa, ± 400 MPa, ± 600 MPa, ± 800 MPa to analyze the influence of residual stress.

2.3 Calculation of stress field near the notch

For the notched sample with the nominal stress concentration factor Kt = 3, the variation law of the stress with the depth from the surface of the root of the notch under tensile and compressive loads was calculated by using the Abaqus finite element software.

In order to ensure the conditions close to the semi-infinite plate, the width of the sample is 30 times the radius of the notch. In order to ensure the calculation accuracy of the stress concentration area of the notch, the calculation grid near the notch is refined. For carburized samples, the test shows that the elastic modulus of the carburized layer is basically equal to that of the matrix, and the elastic modulus is 204 GPa and Poisson's ratio is 0.3.

Figure 2 shows the stress cloud diagram of the finite element analysis and the distribution curve of the stress concentration factor along the root of the notch to the inside of the sample with depth. It can be seen from Figure 2 that the stress concentration only occurs in a small area of the root of the notch. When the distance reaches 2 times the radius of the notch, the stress concentration factor has dropped below 1.1.

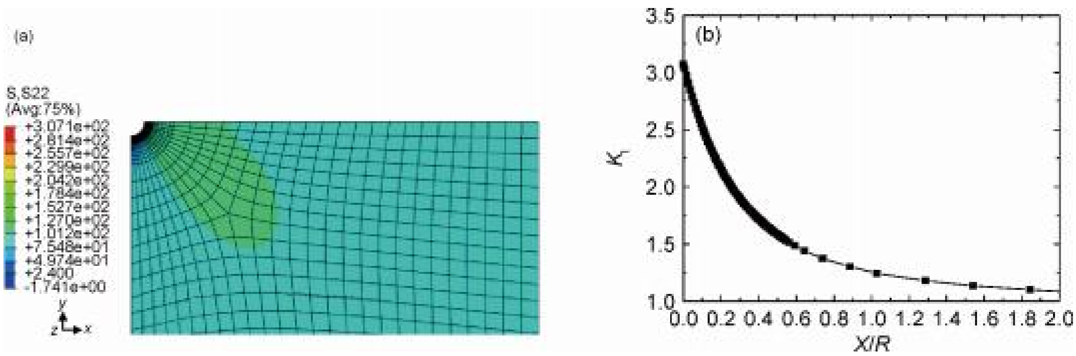

Fig. 2 Stress distribution nephogram

Note: (a) and distribution curve of stress concentration factor along the depth near the root of the notch (b) when the sample with a semicircular notch is subjected to tensile stress

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3 RESULTS AND DISCUSSION OF FATIGUE LIFE ANALYSIS

3.1 Effect of Gradient Strengthening Layer Thickness on Fatigue Life

The corresponding position is the position where fatigue cracks initiate for the samples without strengthening layer, it is obvious that the fatigue initiation life in the strengthening layer is greater than that of the samples without strengthening layer due to the presence of the chemical layer and the higher fatigue resistance of the strengthening layer. It should be noted that for samples with different thicknesses of the strengthening layer, the fatigue initiation life distribution in the strengthening layer has different characteristics. For samples with smaller thickness, the fatigue initiation life decreases with the increase of the distance from the root of the notch, and the minimum value of the fatigue life distribution curve appears at the connection position between the strengthening layer and the matrix. For the thicker sample, the fatigue initiation life first increases and then decreases with the increase of the distance from the root of the notch, and the minimum value of the fatigue life distribution curve appears on the surface of the sample. This result indicates that there is a critical thickness at which the fatigue initiation life of the sample is equal at the surface and the interface.

The fatigue initiation life of samples with different thicknesses is sorted out. As the thickness of the strengthening layer increases, the overall fatigue initiation life of the sample will increase with the increase of thickness. When the thickness of the reinforced layer exceeds the critical thickness, the fatigue life does not increase any more. From this result, it can be seen that for any part with stress concentration, if the surface strengthening treatment does not change the hardness of the sample surface, then at most it is only necessary to make the thickness of the strengthening layer reach the critical thickness. Treatment beyond the critical thickness does not further improve the fatigue initiation life of the part.

3.2 Effect of Hardness Ratio on Fatigue Life

The laws of the fatigue initiation life scores corresponding to different hardness ratios are similar, indicating that there is a critical strengthening layer thickness under different hardness ratios. The effect of strengthening layer thickness on the overall fatigue initiation life of the sample. It can be seen that when the hardness ratio is fixed, the overall fatigue initiation life of the sample will increase with the increase of the thickness of the strengthening layer, and will not change until the critical thickness is exceeded. For the critical thickness with

According to the change law of the hardness ratio RH between the surface and the matrix, it can be seen that the larger the RH value is, the larger the corresponding critical thickness of the strengthening layer is. To further illustrate the influence of hardness ratio, the distribution of fatigue initiation life corresponding to different thicknesses of strengthening layer. For samples with a relatively thin strengthening layer, the fatigue crack initiation locations are all located at the interface between the strengthening layer and the matrix under the conditions of this study. At this time, although increasing the hardness ratio of the surface to the matrix can increase the fatigue initiation life in the strengthening layer, the overall life of the sample does not change. For this type of sample, the life cannot be improved by increasing the surface hardness, so there is no need for further processing.

Increased surface hardness; For samples of intermediate thickness, there is also a change in the location of fatigue initiation when increasing the surface-to-matrix hardness ratio. There is a critical hardness ratio, when the hardness ratio RH is less than the critical value, increasing the hardness ratio can effectively improve the fatigue initiation life of the sample. When the hardness ratio is greater than the critical value, since the crack initiates at the interface, increasing the hardness ratio will not improve the overall fatigue initiation life of the sample. For samples with a relatively thick strengthening layer, the fatigue cracks always initiate on the surface. At this time, increasing the hardness ratio RH of the surface to the matrix is effective to improve the overall fatigue life of the sample.

3.3 Influence of residual Stress on Fatigue Life

Influence of residual stress on fatigue life distribution in gradient hardened layers. When the hardness ratio RH = 1.69, the change law of the applied stress range of 700 MPa is as follows: when the residual compressive stress increases from 0 to 400 MPa, the fatigue initiation life in the strengthened layer can be slightly improved, and when it is further increased, On the contrary, the fatigue initiation life will decrease slightly. Overall, the effect of residual compressive stress on fatigue initiation life is not obvious. For the residual tensile stress, as it increases, the fatigue initiation life in the strengthened layer will decrease monotonically as a whole, and its influence degree is obviously higher than that of the same magnitude of residual compressive stress.

For samples with a thinner reinforced layer, the origin of fatigue occurs at the interface within a larger residual stress range. Therefore, the size of the residual stress has no great influence on the overall fatigue initiation life of the sample. Only when the residual tensile stress is large enough, it is possible to shift the fatigue initiation position to the surface, thereby changing the overall life of the sample; and for the sample with a thicker reinforced layer, the fatigue crack initiation occurs on the surface of the sample, and at this time Residual stress can affect the overall fatigue initiation life of the sample.

It should be noted that only the fatigue crack initiation life was analyzed in this study. Although residual compressive stress has little effect on fatigue crack initiation, it has a significant effect on fatigue crack growth. Therefore, for the case of surface crack initiation, after the fatigue crack initiation is completed, the fatigue crack will be difficult to expand due to the residual compressive stress, and finally the overall fatigue life of the sample will be significantly improved.

4 CONCLUSION

(1) The thickness of the gradient strengthening layer has an important influence on the fatigue crack initiation position and life of the notched sample. There is a critical thickness, when the thickness of the reinforced layer is less than the critical thickness, fatigue cracks will initiate from the interface between the reinforced layer and the matrix; when the thickness of the reinforced layer is greater than the critical thickness, fatigue cracks will initiate from the surface of the strengthened layer.

(2) The greater the hardness ratio of the surface to the matrix, the greater the fatigue resistance of the gradient layer. Without changing the thickness of the gradient strengthening layer, there is a critical hardness ratio. When the hardness ratio is less than the critical hardness ratio, fatigue cracks will initiate on the surface of the sample. The cracks will be initiated from the interface between the gradient strengthening layer and the matrix.

(3) The critical thickness of the strengthening layer is affected by parameters such as the applied stress amplitude and the hardness ratio of the surface to the matrix. As the applied stress amplitude increases, the critical thickness increases slightly; as the hardness ratio of the surface to the matrix increases, the critical thickness increases significantly.
(4) The residual compressive stress has little effect on the initiation of fatigue cracks, while the residual tensile stress can significantly reduce the fatigue crack initiation life. Residual stress will have an effect on the fatigue initiation life only for samples with a strengthened layer thickness greater than the critical thickness and fatigue cracks originating from the surface.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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