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Research Article

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Research on fatigue damage of sucker rod based on damage mechanics

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ABSTRACT

Fatigue failure of sucker rod can occur under the effect of alternating load, and results in failure of sucker rod. In this paper, the damage mechanics theory is applied to the fatigue damage of sucker rod on the study, establish the fatigue damage evolution equation of sucker rod, and the damage mechanics-finite element method is adopted to solve fatigue damage of sucker rod, obtain change law of stress field, strain field and fatigue damage field of sucker rod, and carry out fatigue damage cycles of sucker rod. The study has a certain theoretical significance and practical significance on the rational use of sucker rod, the decrease of sucker rod fracture accident and the improvement of overall economic benefits in oilfield development.

Keywords: sucker rod; damage mechanics; failure; finite element

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INTRODUCTION

Under the alternating load for a long time, coupled with borehole liquid corrosion and up-and-down operation, the sucker rod will fracture, which make the rod string can't work normally. In the fracture accident of sucker rod, failure is caused by fatigue damage fracture, and fracture occurs mostly in sucker rod upsetting segment and threaded connection section[1,2]. The study of sucker rod fatigue damage is start with metallography[3]. At present, the researchers tend to adopt the method of fracture mechanics to study fatigue damage life of metal materials and components. The defects are equivalent to cracks in fracture mechanics, and study propagation rules of cracks under the alternating load, there are a large number of dispersed micro defects inside the engineering material, damage will gradually be evolved under the action of external factors(such as external force, temperature). Centralized development of the damage leads to destruction of the material, macroscopic defects (such as cracks) will be formed eventually. After the formation of macroscopic defects, microcosmic defects will be evolved continually, and promote the development of macroscopic defects. In the expansion process the region near the macroscopic cracks is the highly concentrated area of macroscopic defects[4,5]. The main research object of damage mechanics is dispersed developing evolution of microcosmic defects inside the engineering material, whereas fracture mechanics ignores the damage stage which is before the formation of macroscopic cracks, the damage around macroscopic cracks is also ignored, considering only the ideal macroscopic defects. In view of the fact that fracture damage of pumping well sucker rod is serious, using damage mechanics theory to research the fatigue damage of sucker rod, which has a vital significance on the rational use of sucker rod, the decrease of sucker rod fracture accident, the lower production costs of oil production and the improvement of overall economic benefits in oilfield development[6].

THEORETICAL ANALYSIS SECTION

In the process of sucker rod damage analysis, the first step is to select appropriate damage variable and determine its evolution equation, and then constitute damage definite solution or variational problem of sucker rod with the condition of equilibrium, geometry and physics, and use finite element discrete structure to solve stress, strain field and damage field of sucker rod, finally, according to the critical condition of damage, judge the damage degree of sucker rod and its safe working limits.

Below is the coupling theory of fatigue damage of sucker rod.

The basic equations of the theory are as follows:

Geometric Equation
Relationship between small deformation displacement and strain is stated by the following equation:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{1}$$

where u_i is an equation of displacement component, and ε_{ij} is a range of strain component.

Equilibrium Equation
Under the condition of small deformation, the relationship between strain and body force is defined as

$$\frac{\partial \sigma_{ij}}{\partial x_j} + B_i = 0 \tag{2}$$

where σ_{ij} is a range of stress component, and B_i is a range of body force.

Constitutive Relation
For damaged materials, the relationship between stress and strain is expressed as

$$\sigma_{ij} = C_{ijkl}\left(1-D\right)\varepsilon_{kl} \tag{3}$$

where C_{ijkl} is elastic constant, and D is damage degree of metallic material, which is regard as a scalar, the range of damage degree is from 0 to 1.

Damage Evolution Equation
Equivalent stress is defined as

$$\sigma_e = \sqrt{\frac{3}{2}s_{ij}s_{ij}} \tag{4}$$

where s_{ij} is stress deviator component, its value is

$$s_{ij} = \sigma_{ij} - \frac{1}{3}\delta_{ij}\delta_{rs}\sigma_{rs} \tag{5}$$

According to damage evolution equation of uniaxial loading, the damage evolution equation of sucker rod can be expressed as

$$\frac{dD}{dN} = \frac{\alpha}{p+1}\frac{1}{(2E)^{P+1}}\frac{1}{\left(1-D\right)^{2P+2}} \cdot \left[\left(1-R\right)^{q(p+1)}\sigma_{Me}^{2p+2} - \sigma_{th0}^{2p+2}(1-D)^{(0.5+\beta)(2p+2)}\right] \tag{6}$$

where N is cycle number, R is stress ratio, σ_{Me} is equivalent stress when materials bears the maximum load, σ_{th0} is stress threshold when materials is without initial damage, E is Young's modulus of materials, β, α, p are the parameter of damage mechanics of materials, which are determined by the curve of fatigue properties of materials.

When damage mechanics method is applied to solve the problem of fatigue, there will be two problems. One is to analyze stress field, displacement field and strain field of sucker rod when the damage field is known; the other is to analyze damage evolution field and estimate life of cracks when stress field and damage field are known. Because of the complexity of sucker rod, it is difficult to calculate the damage of sucker rod and estimate the degree of damage as a whole. Consequently, the finite element method which disperses sucker rod model to many units and calculates stress field and strain field is adopted, this is understandable also for calculating the damage of every units, the damage process of sucker rod is simulated to the damage process of units, thus, the life which the first unit damaged is the crack initiation life of cracks, the life which from the damage of the first unit to the complete damage of sucker rod is crack propagation life. Damage mechanics and finite element method are combined, and finite element is utilized to forecast the life of sucker rod.

Stress Analysis Theory of Known Damage Field

Expand equation (3) to obtain the following equation

$$\sigma_{\mathrm{ij}} = \mathrm{C}_{ijkl}\varepsilon_{kl} - D\mathrm{C}_{ijkl}\varepsilon_{kl} \tag{7}$$

Supposing that voxel stress is σ_{ij}^0 if there is no damage, that is $\sigma_{ij}^0 = \mathrm{C}_{ijkl}\varepsilon_{kl}$.

If $\sigma_{ij}^D = -D\mathrm{C}_{ijkl}\varepsilon_{kl}$, the equation (7) may be rewritten as

$$\sigma_{ij} = \sigma_{ij}^0 + \sigma_{ij}^D \tag{8}$$

Putting equation (8) in balance equation (2), the following equation can be obtained

$$\frac{\partial \sigma_{ij}^0}{\partial x_j} + B_i + B_i^D = 0 \tag{9}$$

where B_i^D is additional body force caused by damage, its expression is

$$B_i^D = \frac{\partial \sigma_{ij}^D}{\partial x_j} \tag{10}$$

Putting equation (10) in equation (7) of static boundary conditions, the following equation can be obtained

$$\sigma_{ij}^0 l_j = p_i + p_i^D \text{ (On the } S_P\text{)} \tag{11}$$

where p_i^D additional surface force caused by damage, its expression is

$$p_i^D = -\sigma_{\mathrm{ij}}^D l_j \tag{12}$$

For the stress analysis problem which damage field is given, the equation (9) and (11) indicate that the problem can be solved in no damage circumstance with introducing additional body force and additional surface force.

The Additional Load Additional Load of Stress Analysis with Known Damage Field

According to stress analysis theory of known damage field, the finite element solution- additional load finite element method which corresponded with the theory is given.

For the designate finite element, element strain can be expressed as

$$\{\varepsilon\} = [B]\{\delta_{\mathrm{e}}\} \tag{13}$$

where $\{\varepsilon\}$ is element strain array, $\{\delta_{\mathrm{e}}\}$ is element nodal displacement array and $[B]$ is element geometric matrix.

From constitutive equation (9) the element stress can be expressed as

$$\{\sigma\} = [E][B]\{\delta_{\mathrm{e}}\} + \{\sigma\}^D \tag{14}$$

where $\{\sigma\}$ is element stress array, $[E]$ is elastic matrix of material, $\{\sigma\}^D$ is element stress array caused by damage, that is

$$\{\sigma\}^D = -\mathrm{D}_{\mathrm{e}}[E][B]\{\delta_{\mathrm{e}}\} \tag{15}$$

where D_e is element damage degree.

According to virtual work principle, element nodal force can be expressed as

$$\{f_e\}=[K_e]\{\delta_e\}-\{f_e\}^D \tag{16}$$

where $\{f_e\}$ is element nodal force array, $[K_e]$ is element non-damage elastic stiffness matrix, and it can be expressed as

$$[K_e]=V_e[B]^T[E][B] \tag{17}$$

where V_e is element volume, $\{f_e\}^D$ is element additional nodal force array caused by damage, that is

$$\{f_e\}^D=D_e[K_e]\{\delta_e\} \tag{18}$$

If $\{\delta\}$ is overall displacement array, the relationship between element displacement array and overall displacement array can be built with the condition of displacement coordination:

$$\{\delta_e\}=[A_e]\{\delta\} \tag{19}$$

where $[A_e]$ is coordinate matrix.
Further, according to virtual work principle, the overall force can be expressed as

$$\{f\}=[K]\{\delta\}-\{f\}^D \tag{20}$$

where $\{f\}$ is overall force array, $[K]$ is overall non-damage elastic stiffness matrix, and it can be expressed as

$$[K]=\sum_e[A_e]^T[K_e][A_e] \tag{21}$$

where $\{f\}^D$ is overall additional external force array, that is

$$[f]^D=(\sum_e D_e[A_e]^T[K_e][A_e])\{\delta\} \tag{22}$$

The following equation can be get from equation (1) to equation (20)

$$[K]\{\delta\}=\{f\}+\{f\}^D \tag{23}$$

Thus, after importing additional external force array $\{f\}^{\mathrm{D}}$, the problem of displacement analysis which its damage field is given, can be translate into the problem of non-damage displacement analysis.

Damage Analysis, Crack Formation and Propagation Life Forecast with Known Stress Field
If damage degree of critical element $D(x)$ and its increment are expressed by $D(e_i)$ and $\Delta D(e_i)$, damage degree of some element x and its increment are expressed by $D(x)$ and $\Delta D(x)$, the equation (24) can be obtained according to the equation (6).

$$\Delta D(x)=\Delta D(e_i)\left[\frac{1-D(e_i)}{1-D(x)}\right]^{2p+2}\left\{\frac{(1-R)^{q(p+1)}\sigma_{Me}(x)^{2p+2}-\sigma_{th0}^{2p+2}\left[1-D(x)\right]^{(0.5+\beta)(2p+2)}}{(1-R)^{q(p+1)}\sigma_{Me}(e_i)^{2p+2}-\sigma_{th0}^{2p+2}\left[1-D(e_i)\right]^{(0.5+\beta)(2p+2)}}\right\} \tag{24}$$

If dD/dN is absolute damage evolution rate of element i, then $(dD/dN)_i/(1-D_i)$ is relative damage evolution rate of element i. In a damage field, if relative damage evolution rate of one element is bigger than response value of all the others, then damage evolution of this element must be fastest, and this element is critical element. Therefore, the criterion of critical element can be expressed as

$$\max_{\mathrm{i}\in[1、\mathrm{n}]}(dD/dN)_i/(1-D_i)/(1-D_i) \tag{25}$$

where n is the number of element that divided by component.

For the every increase of critical element damage degree, the cycle number of corresponding load as the following equation (26) can be calculate with equation (24),

$$\Delta N=\Delta D\Bigg/\left\{\frac{\alpha}{(p+1)}\left(\frac{1}{2E}\right)^{(P+1)}\frac{1}{(1-D)^{2P+2}}\left[(1-R)^{q(p+1)}\sigma_{Me}^{2p+2}-\sigma_{th0}^{2p+2}(1-D)^{(0.5+\beta)(2p+2)}\right]\right\} \quad (26)$$

that is, when fatigue cracks growth life is estimated, the Calculation begins from crack formation, to obtain the whole damage field of sucker rod.

APDL language is used to carry out secondary development for ANSYS, the procedure of fatigue damage of sucker rod is written, then stress field, strain field and displacement field of sucker rod is obtained on the process of cyclic loading, and additional load is used to calculate the damage value of every element, the calculated additional force is added to stress which sucker rod bears, damage cycle number and fatigue damage law can be obtained with circulatory calculation.

RESULTS AND DISCUSSION

In forming process of sucker rod, there will be defects (such as inclusion and micro cracks) inevitably in sucker rod, consequently, according to basic principle of rigid-viscoplastic finite element method, the large-scale finite element software DEFORM-3D is used to simulate the upsetting forming process of sucker rod, then the initial damage and initial stress of sucker rod are obtained, and these are for initial conditions of fatigue damage of sucker rod, to make fatigue life forecast of sucker rod more realistic.

The Founding of Finite Element Model of Sucker Rod

For the common sucker rod CYG19 in oil field, the length of its head is 180 mm, the generated nodal element from DEFORM simulation is as shown in Fig.1.

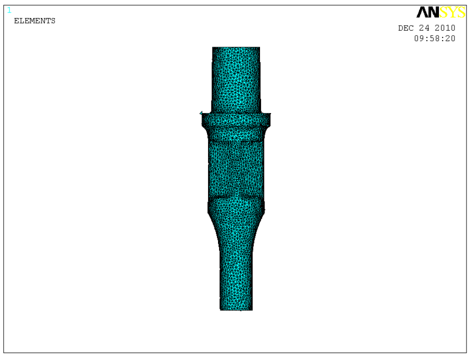

Fig.1 grid chart of sucker rod

The Definition Process of Real Constant and Material Model

By DEFORM software used in the unit of length is mm, so the unit of elasticity modulus is MPa, the unit of density is tons per cubic millimeter. The element attributes in the paper are adopted as the following Tab 1.

Tab 1: Constant of sucker rod

Elasticity modulus(EX)	Poisson ratio(PRXY)	Density (DENS)
2.1E5	0.3	7.8E-9

The Load Parameters of Sucker Rod

The diameter of sucker rod: φ19mm; The diameter of oil well pump: φ44mm; Stroke: 3m; Stroke time: 6 strokes per minute; Moisture content: 0.9; The length of sucker rod: 1000m; Submergence: 400m; Maximum load: 37.7kN; Minimum load: 13.8kN.

The Determination Process of Damage Mechanics Parameter of Sucker Rod Material

The S-N fatigue curve forΦ19 sucker rod is shown in Tab 2. In the test data, fatigue data $K_t=1$, stress ratio $R=0.33$.

Tab 2: the test data of S-N fatigue curve of sucker rod

Project	σ_{max} (MP_a)	N(per)
1	503	7.5E+05
2	425	1.0E+06
3	315	5.0E+06
5	255	7.1E+06
6	231	1.0E+07

The stress threshold value for mid-value fatigue curve, $\sigma_{thm} = 231\text{M}P_a$, the coordinate away from the farthest point of mid-value fatigue curve is $(498{,}800000)$, and $\beta = 0.5$. According to the offered experimental data points, the parameters p and K_m are fitted by the least squares method:

$$p = 0.6404 \quad ,K_m = 3.7714\times10^{14}$$

Further calculated:

$$D_{0m} = 0.070175\, , K_0 = 5.1496\times10^{14} \quad ,$$

$$\sigma_{th0} = 228.14\, , \quad \alpha = 5.527\times10^{-9}$$

One end of sucker rod is fixed and the other end is loaded, in one stroke the stress nephogram and the damage nephogram of sucker rod can be obtained by the calculation method of transient nonlinear, the nephograms are shown in Fig.2 and Fig.3.

As shown in Fig.2, the maximum equivalent stress of sucker rod occurs in upsetting segment and wrench segment. Fig.3 shows the damage location of sucker rod, the maximum damage occurs near the upsetting of sucker rod.

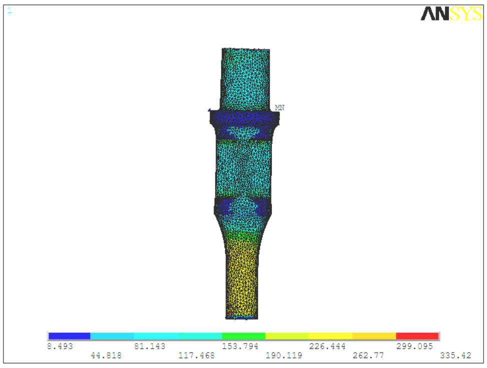

Fig.2 Mises stress nephogram of sucker rod

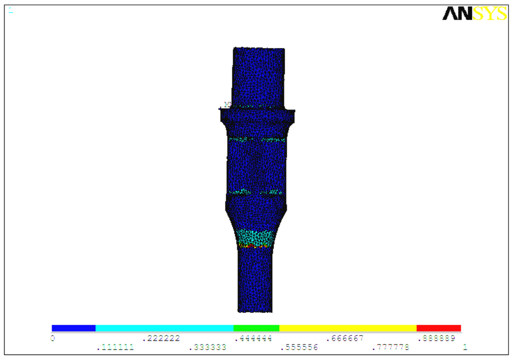

Fig.3 Damage nephogram of sucker rod head

By analog computation, under the circumstance of different initial stress and different initial damage, the cycle number when every critical element is broken can be seen as Tab 3.

Tab 3: the cycle number when sucker rod element damage

The number of element damage	1	5	10	15	16
Cycle number	380579	398661	413356	441178	449490

In Tab 3 the first critical element damage is for the longest time, it explains the formation of cracks is a long process, and is not instantaneous, at the same time the first critical element damage, other critical element also begin to damage, after the first critical element damage, the cracks begin to form. From the formation of cracks to crack propagation, elements are in the damage continuously. With the increasing damage value, the damage elements increase continuously, when the damage elements reach 16, the cycle number increases no longer, the element damage done in an instant, then fracture occurs.

CONCLUSION

In the paper, fatigue damage evolution equation of sucker rod is established, the additional load-finite element method is used to carry out secondary development for ANSYS, APDL language is used to write subroutine, fatigue damage model of sucker rod upsetting segment is built, in the process from the formation of cracks to crack propagation, the cycle number is obtained when every critical element damage and the whole component damage. In the paper, the theory of damage mechanics is used for the first time in research of sucker rod fatigue damage, the research method of sucker rod fatigue is perfected. The paper provides a new theory to predict the fatigue life of sucker rod.

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