Fatigue Analysis of the Cylinder in The Axial Piston Pump

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***Abstract*—For the cylinder of the axial piston pump suffers complicated forces including hydraulic pressure force, mechanical forces and mutual coupling, which causes the cylinder fatigue damage with all forces whose fluctuation is caused by fluid striking on the cylinder of the pump cyclically, it is necessary to develop the fatigue analysis research. And the sensitive fatigue areas of the cylinder in the axial piston pump is presented through the nephogram of the fatigue life, the fatigue safety factor over the whole model and the curve of fatigue sensitivity, which can verify the theory of micro crack propagation and the transient dynamics analysis of the axial piston pump cylinder is simulated. All the results are produced by software, Solidworks is used to build the three-dimension assembling model containing seven pistons and ANSYS Workbench is used to manage the model through setting the parameters of different materials and constrains of the cylinder. It's promising to provide a theoretical basis when optimizing the design of the axial piston pump and to offer new ideas and methods for the study of reliability and fatigue durability on the axial piston pump.**

Keywords—Axial piston pump; Cylinder; Transient dynamics simulation; Fatigue simulation

I. INTRODUCTION

Due to the lack of domestic high-performance hydraulic components, the main engine plants in China can only rely on import and are restricted by foreign suppliers. So the technology level of hydraulic piston pump in China urgently needs to be substantially improved to provide high-performance products that can replace imports for the main engine plants, which can make the main engine plants get rid of the dependence on imported products and reduce purchasing costs to save a lot of foreign exchange for our country[1].

Axial piston pump is a execute component that can convert hydraulic energy into mechanical energy, and the main target market of axial piston pump is the engineering machinery field. In recent years, China's economy grows at a high pace, the scale of investment of infrastructure is great and the real estate industry remains prosperous, which has provided a broad market space for construction machinery. However, using their own technology advantages, foreign companies occupy almost the whole hydraulic components industry so that the hydraulic components with high quality and long service life mainly rely on import. Several research articles have been published on the analysis of the failure of engine cylinders due to manufacturing defects and poor material properties[2]. So it is of great significance to improve the quality, service life and reliability of our country's hydraulic components by studying and analyzing the cylinder block of axial variable piston pump from the fatigue life[3].

The mechanical stress on cylinder block is fluctuating circulating stress when the pump works normally. According to statistics[4], fatigue fracture accident caused by repeated fluctuating load accounts for 80% ~ 90% of the total mechanical structure failure. The risk of fatigue damage is shown in that there is no obvious warning to achieve fatigue life, which is shown that fracture collapse and brittle fracture accident will happen suddenly. For example, the solid rocket engine shells of American "polaris" missile exploded at the time of test in the 1950's, while the stress of the motor body is much smaller than yield limit of the material. In the 1967's, abnormal vibration occurred on a bridge over the American Ohio river with a loud crack so that the bridge finally collapsed into the river, while the load is only 10% of the design load then. It is the micro crack in structural member that results in the fracture phenomenon under low stress. The micro crack in actual component is inevitable, which may come from material defects and air bubbles occurring in the process of smelting and quenching, all kinds of cold working and electroplating in process engineering. Besides, the micro crack may occur when suffering medium corrosion, temperature effect and the effect of cyclic loading in the using process[5]. High levels of reliability and availability are necessary to meet the operating requirements. Thus an analytic strength assessment is required in order to ensure a safe operation[6,7]. For the axial piston pump cylinder block's fatigue problems of fatigue deformation, fatigue crack and so on, the fatigue simulation module of ANSYS Workbench was used to analyze the stress and strain change process of axial piston pump cylinder[8], so that the simulation evolution process of cylinder body's tiny crack propagation and the mechanism process of fatigue fracture damage were got, which provides theoretical basis for batch production of axial piston variable displacement pump cylinder.

II. FINITE ELEMENT ANALYSIS

A. Fatigue Analysis Theory

Uniaxial characteristics analysis of metal can be divided into two kinds of engineering properties and true characteristics. Engineering properties is a kind of characteristic that is applied to compute with original cross-sectional area and length of the sample. While stress-strain characteristics is computed according to the instantaneous area and length in the sample loading process[9].

Engineering stress $S = \frac{P}{A_0}$, True stress $\sigma = \frac{P}{A}$

Engineering strain $e = \frac{L - L_0}{L_0}$,

True strain $\varepsilon = \int_{L_0}^{L} (\frac{dl}{l}) = \ln(\frac{L}{L_0})$

Where, P is axial tension loads. A_0 is original cross-sectional area of the sample. A is instantaneous area of the sample. L_0 is original length of the sample. L is instantaneous length of the sample.

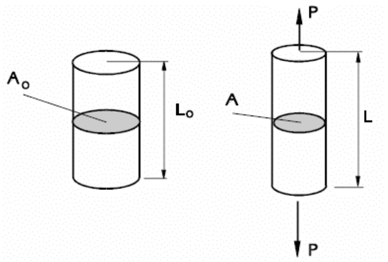


Fig. 1. Engineering stress-strain and the actual stress-strain

The real stress when the sample was broken is

$$\sigma_f = \frac{P}{A_f} \tag{1}$$

The real strain when the sample was broken is

$$\varepsilon_f = \ln(\frac{A}{A_f}) \tag{2}$$

Where, A_f is the cross-sectional area when the sample was broken.

According to the theory of Ranberg and Osgood, the stress-strain curve of the sample under single load is monotonous. The curve includes two parts of the elastic strain that can be restored and the plastic strain that can not be restored after deformation when the load was removed.

The elastic strain

$$\varepsilon_e = \frac{\sigma}{E} \tag{3}$$

The plastic strain:

$$\varepsilon_p = (\frac{\sigma}{K})^{\frac{1}{n}} \tag{4}$$

The total strain is sum of the elastic strain and the plastic strain

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + (\frac{\sigma}{K})^{\frac{1}{n}} \tag{5}$$

Where, E is elasticity modulus. K is strain hardening coefficient. n is strain hardening exponent.

The equation which described the relationship between stress amplitude $\left(\frac{\Delta\sigma}{2}\right)$ and the number of load reverse $2N_f$ is

$$\log_{10}\frac{\Delta\sigma}{2} = b\log_{10}(2N_f) + \log_{10}(\sigma_f^{'}) \tag{6}$$

Or
$$\frac{\Delta\sigma}{2} = \sigma_f^{'}(2N_f)^b \tag{7}$$

Where, fatigue life N_f is cycle-index after the sample is broken under the action of external load. Fatigue strength coefficient $\sigma_f^{'}$ is the real stress when damage occurs in a loop. Fatigue strength exponent b is the slope of real stress amplitude-life's double logarithmic curve.

The relationship between real stress and elastic strain is as follows

$$\Delta\varepsilon_e = \frac{\Delta\sigma}{E} \tag{8}$$

The both sides of the equation(7) are divided by elasticity modulus *E*

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_f^{'}}{E}(2N_f)^b \tag{9}$$

The relationship between plastic strain amplitude and the life which was found by Manson and Coffin is linearin double logarithmic curve. The equation is as follows

$$\log_{10}\frac{\Delta\varepsilon_p}{2} = c\log_{10}(2N_f) + \log_{10}(\sigma_f^{'}) \tag{10}$$

So,

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f^{'}(2N_f)^c \tag{11}$$

The total strain is sum of the elastic strain and the plastic strain, which is as follows

$$\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p \tag{12}$$

The equation described by strain amplitude is

$$\frac{\Delta\varepsilon}{2}=\frac{\Delta\varepsilon_e}{2}+\frac{\Delta\varepsilon_p}{2} \tag{13}$$

According to the equation(9) and (11), the relationship between total strain amplitude and life can be gotten

$$\frac{\Delta\varepsilon}{2}=\frac{\sigma_f^{'}}{E}(2N_f)+\varepsilon_f^{'}(2N_f)^c \tag{14}$$

Where, c is fatigue ductility exponent, $\varepsilon_f^{'}$ is fatigue ductility coefficient.

B. The response of the materials on the strain history and the calculation of fatigue life

Steady stress-strain hysteresis loop of many samples can be drown in the same coordinate, and the stable hysteresis loop of 10 samples under different strain levels is shown in Fig.2. The stress strain curve that connects sharp point of the hysteresis loop is called the steady state cyclic stress strain curve.

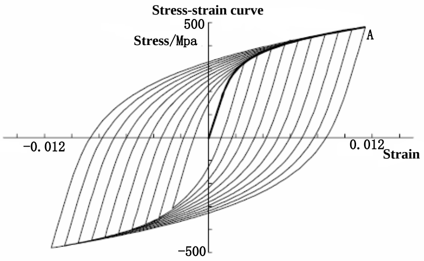


Fig. 2. Stress-strain curves

According to the Fig.2, the total strain equation is as follows

$$\varepsilon=\frac{\sigma}{E^*}+K^{'}\left(\frac{\sigma}{K^{'}}\right)^{\frac{1}{n^{'}}} \tag{15}$$

Where, E^* is circular elastic modulus（the value of circular elastic modulus and monotonous elastic modulus is approximately equal so that $E^*=E$）. $K^{'}$ is cyclic strain intensity factor. $n^{'}$ is cyclic strain intensity index.

Hysteresis loop equation is used to calculate the variable quantity of stress and strain, so that the equation expressed in variable quantity is as follows

$$\Delta\varepsilon=\frac{\Delta\sigma}{E^*}+2\left(\frac{\sigma}{2K^{'}}\right)^{\frac{1}{n^{'}}} \tag{16}$$

Where, Δ is the variable quantity of the stress or strain.

The time response of the materials on the strain history can be gotten according to the local strain time history of material stress concentration. For the local strain time history in the Fig.2, the first section of the strain which ranges from the zero point to A belongs to the normal strain, and the stress and strain response of the material changes along the steady-state cycle stress-strain curve. During the next strain history, the stress and strain response of the material changes along the hysteresis loop.

According to the Miner theory, the damage caused by the cycle is $\frac{n}{N_f}$, the damage caused by one cycle is $damage=\frac{1}{N_f}$. The cyclical total strain amplitude above is $\Delta\varepsilon_{ADG}/2$, multiplied with the stress σ_A of the point A so that the parameters of the cycle Smith-Watson-Topper modified formula can be gotten. Then the damage caused in the cycle can be calculated with the Smith-Watson-Topper equation or the strain life curve.

According to the Miner theory, the total damage of the strain signals is as follows

The total damage=(B-C cycling damage)+(E-F cycling damage)+(A-D-G cycling damage)

$$\sum\frac{n}{N_f}=\left(\frac{1}{N_f}\right)_{B-C}+\left(\frac{1}{N_f}\right)_{E-F}+\left(\frac{1}{N_f}\right)_{A-D-G} \tag{17}$$

When $\sum\frac{n}{N_f}=1$, the lose efficacy in the form of crack occurs so that the total fatigue life is reciprocal of total damage

$$fatigue\,life=\frac{1}{\sum\frac{n}{N_f}} \tag{18}$$

C. Cylinder model building and meshing

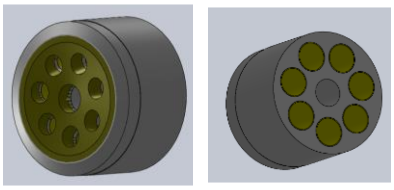


Fig. 3. 3-d model of the cylinder

TABLE I. MATERIAL PROPERTIES OF CYLINDER BLOCK

material name	elastic modulus E Mpa	poisson's ratio σ	density ρ g/cm^3
Rolling manganese bronze	108	0.35	8.8
45#	210	0.28	7.8

The actual cylinder is interference fit of the valve plate pair, the bronze module of piston pair and cylinder body. The fixed pattern is selected after assembly model is fit through 3 d software Solidworks. The material of the valve plate pair tangent module and piston pair model is manganese bronze, and the material of the cylinder body is 45# steel. The parameters of the two materials are shown in Table. 1

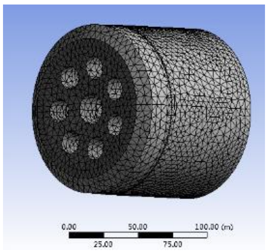


Fig. 4. Cylinder meshing

In the meshing process of ANSYS Workbench, mesh can be driven by parameters and model is updated through the system parameters. Besides, only limited input information is needed to make the basic system analysis finished, control and effect can be added to the mash and the system can automatically model and analyze along with the changes of environment. The mesh generation of ANSYS Workbench has the characteristics of parametric, stability, high automation, flexibility and adaptive structure.

Tetrahedron element with four nodes is adopted when cylinder block is mashed[10]. Automatic meshing method is adopted so that the mash with strong correlation, good continuity and fast conversion is gotten. The number of knots is 238839 and the number of element is 121242, which is shown in Fig.4.

D. Constraint and Load

Gravitational acceleration of cylinder block g=9.8m/m2, the valve plate pair and the load of cylinder block piston pair are simulated by Fluent, and the load curve is shown in Fig.5and Fig.6

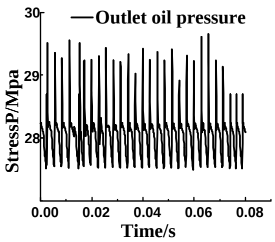
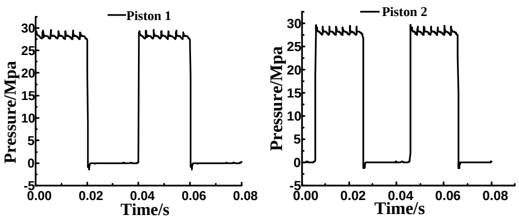
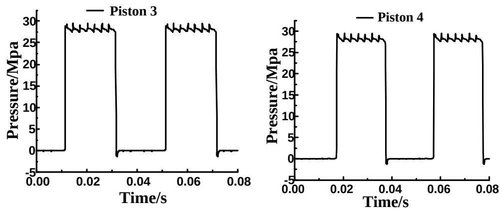


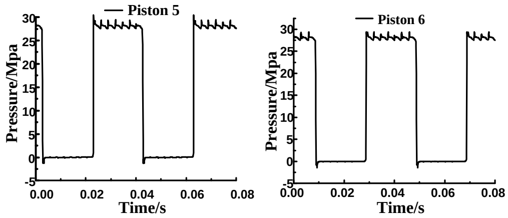
Fig. 5. Load of cylinder valve plate



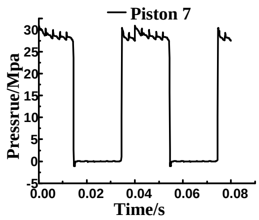
a) pressure curve of piston 1 b) pressure curve of piston 2



a) pressure curve of piston 3 b) pressure curve of piston 4



a) pressure curve of piston 5 b) pressure curve of piston 6



g) pressure curve of piston 7

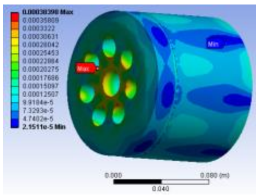
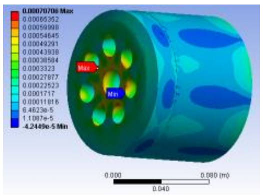
Fig. 6. Load of plunger pump

There is a certain angle between axial plunger pump shaft and cylinder block. Plunger piston slips relatively in the cylinder after the spindle begins to rotate and reciprocates along with the spindle rotation so that oil absorption and extraction can be realized and the cylinder block receives rotation constraint from plungers. Straight shaft end of the cylinder block is inserted into the valve plate so that there are cylindrical constraint, axial constraint and tangential constraint of straight shaft to the cylinder block. Hydraulic oil flows through the valve plate which directly contacted with the cylinder in the process of oil absorption and extraction, which forms the valve plate pair so that there is spherical constraint of the valve plate pair to the cylinder block.

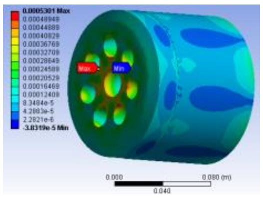
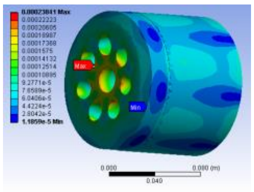
In short, the cylinder block receives spherical constraint from the valve plate pair, axial constraint and tangential constraint from the straight shaft and rotation constraint from plungers.

E. Finite element analysis results of the cylinder block

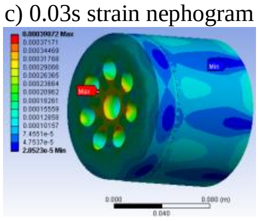
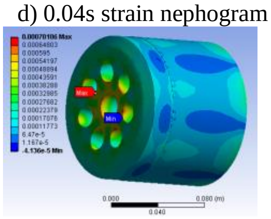
1) Strain analysis

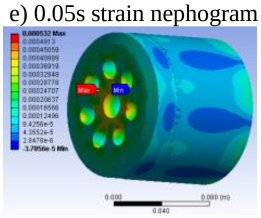
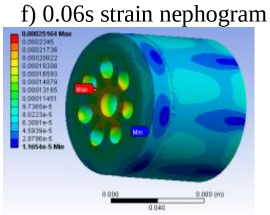
a) 0.01s strain nephogram b) 0.02s strain nephogram

c) 0.03s strain nephogram d) 0.04s strain nephogram

e) 0.05s strain nephogram f) 0.06s strain nephogram

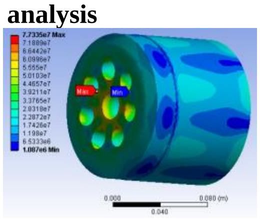
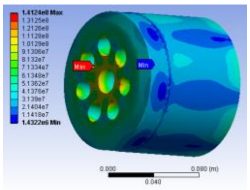



g) 0.07s strain nephogram h) 0.08s strain nephogram

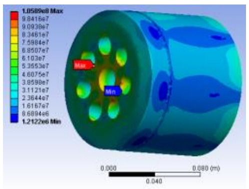
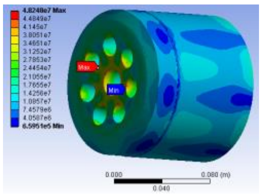
Fig. 7. Cylinder strain deformation graph over time

As Fig.7 shows on the whole, the strain of the same cylinder' place is changing, and the maximum deformation occurs on the place between the region plunger hole and the hole of the straight shaft, which increases leakage of plunger pump, accelerates fatigue wear and reduces fatigue life.

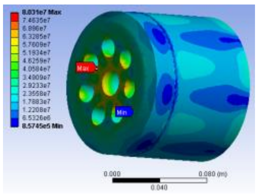
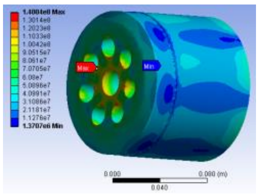
2) Sss analysis

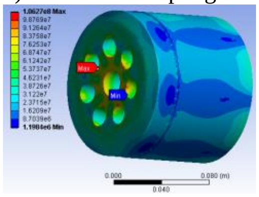
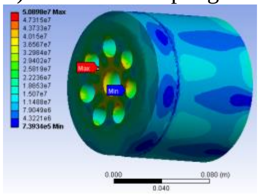
a) 0.01s stress nephogram b) 0.02s stress nephogram

c) 0.03s stress nephogram d) 0.04s stress nephogram

e) 0.05s stress nephogram f) 0.06s stress nephogram

g) 0.07s stress nephogram h) 0.08s stress nephogram

Fig. 8. Cylinder stress deformation variation over time

3) Fatigue analysis

The structure is safe in using process when the safety factor is greater than 1, and damage occurs more likely when lower the safety factor is. As Fig.9 shows, the safety factor of the area near every plunger is lower and the minimum value is 1.3549, which indicates that the safety factor of cylinder is low and it is easy to fatigue.

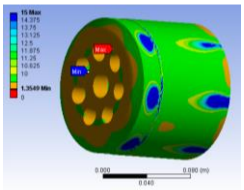
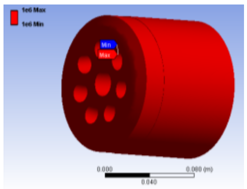



Fig.9. Safety factor nephogram Fig.10. Life nephogram

As Fig.10 shows, the distribution of the cylinder's life is homogeneous, and the shortest life area occurs on the place between the region plunger hole and the hole of the straight shaft, of which safety coefficient is lower, stress value is larger, and deformation is larger.

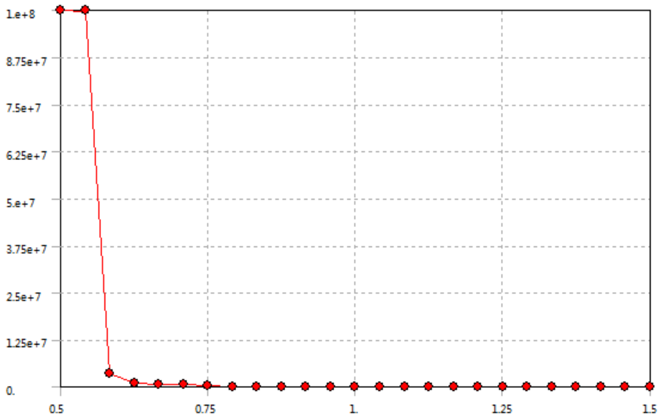


Fig.11 Fatigue sensitivity curve of 45#

As the fatigue curve shows, life decreases as the pressure increases. The fatigue life falls fast until the long life requirement of the 106 cycle-index can not be met at 0.6 times of the average load, because the fatigue life of 45 # steel can not meet the requirement of the durability of cylinder block. But the result will be different if high-speed steel is used. The S-N curve of 45# steel-high speed steel and fatigue sensitivity curve of high-speed steel cylinder are shown in Fig.12 and Fig.13.

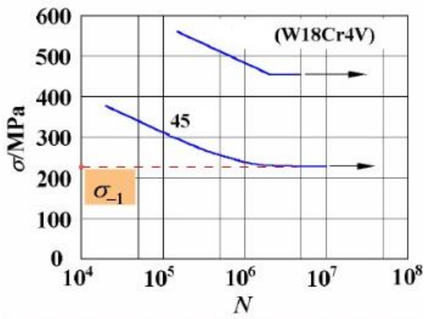


Fig.12. S-N curve of 45# steel-high speed steel

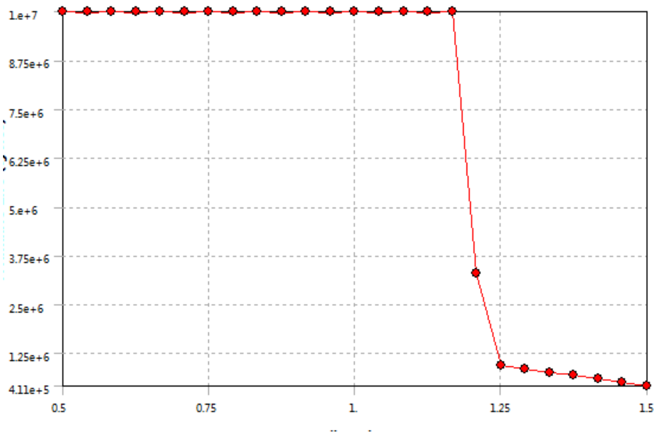


Fig.13 Fatigue sensitivity curve of high-speed steel cylinder

The fatigue life is divided into three areas:

(1) short life area: The fatigue life is roughly within cycle number of 10^4 under the large strain cycle.

(2) middle life area: The fatigue life is roughly in the cycle number range of 10^4 ~ 10^6 under moderate stress.

(3) long life area: The fatigue life is roughly in above 10^6 cycle number under low stress.

Stress level the cylinder block receives is smaller compared to the material's yield limit of the cylinder so that the conclusion can be gotten that stress level the cylinder block receives is low. As Fig.13 shows, the cycle number still can reach 106 times when 1.25 times of the average load can be reached, which meets the requirements of long life. According to the fatigue sensitivity curve of Fig.11 and Fig.13, the conclusion that material properties have a crucial influence on fatigue life of cylinder block can be gotten.

III. CONCLUSION:

1. Fatigue simulation modeling can reflect the general trend of cylinder block's fatigue parts, though the actual conditions cannot be exactly simulated. According to the strain nephogram, the stress nephogram, the safety factor nephogram and the life nephogram, it is easy for fatigue failure of the cylinder block to occur near the plunger piston hole and the straight shaft hole.

2. The stress and strain is changing according to the stress nephogram and the strain nephogram so that tiny crack grows under the load of below the material yield limit, which results in fatigue crack.

3. The fatigue life of the plunger cylinder extends obviously when high-speed steel is selected, which indicates that choosing the material with high fatigue life can meet the requirements of the durability of axial piston pump cylinder.

4. According to the fatigue sensitivity curve, it is a dramatic change process for cylinder from normal work to the fatigue failure. The slope of normal work and fatigue damage's transition curve is very big, which indicates that it is rigid transition between normal work and fatigue damage.

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