Optimization of anti-wear performance evaluation method of hydraulic oil based on four-ball machine

Zhen Penghou1,*, An Haizhena, Chen Lib, Liu Minb,c
1Jiangsu Xuzhou Construction Machinery Research Institute, Xuzhou Construction Machinery Group, Xuzhou, Jiangsu, China
*bzhenpenghou@xcmg.com
*zhenpenghou@163.com
a18205213535@163.com
bchenlixcmg@163.com
c15715213267@163.com

Abstract—To establish a scientific and effective method for evaluating the anti-wear performance of hydraulic oil, the L9 (3^4) orthogonal test scheme with 4 factors and 3 levels is rationally designed by using the four-ball machine and combined with the actual working conditions of the hydraulic system of construction machinery. The test and repeated verification are carried out by taking wear scar diameter, wear scar morphology, oil temperature change during the process and abnormal noise as evaluation indexes. The results show that the selected test method (588N, 90min, 75℃, 600r/min) has good discrimination and repeatability for different quality grades of hydraulic oil; this method can realize the quality control of the anti-wear performance of hydraulic oil, and can be used in the research of hydraulic oil in laboratory and the screening method before the bench test, and provide the basis for the rational selection of lubricating oil in hydraulic system.

1. Introduction
In the hydraulic system, the hydraulic oil not only controls, transforms and transfers the energy in the system through the pressure and flow changes in the flow process [1], but also lubricates the hydraulic components to reduce the wear of the lubricating parts. Therefore, the anti-wear performance of hydraulic oil directly affects the reliability and service life of hydraulic components. If the anti-wear performance of hydraulic oil is poor, it is easy to cause abnormal wear, vibration and abnormal sound of hydraulic components, which will affect the stability and efficiency of the entire hydraulic system. With the development of hydraulic system towards high pressure and large flow, higher requirements are put forward for the anti-wear performance of hydraulic oil[2].

At present, the four-ball machine method which is easy to operate in the laboratory is used to test the anti-wear performance of hydraulic oil[3-6]. The structure of the four ball machine is simple and the amount of oil used is small, but the evaluation index of the current detection method is single, the results can not reflect the actual performance of the oil, and the anti-wear performance of hydraulic oil is not distinguished. Therefore, based on the four ball machine and according to the actual working conditions of the hydraulic system of construction machinery, the test parameters and evaluation indexes are optimized reasonably, the orthogonal test and repeated verification are carried out, and the evaluation test method of anti-wear performance of hydraulic oil is established.
2. Orthogonal test

2.1 Test Equipment and Method
The test is carried out with a four-ball machine. The friction pair is point contact. Three steel balls of the same diameter are clamped in an oil box and immersed in the test oil. Another steel ball of the same diameter is placed on the front top of the three balls. When the oil temperature reaches the specified temperature, the top ball rotates at a certain speed and time, resulting in sliding friction between the friction pairs and forming wear marks.

2.2 Orthogonal test and result
In order to choose a better test scheme, L-1 hydraulic oil (with good anti-wear performance) and L-2 hydraulic oil (with poor anti-wear performance) are selected for the test. The two oils are tested on a four-ball machine at the level of 4 factors and 3 levels according to L9 (3^4) orthogonal scheme. The test index is a quantitative index, and the difference of the wear scar diameter of the two test oils is used to judge the distinguishing performance of the test conditions. The greater the difference between the two test oils, the better the distinguishing performance between the two test oils, and the worse the distinguishing performance between the two test oils. At the same time, the appearance of abnormal noise, the morphology of wear scar and the change of oil temperature are analyzed comprehensively. The test results are shown in table 1.

| Number | Time /min | Speed /r/min | Temperature /°C | Load /N | L-1 wear scar diameter /mm | L-2 wear scar diameter /mm | Difference in wear scar diameter /mm |
|--------|-----------|--------------|-----------------|--------|---------------------------|---------------------------|----------------------------------|
| 1      | 60        | 600          | 54              | 196    | 0.32                      | 0.35                      | 0.03                             |
| 2      | 60        | 1200         | 75              | 392    | 0.42                      | 0.53                      | 0.11                             |
| 3      | 60        | 1800         | 96              | 588    | 0.95*                     | 1.07*                     | 0.12                             |
| 4      | 90        | 600          | 75              | 588    | 0.49                      | 0.63                      | 0.14                             |
| 5      | 90        | 1200         | 96              | 196    | 0.33                      | 0.40                      | 0.07                             |
| 6      | 90        | 1800         | 54              | 392    | 0.60*                     | 0.68*                     | 0.08                             |
| 7      | 120       | 600          | 96              | 392    | 0.42                      | 0.53                      | 0.11                             |
| 8      | 120       | 1200         | 54              | 588    | 0.65*                     | 0.79*                     | 0.14                             |
| 9      | 120       | 1800         | 75              | 196    | 0.37                      | 0.40                      | 0.03                             |

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| 7      | 120       | 600          | 96              | 392    | 0.42                      | 0.53                      | 0.11                             |
| 8      | 120       | 1200         | 54              | 588    | 0.65*                     | 0.79*                     | 0.14                             |
| 9      | 120       | 1800         | 75              | 196    | 0.37                      | 0.40                      | 0.03                             |

range analysis

| K1     | 0.26      | 0.28        | 0.25            | 0.13   |
| K2     | 0.29      | 0.32        | 0.28            | 0.30   |
| K3     | 0.28      | 0.23        | 0.30            | 0.40   |
| k1     | 0.09      | 0.09        | 0.08            | 0.04   |
| k2     | 0.10      | 0.11        | 0.09            | 0.10   |
| k3     | 0.09      | 0.08        | 0.10            | 0.13   |
| Rj     | 0.01      | 0.03        | 0.02            | 0.09   |

note * Oil film rupture
2.3 Judgment of oil film rupture

Both oils in groups 3, 6 and 8 in table 1 would scream at some point during the test, causing a spike in the coefficient of friction, the results show that the oil film of the two oils in groups 3, 6 and 8 are broken under the corresponding test conditions, so that the oils could not form effective lubrication between the steel balls, which resulted in the increase of the wear scar diameter of the steel balls, more friction heat and higher oil temperature. The oil film rupture time, wear scar diameter and oil temperature change during the test of the two oils in groups 3, 6 and 8 are shown in table 2.

At the same time, the oil film rupture will cause abnormal changes of steel ball wear scar, such as pear mark damage phenomenon along the sliding direction of the wear scar surface, the scratch extends beyond the wear mark, and there is excessive metal accumulation outside the wear scar. The morphologies of wear scar are shown in figure 1.

| Number | Sample | Oil film rupture time /min | Wear scar diameter /mm | Oil temperature change °C |
|--------|--------|----------------------------|------------------------|---------------------------|
| 3      | L-1    | 4                          | 0.95                   | 94-131                    |
|        | L-2    | 2                          | 1.07                   | 94-133                    |
| 6      | L-1    | 8                          | 0.60                   | 54-98                     |
|        | L-2    | 8                          | 0.68                   | 54-106                    |
| 8      | L-1    | 28                         | 0.65                   | 54-105                    |
|        | L-2    | 26                         | 0.79                   | 55-106                    |

Figure 1. Morphologies of wear scar
2.4 Data analysis and determination of test conditions

As can be seen from the range values in table 1, the factors influencing the test results are test load, test speed, test temperature and test time in sequence. The oil film of the two test oils in groups 3, 6 and 8 is broken, indicating that the test conditions are too harsh when high load and high speed existed at the same time, and the oil could not provide an effective lubricating film. When the test load is 196N, the discrimination between the two oils is small. In order to select better test conditions, it can be seen from the direct observation of table 1 that the test conditions in group 4 (90min, 600r/min, 75℃ and 588N) have relatively good discrimination between the two oils.

It can be seen from the range analysis that when the test condition is 90min, 1200r/min, 96℃ and 588N, it has good discrimination between the two oils. It can be seen from the conditions of 90min, 600r/min, 75℃, 588N and 90min, 1200r/min, 96℃, 588N that the test speed and test temperature in the above two conditions are cross-tested under the constant test time (90min) and test load (588N). The results are shown in table 3. The film rupture time and oil temperature change during the cross test are shown in table 4.

Table 3. Cross test results of test temperature and test speed

| Number | Load /N | Time /min | Temperature /℃ | Speed /(r/min) | L-1 Wear scar diameter /mm | L-2 Wear scar diameter /mm | Difference in wear scar diameter /mm |
|--------|---------|-----------|----------------|--------------|--------------------------|--------------------------|----------------------------------|
| I      | 588     | 90        | 75             | 600          | 0.47                     | 0.62                     | 0.15                             |
| II     | 588     | 90        | 75             | 1200         | 0.65*                    | 0.82*                    | 0.17                             |
| III    | 588     | 90        | 96             | 600          | 0.46                     | 0.60                     | 0.14                             |
| IV     | 588     | 90        | 96             | 1200         | 0.71*                    | 0.82*                    | 0.11                             |

Note: * Oil film rupture

Table 4. Oil film rupture time and oil temperature change of the cross test

| Number | Sample | Oil film rupture time /min | Oil temperature change /℃ |
|--------|--------|----------------------------|----------------------------|
| II     | L-1    | 19                         | 76-102                     |
|        | L-2    | 3                          | 75-100                     |
| IV     | L-1    | /                          | 96-105                     |
|        | L-2    | 6                          | 94-109                     |

As can be seen from table 3 and table 4, when the test load is 588N and the test speed is 1200r/min, the oil film of the steel ball is broken. The morphologies of wear scar are shown in figure 2. The test results are the same as those in table 1, indicating that the test load (588N) and test speed (1200r/min) are under harsh conditions. Comparing and analyzing the test results of group I and group III in table 3, under the same test load, time and speed, the change of oil temperature has little effect on the test results, and the difference of wear scar diameter between the two oils is close. Therefore, the test conditions of group I and group III can be used as test conditions for evaluating and distinguishing the anti-wear performance of hydraulic oil. But considering the usual temperature and maximum allowable operating temperature of hydraulic oil in hydraulic system, so choose the I group test conditions (588N, 90min, 75℃, 600r/min) as the final evaluation test conditions.
3. Verification test

According to the selected test conditions of anti-wear performance of hydraulic oil (588N, 90min, 75℃, 600r/min), 12 kinds of hydraulic oil are tested by using a four-ball machine to verify the feasibility and discrimination of the established test conditions. The test results are shown in figure 3.

It can be seen from figure 3 that only L-6 and L-8 have oil film rupture, which indicates that the anti-wear performance of these two oils is poor. The wear scar morphologies of L-6 and L-8 are shown in figure 4. The other oils are in normal wear, wear scar surface is relatively smooth. Under the test conditions, these 12 oils can be roughly divided into 4 categories according to the size of the wear scar diameter and the wear scar morphology, as shown in table 5. The results show that this method can distinguish the anti-wear performance of hydraulic oils of different quality grades, and can assist the rational selection of lubricating oils in hydraulic system.
Table 5. Classification of the 12 kinds of hydraulic oil

| Category | Sample                | Wear scar diameter range/mm |
|----------|-----------------------|-----------------------------|
| 1        | L-9, L-10, L-1        | 0.43-0.49                   |
| 2        | L-5, L-7, L-11, L-12  | 0.54-0.58                   |
| 3        | L-3, L-2, L-4         | 0.61-0.64                   |
| 4        | L-6, L-8              | 0.91-0.96                   |

4. Repeatability test

According to the test conditions of anti-wear performance of hydraulic oil, the repeatability test of the above 12 kinds of hydraulic oil are tested on a four-ball machine. The results are shown in table 6. According to the test data in table 6, the test repeatability $r=0.04$mm is calculated according to 95% confidence. From the results, it can be seen that the anti-wear performance test method of hydraulic oil has good repeatability.

Table 6. Repeatability test results

| Sample | Wear scar diameter/mm | average value/mm | Standard deviation |
|--------|-----------------------|------------------|--------------------|
| L-1    | 0.48 0.47 0.51        | 0.49             | 0.017              |
| L-2    | 0.64 0.61 0.63        | 0.63             | 0.020              |
| L-3    | 0.59 0.61 0.63        | 0.61             | 0.020              |
| L-4    | 0.63 0.62 0.66        | 0.64             | 0.021              |
| L-5    | 0.54 0.55 0.54        | 0.54             | 0.007              |
| L-6    | 0.92 0.91 0.91        | 0.91             | 0.007              |
| L-7    | 0.56 0.55 0.56        | 0.56             | 0.007              |
| L-8    | 0.96 0.95 0.96        | 0.96             | 0.007              |
| L-9    | 0.43 0.44 0.43        | 0.43             | 0.007              |
| L-10   | 0.45 0.47 0.47        | 0.46             | 0.012              |
| L-11   | 0.56 0.57 0.58        | 0.57             | 0.010              |
| L-12   | 0.56 0.59 0.58        | 0.58             | 0.016              |

5. Summarize

(1) The selected test method of anti-wear performance of hydraulic oil (588N, 90min, 75°C, 600r/min) has good discrimination and repeatability for hydraulic oil of different quality grades.

(2) This method can realize the quality control of the anti-wear performance of hydraulic oil, and can be used in the research of laboratory hydraulic oil and the screening method before the bench test, and provide the basis for the rational selection of lubricating oil in the hydraulic system.

References

[1] X.Z.Tang, M.R.Su, F.C.Huang, Y.C.Xiao,“Development and application of special anti-wear hydraulic oil used in engineering machinery,” Contemporary chemical industry, vol.42, pp.725-729,2013.

[2] Z.J.Guan,G.F.Zhong,H.Y.Zhang,H.P.Qin,“The selection of Construction machinery hydraulic system hydraulic oil,” Petroleum Products Application Research, vol.25, pp.30-32,2007.
[3] B.T.Liu, H.Gao, H.Zhou, J.Zheng, Y.Xing, “Applications of four-ball testers in evaluation of liquid lubricants,” Physical Testing and Chemical Analysis(Part A:Physical Testing), vol.51, pp.795-798,2015.

[4] S.J.Huang, “Experimental study on the Simulation bench evaluation of anti-wear performance of hydraulic Oil,” Shanghai: Tongji University, 2005.

[5] J.H.Ding,L.Z.Zhou, “Investigation on Influencing Factors of accuracy of four ball wear test results of lubricating oil,” Petroleum Products Application Research, vol.35,pp.78-81,2017.

[6] S. B. Bulgarevich, M. V. Boiko, K. S. Lebedinskii, D. Yu. Marchenko, “Kinetics of sample wear on four-ball friction-testing machine using lubricants of different consistencies,”Journal of Friction and Wear, vol.35,pp.531-537,2014.