Recycling quality evaluation of hydraulic cylinder based on residual strength analysis

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Abstract. Remanufacturing is an effective way to achieve circular economy and sustainable development. Hydraulic cylinder is one of the most important executive parts of construction machinery, which has high quality, high precision and high economic value. In order to evaluate the recycling quality of hydraulic cylinder under unknown load history conditions, a remanufacturability evaluation method based on residual strength and residual life analysis was presented in this paper. Design strength, surface quality, mechanical properties including hardness, stiffness and natural frequency of hydraulic cylinder were taken into account in this model. Based on the strength characteristics change rules of hydraulic cylinder in the fatigue process, a reasonable critical threshold for remanufacturing was given. The results showed that, this model provided an intuitive way to learn about the residual strength and residual life of parts, which has a high application potential.

1. Introduction

With the development of global manufacturing industry, human beings are facing more and more serious problems of resources and environment. For mechanical products, the ideal design is that the components are end of life when they are scrapped. Up to now, it is difficult to realize because of safety reasons, design theory, etc. In fact, many components or parts could be directly reused or remanufactured again. The primary difference between new and reused components and parts is that they call it the three E’s: Economy, Ecology and Energy conservation [1, 2].

However, which components or parts can be reused or remanufactured and the assessment theory and method of components or parts reused are high-degree secreted in different company. Until now, there are no technical publications reported. Due to the lack of remanufacturing evaluation standards, a large number of components are wasted.

Hydraulic cylinder is one of the most important executive parts of construction machinery, which has high quality, high precision and high economic value [3-7]. But the evaluation methods of components or parts reused are seldom reported. Whether the components or parts can be reused or remanufactured are hard to determine. The hydraulic cylinder recyclability assessment based on the experience cannot be quantified and give reliable residual strength and residual life. It is unable to
guarantee the reliability of remanufactured products, and may cause a large number of remanufacturing wastes of resources [8, 9].

Based on residual strength and residual life assessment theory, this work developed a recycling quality evaluation method for retired hydraulic cylinder. And the main contents include: static strength and fatigue strength, strength degradation characteristics of materials, surface quality evaluation, great damage detection and residual strength, residual life assessment.

2. Evaluation method of recycling quality

The strength and life of the parts are highly related, and the mechanical characteristics of the parts can reflect the strength of the parts, so the mechanical characteristics of the parts can also reflect the life of the parts. The residual strength or residual life of reused components or parts could be rationally predicted and assessed if the quantitative relationship between those mechanical properties and the residual strength was established.

First, In order to evaluate the remanufacturability of the part, the static strength and fatigue strength need to be evaluated to determine whether the recovered part has the potential for reuse.

Second, the strength degradation law of the part’s material and the characterization parameters are studied, and mechanical properties including hardness, stiffness and modal of part are taken into account in this model.

Third, the surface quality is evaluated to make sure whether the part surface only has a slight defect and can be repaired. If the surface defects is difficult to repair, then it is recycled as material. If the surface can be repaired, take the next step.

Last, the great damage detection and residual strength, residual life assessments for the part are carried out. Big injuries have a great impact on the fatigue strength and fatigue life of the part, seriously affecting the recycling and manufacturing process. If the residual strength and residual life meet the requirements, the part can be remanufactured, otherwise, it is recycled as material.

The flow chart of this residual strength and life evaluation method is shown in Figure 1.

**Figure 1.** Residual strength and life evaluation method.
3. Application example of recycling quality evaluation

3.1. Static strength and fatigue strength analysis

Take a certain engineering machinery hydraulic cylinder piston rod body as an object, as shown in Figure 2. The piston rod comprises a shaft and an earring. The shaft and the earring are forged together as one-piece shaft forgings. The rod shaft has a diameter of 55mm, and the material is 45 steel. The heat treatment and quenching surface hardening are carried out, so the surface hardness of the hydraulic cylinder piston rod body can reach 50-55HRC. The quenching depth is controlled to be 1-3mm. The piston rod body is chrome plated with the depth of 0.05-0.06mm. The hydraulic cylinder has working pressure of 20MPa, limit pressure of 25MPa.

![Figure 2. Hydraulic cylinder piston rod body.](image)

In order to make sure whether the piston rod recovered had the potential to be reused, it is necessary to carry out the evaluation on the design life and design strength of the hydraulic cylinder piston rod. And in this evaluation, the strength properties, fatigue characteristics, and strengthen process, service conditions, loading spectrum characteristics need to be taken into account.

The Evaluation steps are as follows:
1. Study the strength properties and strengthening process characteristics of the piston rod material.
2. Then determine the static strength, fatigue strength and SN curve of the piston rod.
3. Based on the load spectrum analysis of the piston rod under different working conditions, determine the most dangerous position where the maximum static load and fatigue load occurs.
4. According to the strength properties and stress analysis results of the piston rod, utilize the strength theory to evaluate the strength margin, then utilize the accumulated damage criterion of fatigue to evaluate the fatigue strength and fatigue life of the piston rod.

In this example, the piston rod material is 45 steel, and the machining processes including forging, turning, quenching, surface hardening, hard chrome plated. According to the above process requirements, the static load tensile test specimens and the tension and compression fatigue test specimens are made for mechanical performance analysis.

The limit strength of the piston rod material is 640MPa, yield strength is 350MPa. According to the fatigue performance test results, the piston rod material stress-life curves namely S-N curve can be fitted as the follow equation:

\[
8.1317 \log \sigma + \log N = 26.5903 = 0
\]

Where N is the fatigue life of the material, σ is the stress level. By this equation, the fatigue strength of the piston rod is about 250MPa.

Calculated by the limit work pressure 25MPa of the hydraulic cylinder, the piston rod shaft stress is 66MPa, and the maximum stress at stress concentration position is 180MPa. So the stress of the piston rod during operation is below the fatigue limit, the strength of the piston rod is designed for infinite life.
3.2. Acquisition of strength degradation law of materials
During the fatigue process of the material or parts, the degeneration of strength properties (including static strength and fatigue strength) occurs. When the strength properties of the materials degenerate to be equal to the applied loads, the material or part will be failure. So the strength degradation law of the material is one of the basic data for residual strength and residual life assessment. And the strength degradation characteristics of the piston rod material can be obtained through fatigue tests.

The detailed methods are as follows:
According to the S-N curve of material and considering the actual load cases of hydraulic cylinder, choose the fatigue test load. In this case, under the chosen stress level, the fatigue life is about 50 million times.

Carry out the mechanical property tests of hardness, stiffness, dynamic characteristics, static strength for each specimen in the fatigue test process. According to the test results, fit the curve of mechanical property degradation, such as hardness, rigidity, natural frequency and static strength and so on.

In this case, the experimental relation between the hardness ratio and life ratio is shown in Figure 3. And the experimental relation between the frequency ratio and life ratio is shown in Figure 4.

![Figure 3. Relation of hardness ratio and life ratio.](image1)

![Figure 4. Relation of frequency ratio and life ratio.](image2)

3.3. Surface quality evaluation
The key points of surface quality evaluation for recycling hydraulic cylinder include surface strain injury, rust, bump, pitting, peeling of chrome plating and so on. Surface quality evaluation is based on current technical capabilities and repair costs assessment. The evaluation methods are as follows:

If the piston rod surface only has some slight defects and can be repaired, then proceed to the residual strength and residual life assessment.
If the piston rod surface damage is serious, the repair process is complexity and high cost, the piston rod is only recycled as materials.

If the piston rod appears bump, bending, deformation of earrings and other problems, continue to carry out damage detection and residual strength evaluation.

In this work, three hydraulic cylinder piston rods are taken into recycling quality evaluation. And the surface quality evaluation shows that there is no serious damage beside some slight scratches on the recycled piston rod surface. So it should proceed to the residual strength and residual life assessment.

3.4. Great damage detection and residual strength, residual life assessment
As an important executive component of construction machinery, the hydraulic cylinder is easy to be damaged by inevitable occasional extreme conditions in which the loads are generally much larger than the design load limit. These large damages have a great impact on the mechanical strength and fatigue life of part, seriously affecting the recycling and remanufacturing process. Owing to its structural characteristics, the large damage of piston rod manifest as earrings deformations, earrings broken, shaft bent, shaft cracks and so on. The evaluation methods are as follows:

As for the earrings deformations, earrings broken, shaft bent, shaft cracks, calculate the static load, which can cause large damage to the piston rod, by static crack and yield deformation calculations or finite element method. Then carry out the great damage detection and residual strength, residual life assessment according to the strength data and the fatigue S-N curve.

If there are no earrings deformations, earrings broken, shaft bent, shaft cracks, the evaluation can be carried out by nondestructive testing, hardness test, rigidity test, dynamic characteristics test and so on. And the mechanical properties degradation curves of piston rod materials obtained in the second step are compared to obtain the residual strength and the relevant life stages information. If the residual strength and residual life meet continuing service requirements, and the weld seam is intact without defect, the piston rod can be directly recovered for remanufacturing.

For the piston rods in this case, the surface hardness is measured and the surface hardness ratios are 0.27%, 0.63% and 1.00%, respectively. So compared with Fig.3, it can be seen that the surface hardness of the recycled part changed slightly within the scope of 1%. The dynamic characteristics of the recycled parts are measured. The first-order frequency ratio of the three piston rods are +0.16%, -0.24% and +0.18%, respectively. The second-order frequency ratio of the three piston rods are +0.16%, -0.11% and +0.23%, respectively. So compared with Fig.4, it can be seen that the first-order frequency and the second-order frequency of the recycled parts also changed slightly within the scope of 1%. So according the surface hardness data and the dynamic characteristics data, it can be concluded that the recycled piston rods can be remanufactured.

4. Conclusion
In this example, the recovered hydraulic cylinder piston rods are designed for infinite life. There is no corrosion, no bump, and no major damage on the surface. The strength properties of the recovered piston rods such as average hardness, natural frequency and stiffness have no significant differences with a new part.

So we can infer that the residual strength and residual life of the piston rods can meet the service requirements. Also, after remanufacturing, they can still meet the design requirements of infinite life under normal working conditions and the piston rods can be recycled and manufacturing.

5. Summary
This paper introduces a remanufacturability evaluation method of the hydraulic cylinder, based on the residual strength and residual life assessment. Design strength, surface quality, mechanical properties including hardness, stiffness and natural frequency of hydraulic cylinder are taken into account in this model. The results show that the recovered piston rods under normal working conditions can meet the design requirements of infinite life and can be recycled and remanufactured. So the evaluation method
developed in this work is feasible, it can be used for remanufacturability evaluation of other construction machinery parts.

Acknowledgments
This work was financially supported by the Natural Science Foundation of Jiangsu Province (BK20170246) and the National Key Research and Development Plan (2018YFB1105805).

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