Experimental study on the evolution law of residual stress in the fatigue process of inductively quenched 42CrMo steel

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Abstract. In the process of remanufacturing a crankshaft with a history of service, it is found that the residual stress of the crankshaft will relax during operation. Therefore, the relaxation of residual stress must be considered in the study of crankshaft remanufacturing. X-ray diffraction is used to measure the initial and final residual stresses after each loading cycle, and the changes in the microstructure of the material after induction quenching were also measured by scanning electron microscopy. The results show that the maximum residual compressive stress appears inside the sample, and its size decreases with increasing depth. The relaxation of residual stress on the surface of the sample with hardened layer can be roughly divided into three stages: rapid relaxation, stable relaxation, and instantaneous release of the final fracture residual stress. An empirical model is proposed to estimate the residual stress relaxation, considering the depth of the hardened layer and the external load during the fatigue process to predict the relaxation law of the residual stress.

1. Introduction
Crankshaft is one of the most typical and important core components of heavy-duty engines. In the service process, fillet bending fatigue fracture is the most common cause of crankshaft failure, accounting for about 80% of the total failure[1-9]. In order to improve the surface performance of the crankshaft and increase the fatigue strength, carburizing[10], nitriding[11], induction hardening[12], shot peening[13] and other surface strengthening technologies are usually used at home and abroad. At present, induction hardening has become one of the most widely used surface treatment technologies due to its advantages such as easier control of the hardened layer, short heating time, and small deformation[14-16].

Heavy-duty crankshaft has become one of the main research objects of remanufacturing technology due to its complex structure, difficult processing technology and high processing cost[7]. Compared with new products, the stress state of induction hardened crankshafts with service history will change, with both stress relaxation[17] and changes in stress concentration positions. Therefore, precise control of the residual stress state during service will become a powerful challenge in the crankshaft remanufacturing process.

It is the core of the research work to reveal the nature and size of the residual stress and the law of change along the surface depth. Some documents show that surface strengthening technology has a greater impact on residual stress. Yan[18] studied the effect of shot peening residual stress on the fatigue life of TC11 titanium alloy. The results showed that a significant residual compressive stress field would
be formed on the surface of the material after shot peening, and the fatigue strength of the material increased by 37.6% after shot peening. Yin\cite{19} studied the influence of induction heating and quenching process on the residual stress distribution and fatigue properties of 45 steel pin shaft. The results show that the residual stress distribution of hardened layer is mainly compressive stress, and its value decreases first and then increases with the increase of depth. Using laser shot peening to introduce gradient residual stress on the surface of titanium alloy, Xian\cite{20} found that the residual stress relaxation rate of high temperature shot peening (WLP) was about 66% after 10 fatigue cycles, while the relaxation rate of room temperature shot peening (RT-LP) was as high as 91%. Lu\cite{21} established a residual stress relaxation model. The results show that the residual stress relaxation of the cyclic softening material under fatigue load increases with the increase of the cyclic stress amplitude and the number of cycles, while the residual stress relaxation of the cyclic hardening material mainly occurs in the first few fatigue cycles. The purpose of this research is to explore the change law of residual stress of specimens in different cycle stages through three-point bending fatigue experiment, and establish a residual stress relaxation model to explore the main reasons that affect the change of residual stress relaxation.

2. Experiments

2.1. Substrate materials and specimens
The experimental research object is the 6DL induction hardened crankshaft manufactured by FAW. The material is 42CrMo steel. This material has good hardenability, no obvious temper brittleness, and has high strength and toughness. The matrix material composition and mechanical properties are shown in Table 1 and Table 2. A sample of 200mm×30 mm×10 mm was cut with a wire cutter, as shown in Fig. 1.

| Table 1  | Chemical composition of the 42CrMo (wt%) |
|----------|----------------------------------------|
| element  | C           | Si          | Mn          | P          | S          | Cr         | Mo         |
| percentage | 0.38~0.45 | 0.17~0.37 | 0.50~0.80 | ≤0.035 | ≤0.035 | 0.90~1.20 | 0.15~0.25 |

| Table 2  | Mechanical properties of 42CrMo substrate (wt%) |
|----------|-----------------------------------------------|
| Strength of extension/Rm | yield strength /Rp0.2 | elasticity modulus /E | Density /ρ | hardness |
| 830MPa | 510MPa | 207.7GPa | 7.85g/cm³ | 305.6HV₀.2 |

Figure 1 Size of matrix sample

2.2. Induction hardening processing
The induction heating of parts mainly relies on the phenomenon of electromagnetic induction, which is essentially an alternating magnetic field that can cause an alternating electric field\cite{22}. The research object of this experiment is 6DL induction hardened crankshaft, the depth of the fillet hardened layer is 3.6mm, the shaft diameter is 76mm, and the hardening ratio is about 5%. The thickness of the sample used in this experiment is 10 mm, so there are two main considerations. The depth of the hardened layer is 0.5 mm, 1.6 mm.

The induction hardening equipment uses a super audio GCT-1200 vertical induction hardening machine tool, as shown in Figure 2. This equipment mainly completes the preparation of samples with
different hardened layer thicknesses by controlling the power output and operating speed. The sample is single-sided induction quenching, and the quenching area is 100 mm in the center of the sample. The quenching process parameters are shown in Table 3. The quenching coolant is water. After quenching, it is tempered at 180°C for 1 hour and cooled at room temperature.

Table 3  Induction quenching process parameters

| technological process | Voltage /V | Anode flow /A | Grid current /A | Running speed mm/min | Depth of hardening zone/mm |
|----------------------|------------|---------------|-----------------|----------------------|---------------------------|
| 1                    | 10000      | 5             | 1               | 1200                 | 0.51                      |
| 2                    | 8000       | 4             | 0.8             | 300                  | 1.6                       |

Figure 2  GCT-1200 vertical induction quenching machine tool and schematic diagram of sample quenching area

2.3. Three-point bending fatigue test
The equipment used in the experiment is a GPS-20 high-frequency fatigue testing machine, as shown in Figure 3. The maximum static load of the equipment is 20kN, and the maximum alternating load is 10kN. The side of the quenched surface is the tensile side, and the stress ratio is R=0.1.

Figure 3  GPS-20 high frequency fatigue testing machine

The final test loads are determined to be 540 MPa and 450 MPa respectively. Two kinds of loads are applied to the samples of the two induction hardening processes respectively until the samples are broken, and the samples under different fatigue cycles are obtained. For the matrix samples, the first $100 \times 10^4$ weeks are mainly studied.
3. Establishment of stress relaxation model and analysis of influencing factors

3.1. Residual stress relaxation

Figure 4 shows the surface residual stress relaxation curves of the two kinds of induction hardening process specimens in the fatigue process under two kinds of loads.

Figure 4 Relaxation curve of residual stress of induction hardening sample. (a) 0.51mm, 450Mpa; (b) 0.51mm, 540Mpa; (c) 1.6mm, 450Mpa; (d) 1.6mm, 540Mpa

According to Figure 4, the residual stress relaxation of the sample containing the hardened layer can be roughly divided into three stages: the rapid relaxation of the initial residual stress, the stable relaxation of the mid-term residual stress, and the instantaneous residual stress around the crack after the final sample fractures, freed. The initial rapid relaxation belongs to static relaxation, while the mid-term residual stress relaxation belongs to stable relaxation. Afterwards, in order to obtain the relaxation model, the residual stress value when the cycle cycle is 0 is removed.

After taking the logarithm of the abscissa cycle cycles, the results are shown in Figure 5. It can be clearly seen that in the early stage of fatigue, the residual stress value after relaxation of the sample containing the hardened layer exhibits an obvious power function relationship with \( \lg N \). Power function fitting is performed on the data, followed by data regression processing, the fitting results are shown in Figure 6.
Figure 5  Residual stress relaxation curve after logarithm of abscissa. (a) Hardened layer 0.51 mm, Maximum stress 450 MPa; (b) Hardened layer 0.51 mm, Maximum stress 540 MPa; (c) Hardened layer 1.6 mm, Maximum stress 450 MPa; (d) Hardened layer 1.6 mm, Maximum stress 540 MPa

Figure 6  Residual stress and $\lg N$ fitting curve
The main variables of the experiment are the depth $b$ of the hardened layer and the applied load $\sigma$ during the fatigue process, so there are

$$\sigma_{Rs} = a\sigma \lg N_{bf} + c$$  \hspace{1cm} (1)

Make $\sigma_{Rs} = f(A, B, C, x)$, \hspace{0.5cm} $A = a\sigma$, \hspace{0.5cm} $B = b_{f}$, \hspace{0.5cm} $x = \lg N$, \hspace{0.5cm} $C = c$

Power function

$$\sigma_{Rs} = f(A, B, C, x) = Ax^{B} + C$$  \hspace{1cm} (2)

Use this power function as a fitting function to fit the data. In the formula, $A$, $B$, and $C$ are the fitting coefficients, and the method of solving the coefficients is given below.

Find the first derivative on both sides of equation (2) to get

$$x \frac{d(A, B, C, x)}{dx} = ABx^{B}$$  \hspace{1cm} (3)

which is

$$x \frac{d(A, B, C, x)}{B} = Ax^{B}$$  \hspace{1cm} (4)

Bring formula (3) into formula (4) and organize it to get

$$x \frac{df(A, B, C, x)}{dx} = -BC + Bf(A, B, C, x)$$  \hspace{1cm} (5)

Make $D = -BC$, then there are

$$x \frac{df(A, B, C, x)}{dx} = D + Bf(A, B, C, x)$$  \hspace{1cm} (6)

In this way, the nonlinear fitting problem in equation (5) is transformed into a linear fitting problem. According to the measured data $(x_i, y_i)$ ($i=1,2, \ldots, m$), The numerical differential formula is used to find the corresponding $(\frac{dy}{dx})$ value of data $(x_i, y_i)$, and then according to the least squares method, the equations for determining the coefficients $D$ and $B$ in the formula (6) are:

$$\begin{vmatrix}
\sum x_i y_i & \sum y_i \\
\sum y_i & \sum y_i^2
\end{vmatrix} \cdot \begin{bmatrix}
D \\
B
\end{bmatrix} = \begin{bmatrix}
\sum x_i (\frac{dy}{dx})_i \\
\sum (\frac{dy}{dx})_i y_i
\end{bmatrix}$$  \hspace{1cm} (7)

Solve the equations (7) to obtain $B=0.281$, $C=-5240.818$, and then use the least square method to determine $A=3166.207$, the fitting function is

$$y = 3166.207 x^{0.281} - 5240.818$$  \hspace{1cm} (8)

Then the final data model can be expressed as:

$$y = \frac{3166.207}{\sigma^{0.281}} x^{-5240.818}$$  \hspace{1cm} (9)

3.2. Study on the influence factors of residual stress relaxation

Table 4 shows the residual stress relaxation of the two induction hardening process samples (the hardened layer depth is 1.6 mm and 0.51 mm respectively) under two loads (450 MPa, 540 MPa) in the three-point bending fatigue test. The calculation formula is shown in formula (10):

$$m = \frac{\sigma_{N1} - \sigma_{N2}}{\sigma_{0}}$$  \hspace{1cm} (10)
Among them, $\sigma_{N1}$ and $\sigma_{N2}$ are the residual stress values on the surface of the sample after fatigue cycles of $N_1$ and $N_2$, where $N_1$ is greater than $N_2$; $\sigma_0$ is the residual stress value when the fatigue cycle of the sample is 0.

### Table 4  Three-point bending fatigue residual stress relaxation of specimen

| Serial number | Hardened layer depth/mm | Maximum stress/MPa | Residual stress relaxation in the first stage | Residual stress relaxation in the second stage | Total slack | Fatigue life ($\times 10^4$) |
|---------------|-------------------------|--------------------|---------------------------------------------|-----------------------------------------------|-------------|----------------------------|
| 1             | 1.6                     | 450                | 40%                                         | 26.7%                                         | 66.7%       | 103                        |
| 2             | 1.6                     | 540                | 50.1%                                       | 23.3%                                         | 73.4%       | 75                         |
| 3             | 0.51                    | 450                | 10%                                         | 51.39%                                       | 61.39%      | 350                        |
| 4             | 0.51                    | 540                | 19%                                         | 39.5%                                         | 58.5%       | 280                        |

According to the data in Table 4, comparing 1 group of samples and 2 groups of samples and 3 groups of samples and 4 groups of samples, it can be seen that as the fatigue load increases, the residual stress relaxation in the first stage of the sample surface is increasing trend, while for the second stage, the amount of relaxation has a decreasing trend. For the total slack, there is a big difference between the first group of samples and the second group of samples. As the load increases, the amount of slack also increases; while for the third group of samples and the fourth group of samples, the difference is not obvious. It can be seen that the effect of the change of fatigue load on the relaxation of residual stress is mainly reflected in the first stage. The greater the load, the greater the amount of relaxation of residual stress.

### 4. Conclusions

The following conclusions can be drawn from the experimental results:

1. After surface quenching, the maximum residual compressive stress of 42CrMo material samples appears in the inside of the sample. The deeper the hardened layer is the closer the maximum residual stress point is to the surface. After the maximum residual stress point, the magnitude of residual stress decreases with the increase of depth.

2. The residual stress relaxation model is proposed, which is a power exponential relationship. The depth of hardened layer and the applied load in the fatigue process are taken into account to predict the relaxation law of residual stress. It is found that the estimation is in good agreement with the experimental data.

3. The residual stress relaxation on the surface of the sample containing the hardened layer can be roughly divided into three stages: the rapid relaxation of the initial residual stress, the stable relaxation of the intermediate residual stress, and the instantaneous release of the residual stress around the crack after the final specimen fracture.

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