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Experimental study on fatigue damage of train K6 spring

***Abstract**. Springs' fatigue life and damage are key evaluation parameters for railway train bogies. Fatigue experiment on K6 bogie spring is carried out by digital display hydraulic pulse fatigue test device. Spring fatigue life is estimated by using nominal stress method. Based on the technology of ultrasound nondestructive test device, the relationship between accumulation of internal fatigue damage and cycle loading times is obtained. The results indicate that same batches of K6 springs have high reliability; spring material internal fatigue damage increases as cycle loading times.*

***Streszczenie.** W artykule przedstawiono wyniki badań dotyczących zmęczenia sprężyn w podwoziach wagonowych. Analizie, przy pomocy hydraulicznego urządzenia testującego poddano sprężynę wagonową typu K6. Korzystając z badań ultradźwiękowych określono związek między tworzeniem się skupisk uszkodzeń wewnętrznych a cyklicznym obciążaniem. (**Badania eksperymentalne uszkodzeń zmęczeniowych w sprężynach wagonowych typu K6**).*

Keywords: fatigue experiment, fatigue damage, ultrasonic non-destructive test, spring rigidity.
Słowa kluczowe: badanie zmęczenia, uszkodzenie zmęczeniowe, test ultradźwiękowy, twardość sprężyny.

Introduction

With the continuous development of heavy vehicles, as well as improved requirements of the quality on vehicle operation, the structure of railway train bogie is also changing. Bogie spring is one of important parts of railway train bogie; its quality is directly related to movements of railway trains and the safety of passengers. So the analysis on fatigue life and damage of railway train bogie spring is essential. Generally, the study about spring fatigue life, damage and strength concentrates on failure modes [1], like extending modes of spring fatigue cracks [2, 3]. And yet some studies about influence factors, including spring materials, surface shot technique and internal impurities [4-6]. All these factors influence the use of spring directly or indirectly. Meanwhile, in order to know about deformation and behavior of springs in the process of loading, shape memory alloy is manufactured into helical springs, and a combined analytical, numerical, and the experimental study is established. Also someone evaluates the fatigue life on the basis of kurtosis technique from concepts of statistics. But spring damage still happens occasionally within the theoretical fatigue life. Ultrasonic fatigue test technique is a new effective way to study the internal fatigue damage and microstructure changes of materials. Some experiments and analysis have been developed to clarify the fatigue properties of some materials under certain conditions. The object of this study is to estimate spring fatigue life based on experiments of fatigue load. Ultrasonic nondestructive test device is brought into this experiment to explore the relationship between accumulation of spring internal fatigue damage and cycle loading times. Spring rigidity before and after the experiment is tested and analyzed.

Experiment and estimation

1. Main parameters of experiments

The railway train K6 bogie spring is made of high-stiffness spring steel 60Si2CrVAT. Bogie spring plays the role of cushioning, shock absorption, connection, support, power transmission. Fatigue failure is prone to occur under the loading conditions of alternating, shocking, sharp change. So quality requirements of spring steel on the chemical composition, mechanical properties, grain size, harden ability and non-metallic inclusions are strict (as shown in Table.1). In this experiment, digital display hydraulic pulse fatigue test device is used to apply fatigue load on springs for 400 millions of times, and ultrasonic nondestructive test devices are established to finish dynamic detection on certain position of spring. Three springs are extracted from same batches of springs randomly. Experimental load is calculated as equation (1):

$$P_{1,2} = (1 \pm K_d) \cdot P_m \qquad (1)$$

where Pm is vertical static load under standard working condition, for the single spring, Pm=19455 N, so the theoretical preloading displacement load Hp=52.3 mm； Kd denotes spring impulsive loading coefficient, and Kd=0.3 in this experiment. Traditionally, in the experiment of spring fatigue load and assessment of reliability, deformation load (Ha) is used as experiment load. Ha is obtained from equation (2):

$$H_a = \frac{8D^3 n P_a}{G d^4} \qquad (2)$$

where P_a denotes amplitude of load, and $P_a = P_1 - P_2$. Main parameters of springs are shown in Table.2.

Table 1. Quality Requirements of Spring Steel 60Si2CrVAT

Components	W(P)%	W(S)%	Elongation A%	Shrink Rate Z%	Grain size	Non-metallic Inclusions	W(H)%	W(O)%
60Si2CrVAT	≤0.015	≤0.015	≥ 9	≥ 30	≥ 7	A,B≤1.5; C,D≤1.0	<1.3	<1.3

Table 2. Main Parameter of Springs

Parameters	Diameter	Mean Diameter	Free Height	Effective Number	Spring Rigidity	Shear Modulus
Symbol	d [mm]	D [mm]	H_0 [mm]	n	F' [N·mm^{-1}]	G [Mpa]
Data	24	115	252	5.75	372.1	78000

2. Estimation of fatigue life

The yield limitation of spring steel 60Si2CrVAT, σ_s=1666 MPa, ultimate strength σ_b=1862 MPa, shear fatigue limitation can be calculated from formula τ_{-1}=0.156×(σ_s+σ_b) =550.37 MPa. S-N curve of spring material in the double logarithmic coordinate is drawn according to the two-point method (as shown in Figure.1). Meanwhile, equation of fatigue life is obtained:

$$\tau^{11.15} \times N = 3.7 \times 10^{37} \quad (3)$$

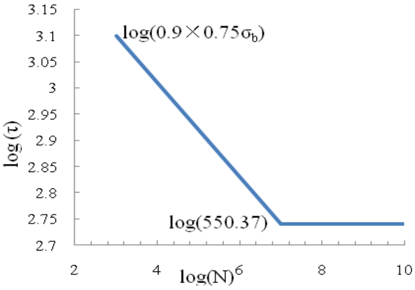

Fig.1. S-N Curve of Spring Material 60Si2CrVAT

On the surface of spring, there are no nicks, cracks and other defects, so the effective stress concentration factor K_τ≈1 in accordance with the specification. Considering other influence factors on spring fatigue life: dimensional factor ε_τ=0.87; surface machining factor β_1=0.31; intensification coefficient after shot peening β_q=1.4; asymmetric cycle factor Ψ_τ=0.14. Then comprehensive effect coefficient of fatigue limit is calculated K_τ=2.41 and symmetry circulating equivalent stress in this experiment τ_d is: τ_d=*473.465* [Mpa]

At last, fatigue life can be deduced from equation (3): N=5.48 × 10^7 [cycle loading times]. In this theoretical calculation, internal impurities and surface defects are considered into computational formula.

Fig.2. Dynamic Detection

Fatigue damage and rigidity

1. Ultrasonic nondestructive test of fatigue damage

At present, applications of ultrasonic nondestructive test technology focus on the starting and ending periods of fatigue life, like detecting the existence and distribution of the pores, micro-cracks and other defects in the material which mainly combines the information of wave schedule, sound velocity, attenuation, impedance, scattering, and others. But studies on the degradation of material properties still rely on experience. In recent years, series of studies show that performance degradation is closely related to the nonlinear effect of ultrasonic through the material. It means that performance degradation always appears accompanied with some form of nonlinear mechanical behavior of material that leads to non-linear effect of ultrasonic propagation, which named high-frequency harmonics. In this experiment, ultrasonic nondestructive test is carried out in any position of springs. Couples of probes and fixed brackets are designed to coincide with shape and size of springs. Ultrasonic probes' simulating and receiving center frequency are 5 MHz and 10 MHz respectively, and the excitation signal frequency is set as 4.35 MHz because the distortion rate of ultrasonic is at a minimum in this range. Dynamic detection is carried out (as shown in Figure. 2).

Figure.3 shows waveform of received ultrasonic. According with experimental data, fast Fourier transform is used to get amplitudes of fundamental harmonics and multiple-harmonics (as shown in Figure.4).

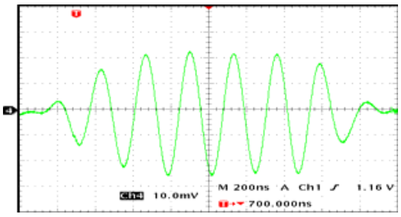

Fig.3. Received Ultrasonic Waveform

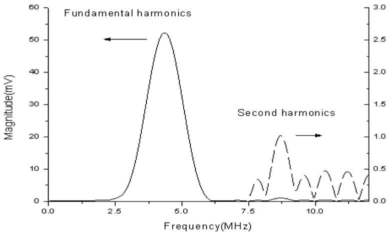

Fig.4. Amplitudes of Fundamental Harmonics and Multiple-harmonics

The definition of nonlinear coefficient β is:

$$\beta = \frac{A_2}{A_1^2} \quad (4)$$

where A_1, A_2 are amplitudes of fundamental harmonics and multiple- harmonics respectively. When fatigue load is applied on the spring, material internal microstructure changes. Certain range of ultrasonic goes through materials and only multi-harmonic is received by probes. As cycle loading times grow up during the experiment, amplitudes of multiple-harmonics increases ceaselessly. In other words, nonlinear coefficient β is a key parameter to represent the accumulation of internal damage. On the basis of mathematical method and experimental data, the relationship between cycle loading times and nonlinear coefficient can be illustrated as shown in Figure.5.

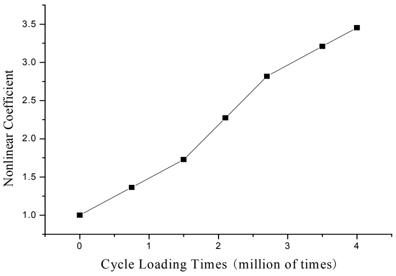

Fig.5. the Relationship between Cycle Loading Times and Nonlinear Coefficient

Figure.5 shows different growth rate of nonlinear coefficient in different periods. It means that internal damage accumulation velocity is different in different periods. At the early stage of experiment, before 1.5 million of cycling loading times, internal fatigue damage starts accumulating linearly with cycle times, but growth is slow; in the process from 1.5 million to 3.0 millions, internal fatigue damage increases rapidly. Springs have been loaded regularly with frequency 3 Hz for some time and internal microstructure has changed and adapted to cycling fatigue load. So fatigue damage accumulates faster than before; in the late period of fatigue load, after 3.0 millions, the growth rate slows down. Internal microstructure tends to be steady. Material properties changes more during this time. But at the end of experiment, fatigue failure does not happen and also other surface damage does not come out, like cracks, nicks and pores. In the future, further experiment and analysis about internal damage need to be done when fatigue failure happens.

2. Spring rigidity test and analysis

Rigidity reflects the ability of material to resist external loads. Theoretical rigidity *F'* of spring is:

$$F' = \frac{P_j - P_i}{H_j - H_i} \tag{5}$$

where $P_{i,j}$ denotes external static loads respectively, and Hi,j denotes heights of spring corresponding to loads. In theory, spring theoretical rigidity *F'* is a constant under standard conditions, *F'*=372.1 N·mm^{-1}. In this experiment, spring rigidity is measured with universal testing machine before and after fatigue experiment. On the basis of generalized Hooke law, rigidity value can be calculated from equation (5) and results are shown in Table.3. The data shows that measured spring rigidity is obvious smaller than theoretical value. Furthermore, spring rigidity increases when fatigue experiment is finished. The results indicate that spring rigidity is affected by the change of material internal microstructure when springs subject to fatigue load.

Conclusions

In summary, spring fatigue life and damage is studied in this paper. Firstly, fatigue experiment on railway train K6 bogie spring is carried out with digital display hydraulic pulse fatigue test device. Secondly, by using nominal stress method, spring fatigue life is estimated. Then based on mathematical method and theoretical analysis, ultrasonic nondestructive test technique is brought in to study the relationship between accumulation of spring internal fatigue damage and cycle loading times with one parameter called nonlinear coefficient which relates to amplitudes and frequencies of ultrasonic, and internal fatigue damage increases rapidly in the process from 1.5 million to 3.0 millions. At last, spring rigidity before and after fatigue experiment is measured. The experimental data reveal that accumulation of internal fatigue damage is tied in with cycle loading times in different period and spring rigidity increases a little when fatigue load is applied.

Table 3. Measured spring rigidity [N·mm^{-1}]

Parameters/Numbers	No.1	No.2	No.3	Average Rigidity
Before	349.6	353.1	349.8	350.8
After	350.5	361.7	354.7	355.6

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