Impact Damage Evaluation Method of Friction Disc Based on High-Speed Photography and Tooth-Root Stress Coupling

L Yin, Y M Shao, J Liu and H L Zheng
State Key Laboratory of Mechanical Transmission, Chongqing University, PR China
E-mail: ymshao@cqu.edu.cn

Abstract. The stability of friction disc could be seriously affected by the tooth surface damage due to poor working conditions of the wet multi-disc brake in heavy trucks. There are few current works focused on the damage of the friction disc caused by torsion-vibration impacts. Hence, it is necessary to investigate its damage mechanisms and evaluation methods. In this paper, a damage mechanism description and evaluation method of a friction disc based on the high-speed photography and tooth-root stress coupling is proposed. According to the High-Speed Photography, the collision process between the friction disc and hub is recorded, which can be used to determine the contact position and deformation. Combined with the strain-stress data obtained by the strain gauge at the place of the tooth-root, the impact force and property are studied. In order to obtain the evaluation method, the damage surface morphology data of the friction disc extracted by 3D Super Depth Digital Microscope (VH-Z100R) is compared with the impact force and property. The quantitative relationships between the amount of deformation and collision number are obtained using a fitting analysis method. The experimental results show that the damage of the friction disc can be evaluated by the proposed impact damage evaluation method based on the high-speed photography and tooth-root stress coupling.

1. Introduction
Wet multi-disc brakes are widely used in heavy trucks due to the big braking torque, ability to resist thermal recession and pollution. During the work process, the stability of the wet multi-disc brake could be seriously affected by the damage of the friction disc tooth in poor working conditions. Therefore, it is important for researchers to investigate the damage mechanisms of the friction disc tooth to improve the stability and useful life of the wet multi-disc brake.

A significant amount of research works has been presented to investigate the wear and thermal damage of friction pairs. For instance, Zhang et al. [1] studied the wear law of a clutch friction plate by the experimental method. Li et al. [2] used the surface analysis techniques and iron spectrum technology to study the wear failure mechanisms of a clutch friction plate. Chen et al. [3] analyzed the thermal stress of a friction plate, and obtained the temperature and thermal stress distributions under the thermal loads. Przemyslaw et al. [4] investigated the local high temperature regions of a friction plate by the temperature simulation analysis on the combination of clutch. Zagrodzki [5] analyzed the influences of the different pressure distributions on the thermal stress based on a finite element analysis of thermal elastic theory. As for the methods that can be used to evaluate the impact damage, some researchers adopted the finite element analysis [6], nonlinear fatigue damage theory [7] and high-speed digital cameras [8].
However, there are few works focused on the damage of the friction disc tooth caused by the torsion-vibration impact. Hence, in order to improve the stability and useful life of the wet multi-disc brake, it is very useful to study the damage mechanisms and evaluation methods of the friction disc. In this work, an impact damage evaluation method of a friction disc based on the high-speed photography and tooth-root stress coupling is proposed to investigate its damage mechanisms.

2. Experiment and impact damage evaluation method

2.1. Experiment setup
To observe the actual impact damage of the friction disc tooth caused by the torsion-vibration impact, an experiment setup is carried out. A impact damage experimental system consists of the impact test rig of friction disc, strain signal acquisition module, ultra high speed photoelectric framing camera, coupling, drive shaft, strain measuring instrument, 3D super depth digital microscope (VH-Z100R), as shown in figure 1.

The specimen material is 45 steel. By the strain gauges at roots of the teeth, the strains of the friction disc tooth are measured under torsion-vibration impact loads. A repeated impact load is applied to the friction disc, and the impact frequency is determined by the frequency conversion motor to meet the requirements of the impact frequency range. The tooth surface elastic-plastic deformation of the friction disc under a single load is obtained by an ultra high speed photoelectric framing camera. The real-time root strain data of the friction disc is obtained by the strain measuring instrument. The tooth surface cumulative elastic-plastic deformation of the friction disc under the repeated impact load is obtained by the 3D super depth digital microscope (VH-Z100R).

2.2. Ultra high speed photoelectric framing photography
The ultra high speed photoelectric framing camera is used to output object by six channel using the prism spectrometer system, as shown in figure 2. Same images can be output from the each channel output by using a fine adjustment light path. The images from the six channels are coupled to the photocathode of the six image-intensifiers. The high-pressure gating pulse from the each channel is controlled by the precise timing circuit, respectively. Therefore, it can control the exposure moment and exposure time of the six image-intensifiers independently. The six CCD cameras are used to record the output image of image-intensifiers. The camera can acquire six images of the target in
different time in a shot, the exposure time of the each image is 5 ns, the picture interval is adjustable from 5 ns to 10 ms. Compared with the high-speed camera, using a camera to record the high-speed collision process can greatly shorten the exposure time, which can eliminate the boundary motion blur caused by the movement of the object. Shortening the exposure time does not affect the spatial resolution of the camera.

The target is imaged on the cathode plane of the gating type micro-channel panel image intensifier through the main objective, second objective and spectroscopic prism. The image amplified by the image-intensifier is coupled to the CCD chip. The images from the CCD camera are displayed and processed in a computer. Shooting frequency and single exposure time are set by the synchronization control part and special pulsed power supply of gating type micro-channel panel image intensifier.

![Figure 2. Schematic diagram of the ultra high speed photoelectric framing camera.](image)

### 2.3. Impact damage evaluation method

According to linear cumulative damage theory, a method for estimating the impact damage life for a wet multi-disc brake of heavy trucks under load spectrum is proposed. For a constant stress amplitude $\sigma$, the friction disc may be fail when the number of cyclic loading is $N$. The large plastic deformation occurs on the contact surface between the contact components could cause their damage and failure. If the number of the cyclic loading is $n$ less than $N$, the damage rate is equal to $n/N$ for the constant stress amplitude $\sigma$. The tooth surface impact damage of the friction disc under a single load can be assumed to be same [9].

If a component is given in a series of stress levels, each stress level will cause an amount of impact damage rate. The friction disc will fail when the sum of these damage rates is equal to level one. Therefore, the impact damage evaluation expression can be written as follows:

$$\sum_{i=1}^{j} \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \ldots + \frac{n_j}{N_j} = 1$$

(1)

Where $\sum_{i=1}^{j} \frac{n_i}{N_i}$ can be used to evaluate the impact damage of the friction disc.

The following steps are presented to verify the impact damage evaluation method based on the linear cumulative damage theory.
• $d_i$ is the tooth surface plastic deformation of the friction disc of a single load obtained by the ultra high speed photoelectric framing camera and image processing technology for a stress level $\sigma_i$. The photograph from the ultra high speed photoelectric framing camera is shown in figure 3.

• The actual stress $\sigma$ and number of cyclic impact loading $n$ can be measured with the strain measuring instrument. The stress spectrum of the actual stress $\sigma$ is obtained by rain flow counting method. $n_i$ should match the following conditions:

$$\sum_{i=1}^{n} n_i = n_1 + n_2 + \ldots + n_i = n$$

(2)

• According to linear cumulative damage theory, the total plastic deformation of the cumulative impact damage is calculated by the expression as follows:

$$D' = n_1d_1 + n_2d_2 + \ldots + n_id_i$$

(3)

• The actual total plastic deformation $D$ is obtained by the VH-Z100R. A photograph from the VH-Z100R is shown in figure 4. The absolute error is determined by the absolute value of the difference between $D'$ and $D$. The absolute error and relative error are analyzed to validate the impact damage evaluation method. Therefore, the absolute error can be written as follows:

$$AE = |D' - D|$$

(4)

and the relative error can be written as follows:

$$RE = \frac{|D' - D|}{D}$$

(5)

For a same stress level, the plastic deformation values $d$ on the tooth surface are $15.6\mu m$, the minimum measurable height is $15.6\mu m$, as shown in figure 5. Therefore, the value between 0 and $15.6\mu m$ is displayed as $15.6\mu m$. The plastic deformation $d$ is $15.6\mu m$. The number of the cyclic impact loading $n$ is 10. The total plastic deformation $D' = 156\mu m$. The actual total plastic deformation $D$ is $24.2\mu m$ as shown in figure 6. The absolute error $AE = 131.8\mu m$, and the relative error: $RE = 544\%$. 

Figure 3. Photograph from the ultra high speed photoelectric framing camera.

Figure 4. Photograph from the VH-Z100R
3. Conclusions

- The instantaneous impact state of the friction disc under the impact loading, and the tooth surface impact damage of the friction disc under a single load are obtained by the ultra high speed photoelectric framing camera. The cumulative damage value is obtained by the VH-Z100R, and the surface morphology characteristics of damage location are presented.
- According to linear cumulative damage theory, a method for estimating the impact damage based on the high-Speed photography and tooth-root stress coupling is proposed. The results show that the proposed method can provide some valuable conclusions for the impact damage evaluation method for the friction disc.

Acknowledgments

The authors are grateful for the financial support provided by the project of the National Key Scientific Instrument and Equipment Development Projects of China under Contract No. 2011YQ13001906.

References

[1] Zhang X Y, Liu W Y, Tao F H and Wang P 2002 A study on the wear rules of the friction disk Lubrication Engineering 5 44-45
[2] Li L, Zhu Y L, Huang Y L, Xu B S and Chen J M 2005 Failure mechanism of the driving clutch of a heavy loaded pedrail vehicle based on surface analysis and ferrography Tribology 25 270-274
[3] Chen G J, Yin X L, Gong Y P and Yin L P 2008 Coupling heat stress analysis of the friction disk in clutch Mechanical & Electrical Engineering Magazine 25 100-102
[4] Przemyslaw Zagrodzki and Todd D. 1998 Analysis of Temperatures and Stresses in Wet Friction Disks Involving Thermally Induced Changes of Contact Pressure SAE Transactions 107 360-367
[5] Zagrodzki P and Trunce S.A. 2003 Generation of hot spots in a wet multidisk clutch during short-term engagement Wear 254 474-491
[6] Dean G and Wright L 2003 An evaluation of the use of finite element analysis for predicting the deformation of plastics under impact loading Polymer Testing 22 625-631
[7] Zhang W H, Ren T H and Qiu Z H 2005 Analysis of impact fatigue damage in hammer foundation Journal of Vibration Engineering 18 506-511
[8] Timothy E, Schmidt, John Tyson, Konstantin Galanulis, Duane M Revilock and Matthew E
Melis 2005 Full-field dynamic deformation and strain measurements using high-speed digital cameras 26th International Congress on High-Speed Photography and Photonics (Alexandria, VA, United states, 20-24 September 2004) vol 5580 (SPIE) p 174-185

[9] Zhao S B Study 2000 On the accuracy of fatigue life predictions by the generally used damage accumulation theory Journal of Mechanical Strength 22 206-209.