Study on Internal Stress Vibration and Edge Wear of a Cleaning Blade

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要旨

電子写真プロセス内で使用される部品の一つであるクリーニングブレードの寿命はエッジの摩耗量が律速であり，エッジの摩耗については疲労摩耗が寄与することが知られている。疲労摩耗は，繰り返し応力が作用し，摩耗部に微小な亀裂が生じて剥離が発生する現象として知られており，線形累積損傷則が剛体の疲労破壊をよく説明する経験則として使われている。他方で，クリーニングブレードを構成する粘弾性体の疲労摩耗を線形累積損傷規則に適用した研究はほとんど無い。

本研究の目的は，線形累積損傷則の基礎であるS-N曲線がブレードの摩耗で成立することと，ブレードの摩耗幅と$\Sigma n_i/N_i$の間に相関関係があることを確認することとした。

本研究では，光弾性法を適用し，光弾性高速動画からブレードのエッジ周辺に作用する内部応力を動的に解析した。応力の繰り返し回数の動的解析に使用したレインフロー法は，繰り返し回数をカウントする一般的な方法の中でヒステリシスを考慮したカウント方法である。

結果として，ブレードのS-N曲線は，Sが増加するにつれてNが減少する典型的なS-N曲線の挙動を示した。またブレード摩耗幅と$\Sigma n_i/N_i$は良好な相関関係を示し，$\Sigma n_i/N_i$，つまり累積疲労損傷度が大きいほど，ブレード摩耗幅が大きくなった。

本研究の結果から，短時間の光弾性高速動画を撮影して，ブレードの内部応力を可視化，さらに応力変動を追跡して得られたデータを分析し，$\Sigma n_i/N_i$を算出することで，摩耗幅を予測することが可能になったと言える。

Abstract

A cleaning blade is one of the parts used in the electrophotographic process. The life of the cleaning blade is determined by the amount of wear on its edge, and it is known that fatigue wear dominates the of edge wear. Fatigue wear process is known as follows; when repeated stress acts, micro cracks progress in the wear part, causing peelings. The linear cumulative damage rule is used as an empirical rule that explains fatigue fracture of rigid body well. On the other hand, few studies have applied the fatigue wear of viscoelastic bodies that make up the cleaning blade to the linear cumulative damage rules.

The purpose of this study is to confirm that the S-N curve, which is the basis of the linear cumulative damage rule, holds for blade wear, and that there is a correlation between blade wear width and $\Sigma n_i/N_i$.

In this study, we applied photoelastic method and dynamically analyzed the internal stress acting around the edge of the blade from the photoelastic high-speed moving image. The rainflow method was used for the dynamic analysis of the number of stress repetitions, which is a counting method that considers hysteresis among the typical methods for counting the number of repetitions.

As the results, the S-N curve of the blade showed typical S-N curve behavior in which N decreased as S increased. The blade wear width and $\Sigma n_i/N_i$ also showed a good correlation, and the larger the $\Sigma n_i/N_i$, that is, the cumulative fatigue damage, the larger the blade wear width.

By the results of this study, it can be said possible to predict the wear width by visualizing the internal stress of the blade from a short-time photoelastic high-speed video, analyzing the data obtained by tracking the stress fluctuation, and calculating $\Sigma n_i/N_i$.

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1 Introduction

In the electrophotographic process, toner used as colorant causes image noise when it remains on an image carrier. A toner cleaning system is installed and a cleaning blade, hereinafter referred to as a 'blade', is widely applied to the cleaning system. The blade is composed of a viscoelastic body cut into a strip shape supported by a metal member, and is held under pressure at the edge of the blade against the image carrier. While the image carrier, formed in a cylindrical shape, rotates to repeat imaging sequence, frictional force is generated between the image carrier and the edge of the blade, which results in wear of the edge. As the edge wear increases, the blade cleaning performance deteriorates, and image noise is triggered due to toner slipping through. Various studies have been reported to reduce the blade edge wear and extend life of the blade. Several types of wear mechanisms have been proposed. Seino et al. proposed wearing equations based on the fatigue wear model [1]. They predicted stick-slip behavior causing fatigue wear of the edge and successfully examined the possibility by their experiments. At the time of Seino et al.'s research, there was no technique to measure the stress acting on the edge of the blade, so a tensile fatigue test was conducted by applying a repetitive stress with constant amplitude and frequency to the blade. They concluded inductively that the vibration acting on the edge caused fatigue wear.

In our previous report, "Visualization of internal stress of cleaning blade by photoelastic method" [2], we proposed a method to visualize the internal stress of the blade and discussed its validity as a measurement method by means of static analysis, and the magnitude of the stress. Dynamic analysis was carried over to the next report. Therefore, in this study, we brushed up this method and dynamically analyzed the internal stress acting around the edge of the blade from the photoelastic high-speed moving image. Since it became possible to analyze the number of repetitions in addition to the magnitude of the stress acting around the edge of the blade by dynamic analysis, we tried to explain the amount of wear of the blade by applying the linear cumulative damage rule.

The purpose of this study is to confirm that the S-N curve, which is the basis of the Minor's rule of cumulative damage, holds for blade wear, and that there is a correlation between blade wear width and $\Sigma n_i/N_i$.

2 Model

2. 1 Photoelastic method

When an external force is applied to an elastic body having a transparent and uniform structure such as celluloid to generate stress in the elastic body, the elastic body temporarily exhibits birefringence. When polarized light is incident on a photoelastic body, birefringence produces a pair of plane polarized lights that oscillates in the direction of the internal force and in the direction perpendicular to the internal force. Since the pair of plane polarized lights passes through the elastic body at different velocities, the light exiting the photoelastic body has a phase difference δ with respect to the incident light. Since this δ is proportional to the principal stress difference, the photoelastic method is used as a method to analyze the stress distribution in the elastic body by measuring δ.

The detailed method for measuring the internal stress of the cleaning blade by the photoelastic method is as described in the previous report [2].

2. 2 Linear cumulative damage rule

The linear cumulative damage rule is used as an empirical rule for estimating the life when the amplitude and frequency of stress acting on an object are irregular. This method is used when external stress acts on a rigid body that receives repeated loads. Fig. 1 is called a fatigue strength curve, and it is also called a S-N curve because it takes the magnitude of stress and the number of repetitions as axes. When the fatigue life due to constant repetitive stress of stress σ_i (i = 1,2,⋯, m) of arbitrary magnitude is N_i (i = 1,2,⋯, m), respectively, the σ_i that actually acts if the number of stress repetitions is n_i, the degree of fatigue damage due to σ_i is n_i/N_i, and it is considered that fatigue fracture occurs when the cumulative fatigue damage due to all σ_i exceeds 1, which can be expressed by Equation 1 [3].

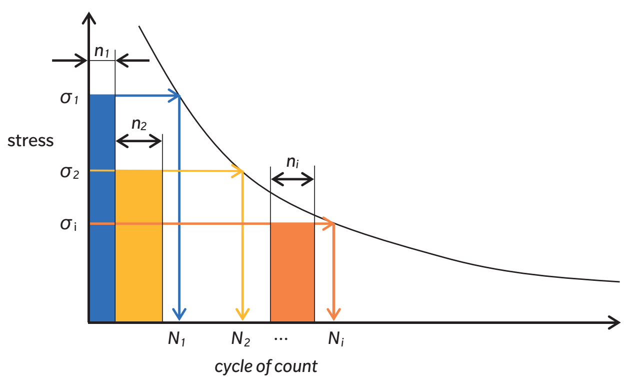

Fig. 1 Example of S-N curve.

$$\sum_{i=1}^{m} \frac{n_i}{N_i} \geqq 1 \tag{1}$$

Although many studies have applied the linear cumulative damage rule to fatigue fracture of rigid bodies, few reports have been employed it to predict the occurrence of fatigue wear in viscoelastic bodies [4]. In this study, we tried to adopt the linear cumulative damage rule to predict the fatigue wear of the blade from the magnitude and number of repetitions of the internal stress caused by the self-excited vibration generated in the viscoelastic body. Firstly, we focused the difference between fatigue fracture and fatigue wear. Equation 1 expresses the conditions under which fatigue fracture occurs, but fatigue wear can be considered to be the repeated discontinuous occurrence of minute fatigue fracture at the wear-generated portion. On this supposition, we considered that the larger the $\Sigma n_i/N_i$ and the larger the number of fatigue fractures, the larger the wear width of the blade. Based on this hypothesis, we hypothesized Equation 2 to represent the wear width 'W_f' under the constant 'a'.

$$Wf = a \times \sum_{i=1}^{m} \frac{n_i}{N_i} \tag{2}$$

2. 3 Cycle counting method

When the number of stress repetitions is measured by the cumulative linear damage rule, it is necessary to consider the properties of the object on which the stress acts, the surrounding environment, and so on. For example, when some phenomena such as stress corrosion cracking are involved, the effect of the repetition rate is taken into consideration. And in the case of low cycle fatigue (fatigue phenomena in which the number of repetitions is 10^4 times or less) accompanied by the same phenomena, it is necessary to consider the waveform shape of stress, that is, triangular wave, rectangular wave, and the like rather than the speed. Since the blade edge of this study is classified as high cycle fatigue in which wear becomes remarkable after 10^4 or more repetitions, it is not necessary to consider the repetition rate and waveform shape. On the other hand, since the blade is composed of a viscoelastic body as a material, it is desirable to use a method of counting the number of repetitions in consideration of hysteresis [5].

Among typical methods for counting the number of repetitions such as the peak method, the range method, and the range-mean method, the rainflow method is a method for counting the number of repetitions in consideration of hysteresis. Hereinafter, the rainflow method will be described. As shown in Fig. 2, stress is on the horizontal axis and time is on the vertical axis. Unlike normal, the vertical axis is time, pointing downwards. The time-series waveform is likened to a multiple roof structure, and the behavior of rain flowing from the top of the roof is emulated. Rain flows downward from the base of the roof. When it reaches the eaves of the roof, it falls down to the lower roof and start flowing again until the flow stops due to the conditions for stopping the flow described later. After the flow stops, the next flow begins.

There are two conditions for the falls to stop. The first is, for example, when the flow from point 0 falls down from point 1, it can fall down to point 3 as it is because the starting point of the flow 2 in the next tensile direction is on the tension side of point 0, it flows down as it is, but the flow stops at the point 3 and the next tensile flow starts because point 4 is on the compression side of the point 0. The second is, for example, the flow from the point 2 stops at point 1, because the roof is already wet with the flow that has fallen from the point 1.

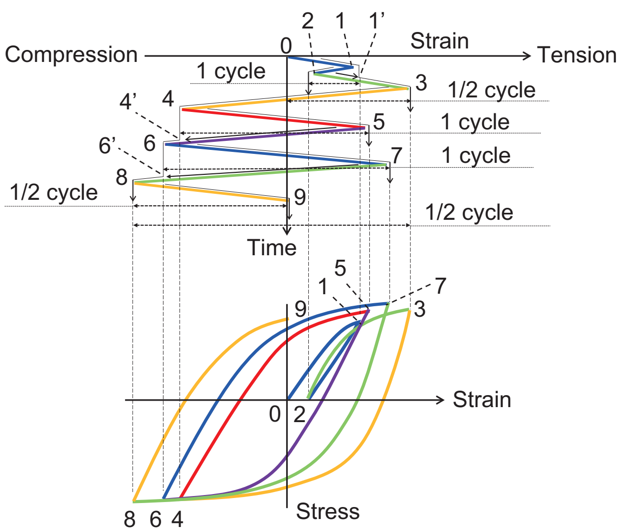

Fig. 2 Relationship between distortion interval and hysteresis loop by rain flow method.

Amplitude and frequency are determined as follows; when the conditions for stopping the flow are met, or when the flow is not stopped and the water falls down toward an infinite bottom, the length in the horizontal axis direction of the water flow is measured as the amplitude of the corresponding half cycle wave [6]. One of the features of the rainflow method is that it deals the waveform in half cycle units. It means the method can count the wave even if the hysteresis loop is not closed as can be seen from the hysteresis loop corresponding to the distortion.

3 Experiment

3. 1 Experimental equipment and analysis method

Fig. 3 shows an external photograph of the friction tester manufactured for this study. It is a blade-on-disk type friction tester that imitates the cleaning system of the electrophotographic process, and can test the line contact slip friction between the disc and the blade. This tester consists of the following units: a disk drive unit that rotates a disk, a blade holding unit not shown in the photo that holds the blade and presses it against the disk, a polarized light source unit that polarizes the light emitted from the light source with a polarizing plate and transmits the blade, and an imaging unit consisting of a 'camera' CRYSTA PI-1P manufactured by Photoron Co., Ltd. with a built-in 1/4 wave plate connected to a lens holding a circularly polarizing filter at the tip to create a photoelastic image from transmitted light.

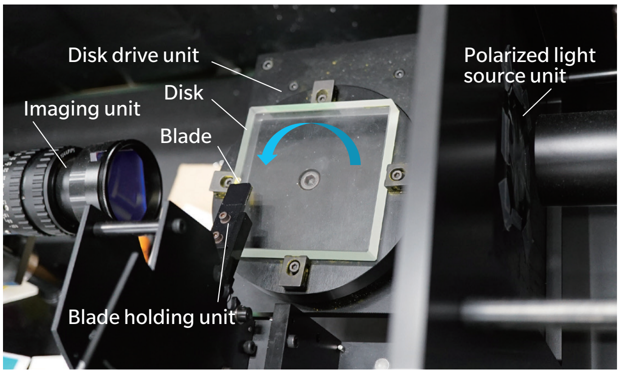

Fig. 3 Photograph of the friction tester prototyped for this research.

Fig. 4 shows an example of a photoelastic image taken by the friction tester. This is a snapshot from a photoelastic video. Fig. 5 shows a snapshot of the optical image taken at the same time. In the optical image, deformation of the edge cannot be observed, but in the photoelastic image, the color matching lines are lined up at narrower intervals near the edge, which means that higher internal stress is acting. In the high-speed moving image acquired by applying the photoelastic method, the movement of the color matching line, that is, the fluctuation of the internal stress acting near the edge of the blade was quantified using the tracking software. The high-speed video was shot for about 5 seconds at a frame rate of 10000 fps. Kinovea [7] was used as the tracking software, and Fig. 4 also displayed the trajectory during tracking. Since this study focused on the stick-slip of the blade, the data acquired by tracking is limited to the direction in which the frictional force acts. The obtained data were output in csv format and used for cycle counting. We used the Python rainflow module for the analysis. Among the outputs obtained by the rainflow module, the range and count are equivalent to the strain and cycle of count on the S-N curve. The cycle of count was divided by the video recording time to obtain the number of repetitions per unit time.

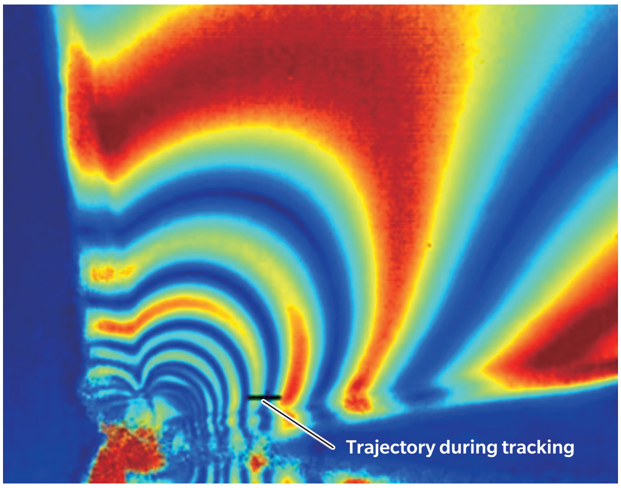

Fig. 4 An example of a photoelastic image of the edge of a blade.

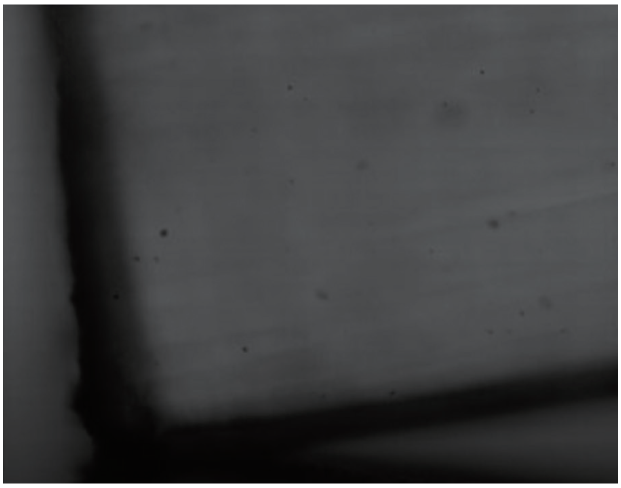

Fig. 5 An example of an optical image of the edge of a blade.

3. 2 Derivation of S-N curve

In order to derive the S-N curve of the blade, we first extracted the conditions under which remarkable fatigue wear occurs in the blade. A blade set to the specified conditions was installed on the AccurioPress C6100 manufactured by Konica Minolta, hereinafter referred to as the 'actual machine', durability was evaluated, and then the edge of the blade was microscopically observed. The presence or absence of fatigue wear was confirmed. When no significant fatigue wear occurred, the level of the pure water contact angle on the surface of the image carrier was changed and the durability was evaluated again. By repeating above operations, the conditions under which fatigue wear remarkably occurs were extracted.

Next, by using the friction tester, the blade and the image carrier were set under the conditions that cause remarkable fatigue wear extracted in the durability evaluation of the actual machine. Photoelastic video was captured and the magnitude of stress when fatigue wear occurs in the blade and the number of repetitions were obtained by analyzing the video. The S-N curve of the blade was derived by dividing the magnitude of the stress thus obtained into a predetermined range and measuring the number of repetitions in each stress range.

3.3 Wear width - $\Sigma n_i/N_i$ correlation

In order to verify the relationship between the blade wear width and $\Sigma n_i/N_i$, it is necessary to acquire the wear width and n_i data under different conditions, excluding N_i verified in 3.2. Durability evaluation using the actual machine was carried out to acquire wear width data. For the acquisition of n_i data, the data obtained by tracking the photoelastic image was analyzed by the rainflow method. The parameters whose levels were changed were the pure water contact angle of the photoconductor, the blade material, and the blade edge angle, and the other parameters were fixed and verified.

4 Results and discussion

4.1 Resutlts of S-N curve

The S-N curve of the blade shown in Fig. 6 was typical S-N curve behavior in which N decreased as S increased. In addition, there is no fatigue limit that appears only in iron-based materials (at a certain stress or less, fatigue fracture does not occur even if the number of repetitions increases), and the linear cumulative damage rule was agreed.

4.2 Wear width - $\Sigma n_i/N_i$ results

As shown in Table 1, the wear width of the blade changed when the contact angle of the photoconductor, the material of the blade, and the angle of the edge of the blade were changed. Since no trend can be found from here, the life of the blade cannot be predicted.

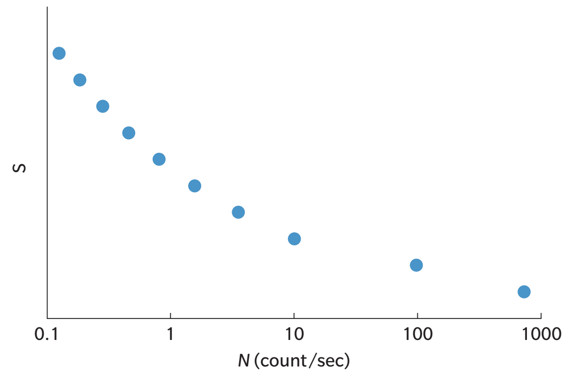

Fig. 6 S-N curve of blade.

Table 1

Material	Edge angle	Pure water contact angle	Wear	$\Sigma n_i/N_i$
A	X	Low Middle High	61.8 22.2 25.2	15.1 4.0 8.4
A	Y	Low High	29.3 25.8	8.5 5.3
B	X	Low Middle	36.0 29.0	9.1 6.7

On the other hand, the blade wear width shown in Fig. 7 and $\Sigma n_i/N_i$ showed a good correlation, and the larger the $\Sigma n_i/N_i$, that is, the cumulative fatigue damage, the larger the blade wear width. This relationship was maintained even if the pure water contact angle of the photoconductor, the material of the blade, and the angle of the edge of the blade were changed.

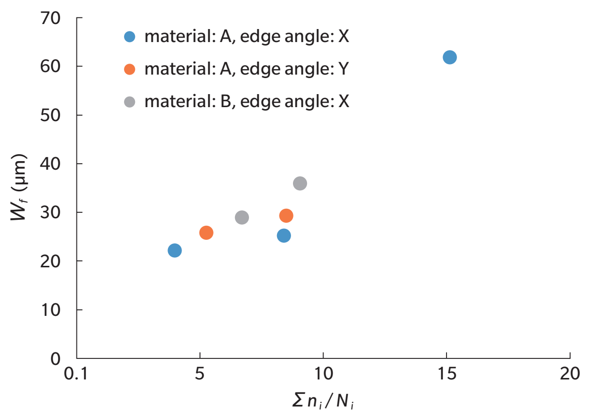

Fig. 7 Blade wear width - $\Sigma n_i/N_i$.

5 Conclusion

The S-N curve derived by counting the magnitude of the internal stress of the blade and the number of repetitions by the rainflow method showed a typical S-N curve, and it was suggested that the linear cumulative damage rule holds for the blade as well.

Furthermore, it was confirmed that a direct proportional relationship was held between the wear of the blade and $\Sigma n_i/N_i$ regardless of the conditions such as the surface condition of the blade and the photoconductor.

Previously, we have used actual machines to study for extending the life of blades (with many materials) by measuring the wear width of the blade tested in the durability evaluation (which requires evaluation time). By utilizing the results of this study, it can be said possible to predict the wear width by visualizing the internal stress of the blade from a short-time photoelastic high-speed video, analyzing the data obtained by tracking the stress fluctuation, and calculating $\Sigma n_i/N_i$.

This study suggests that the cumulative linear damage rule, a method for predicting fatigue fracture when an external stress is applied to a rigid body, may also be applied when measuring the internal stress of a viscoelastic body. Viscoelastic bodies such as blades have become widely applied in other fields (for example, in the case of electrophotographic process, rubber rollers for paper transport, charging, transfer, fixing rollers, etc.), and similar verifications will continue in the future. It is hoped that this will be carried out and that the technology for predicting fatigue fracture of viscoelastic bodies will advance.

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