Fatigue Reliability Evaluation of the Kiln Roller

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Abstract: The fatigue reliability model of the kiln roller in crack initiation stage is developed by using the $S-N$ curve approach in this paper. All related variables are discussed. Among them, the stress variable is obtained from the resultant stress calculated by using the finite element (FE) code ANSYS. Monte Carlo simulation technique is utilized for fatigue reliability evaluation. Some useful conclusions are drawn from the reliability curve of the example roller, that can help to make the maintenance schedule more effective.

Keywords: Fatigue reliability; roller; $S-N$ curve; rainflow Counting; Miller Rule

I. INTRODUCTION

Rotary kiln is an important equipment used in metallurgy, concrete, and chemical industry. Kiln weighs around thousand tons, generally has 4-9 groups of supporting structure, and its rollers are supported by two wheels. Rollers are always subjected to overlarge and alternate loading, which causes considerable fatigue damage in service. The predominant failure type of the roller is fatigue failure. This paper focuses on crack initiation reliability, but parameters related with the crack initiation, such as material property, applied loading, are random generally. Although fatigue damage of rollers have been calculated in many methods[1,2], the use of probabilistic method has not been considered previously. The $S-N$ curve approach has been widely used for the estimation of fatigue life, which is appropriate for non-crack components or without large initial defects. A number of researches about considered components are based on the $S-N$ curve together with Miner’s rule[3-6]. Similarly, the fatigue reliability analysis of the roller is performed in this paper.

By considering the characteristic of all variables, the fatigue crack initiation model is established. The stress of the roller is calculated by using FE-code ANSYS. Subsequently, the Rainflow Counting method is employed to treat the obtained stress curve. The analytical stress results together with other variables are discussed for fatigue reliability analysis. Monte Carlo simulation technique is employed for reliability estimation. The fatigue reliability of a kiln roller is performed. The resultant reliability curve is significantly useful to determine when the roller need to check and repair the crack.

The proposed analysis is highly valuable for equipment maintenance.

II. CRACK INITIATION RELIABILITY ANALYSIS

A. Crack initiation reliability model

In the crack initiation stage, the fatigue damage accumulation is based on the $S-N$ curve of the material of the roller. In this approach, the fatigue strength is expressed according to $S-N$ curve which gives the number of stress cycles $N$ with specific stress range $S$ to cause failure. The $S-N$ curve can be expressed as:

$$N = AS^{-m}$$

(1)

Where $m$ and $A$ are empirical constants.

The estimation of fatigue damage under scattered stress is commonly calculated according to Miner’s rule. The damage for a single cycle at a given stress range can be expressed as:

$$D = \sum_{i=1}^{L} \frac{1}{N_i} = \frac{1}{N_{eq}}$$

(2)

where, $L$ is the number of stress range levels, $N_i$ is the fatigue life estimation from the $S-N$ curve under constant stress amplitude $S_i$. According to the Miner’s rule the total damage of all stress levels is equal to the damage caused by the equivalent stress $S_{eq}$ (discussed in Section 2.2), that is associated with $N_{eq}$ from the $S-N$ curve. The applied loading varies as the axis line dynamical changes. In general, there is a large degree of scatter in the stress distribution of the roller. Thus, $S_{eq}$ is also a random variable. The total damage accumulation $D_{total}$ can be expressed as:

$$D_{total} = \sum_{i=1}^{L} D_i = \frac{n}{N_{eq}}$$

(3)

where $n$ is the number of stress cycles under specific stress range $S_{eq}$. By combining the $S-N$ curve of the material of the roller, the variable amplitude of the stress range $S_{eq}$, and Miner’s damage assumptions, Eq.(3) can be rewritten as.

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where $n_{\text{initiate}}$ is the number of stress cycles in crack initiation stage. Failure due to fatigue occurs when $D_{\text{initiate}} \geq 1.0$, then the initial fatigue crack is assumed to be formed. The definition of fatigue failure is expressed as:

$$D_{\text{initiate}} \geq \lambda$$

(5)

where $\lambda$ is a random variable with mean value of 1.0. Several researchers have observed that the lognormal distribution is a reasonable model for $\lambda$ with mean of 1.0 and coefficient of variable (COV) of 0.3 [6,8]. By combining Eqs.(4) and (5), the limited-state formulation for crack initiation reliability analysis can be defined as:

$$\frac{n_{\text{initiate}}}{A} \lambda - \geq 0$$

(6)

The average number of cycles $n_{\text{initiate}}$ can be converted into time(years) to failure by defining the variable $t_f = n_{\text{initiate}} / N_{\text{year}}$, where $N_{\text{year}}$ is the annual number of operation cycles and is a deterministic variable. Therefore, the failure probability at time $t_{\text{initiate}}$ can be expressed as:

$$P_{\text{initiate}} = P\left(\frac{n_{\text{initiate}}}{A} \lambda - \geq 0\right)$$

(7)

Using Monte Carlo simulations to solve Eq.(7) though Matlab, the probability fatigue crack initiation at time $t_{\text{initiate}}$ can be obtained. To quantify the uncertainty of each random variables in Eq. (7), namely $A$, $m$, $S_{eq}$, and $\lambda$, discussed subsequently.

**B. Stress variable**

It is a proven fact that the equivalent stress $S_{eq}$ is linearly related to the load ratio, when it is introduced to express the axis line deflection condition [7]. A brief illustration of stress in ANSYS is presented here, and more detailed explanation can be found in Ref. [9].

Consider one rotary kiln of some factory, which has 5 groups of supporting structure, and the total weight is $950 \times 10^6$ N. The roller is supported by two supporting wheels, which are located on both sides at $30^\circ$ angle with vertical line. Physical dimensions of the roller are width $B_r = 0.725$ m, inner radius $R_i = 2.1$ m, and outer radius $R_o = 2.33$ m. In addition, wheel are width $B_w = 0.78$ m, inner radius $R_i = 0.2$m, and outer radius $R_o = 0.7$ m. The finite element modal of roller and wheels is shown of Fig.1, where two contact pairs are defined as roller surface and each wheel.

The applied loads must be included constraint on internal surface of wheel and pressure on internal surface of roller. Wheel shaft is fixed tightly in the wheel, and nodes on internal surface of the wheel are all constraint. It is already learned that vertical axis line deflection influences load distributed of every supporting structure, while the horizontal axis line deflection of the left and right wheel [9]. Internal surface of the roller is applied cosine pressure by the kiln body, as a result of the axis line deflection its distribution is changed accordingly. Without horizontal deflection the two side wheels bear identical load, and the cosine pressure $p$ of roller is shown in Fig.2 [9].

$$p = \frac{Q}{\pi R_c} (A - \cos \alpha)$$

(8)

where $Q$ is the vertical load of per axial length. In this paper, only one largest load, namely $Q = 2.39 \times 10^6$ N, is considered. $p$ is the uniform load of circumference roller; $R_c$ is the mean of inner and outside radius; $\alpha$ is the initial contact angle. $A$ is the coefficient related with contact angle $\beta (\pi - \alpha)$, which obey the following equation:

$$A = \frac{1}{2} \left( \frac{\beta}{\sin \beta} + \cos \beta \right)$$

(9)

After programming ANSYS, the stress history of the external surface of the roller is obtained, as shown in Fig.3. The horizon ordinate of this picture is the arc length from one location to the top, while the vertical ordinate is the alternative stress value.

By using the Rainflow Counting method, the stress waveform can be decomposed into a series of closed expedient

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**Figures:**

- Figure 1. Finite element model of roller and wheels
- Figure 2. Cosine pressure distribution of the roller
- Figure 3. The stress history of the outside roller
- Figure 4. Obtained closed expedient stress cycles
stress cycles, which is quit convenient for cumulative damage calculation. Fig.4 shows all full stress cycles drawn from the stress history, and Table.1 shows the corresponding stress amplitude $S_m$ and mean stress $S_u$ of each stress cycle.

Using the commonly $S-N$ curve, the equivalent conversion for the symmetrical stress is required. Based on Goodman ruler, each stress cycle can be represented by the equivalent stress amplitude $S_{eq}$, and expressed as:

$$
(S_a/S_{(R-1)}) + (S_m/S_u) = 1
$$

Where $S_a$ is the ultimate strength of the material. The results are presented in Table.1. The equivalent stress $S_{eq}$ can be determined, according to the Miner rule that the total damage of all stress level is equal to the damage caused by the equivalent stress $S_{eq}$. In this paper, the equivalent stress $S_{eq}$ is assumed to be normally distributed with mean of 73.16MPa, and a COV of 0.1.

C. The remaining variables

TABLE 2. Variables used in the crack initiation reliability model

<table>
<thead>
<tr>
<th>Variables</th>
<th>Distribution</th>
<th>Mean</th>
<th>CoV</th>
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</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Lognormal</td>
<td>2.0×10^{-20}</td>
<td>0.45</td>
</tr>
<tr>
<td>$m$</td>
<td>Determinate</td>
<td>7.1</td>
<td>0</td>
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<tr>
<td>$S_{eq}$</td>
<td>Normal</td>
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<td>0.1</td>
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<td>$\lambda$</td>
<td>Lognormal</td>
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<td>0.3</td>
</tr>
<tr>
<td>$N_{crack}$</td>
<td>Determined</td>
<td>1036800</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2 shows the characteristics of all variables used in the crack initiation reliability analysis. The material $S-N$ curve is characterized by a scale parameter $A$ and a slope parameter $m$. $m$ is considered to be a constant of value 7.1. The fatigue strength coefficient $A$ is always modeled as a lognormal variable. In this paper $A$ is assumed to be lognormal distributed with a mean of $2.0 \times 10^{-20}$, and a COV of 0.45 that corresponds to a 95% confidence level of the fatigue $S-N$ curve.

$t_{init}$ is considered as a constant. As discussed above, $\lambda$ is assumed to follow lognormal distribution with a mean of 1.0 and a COV of 0.3 here.

III. FATIGUE RELIABILITY ANALYSIS

Monte Carlo simulations technique is used to evaluate reliability of the roller in this paper. Various uncertainties from material properties, and applied stress are included in the proposed calculation. The reliability of the roller is evaluated according to Eq.(7). Using Monte Carlo simulations, the reliability curve at crack initiation stage is shown in Fig. 5. It is observed that the reliability of the roller is above 90% in a 3-year crack initiation life. After that, the reliability decreases, approximately linearly.

The example roller is applied one largest loading $Q = 2.39 \times 10^5$ N, when the others, from Ref.[7], are $2.21 \times 10^5$ N, $2.33 \times 10^5$ N, $1.77 \times 10^5$ N, and $0.76 \times 10^5$ N, respectively. Therefore, the reliability values are conservative in this paper. Theoretically, less is the applied stress, higher is the reliability. From the previous research, it is well deduced that the kiln supporting loading distribution among all rollers is linear with the axis line deflection[17]. Consequently, the loading can be mostly even on each roller by adjusting the axis line deflection properly, namely, the largest loading of the roller can be reduced by adjusting the axis line deflection. By examining the reliability of the roller under a certain axis line condition, the detection schedule of crack will be more reasonable. The reliability curve is very useful for equipment maintenance.

This paper is only a preliminary research as the applied loading is given one largest loading. Future work is required to study the mathematical relationship between the reliability about each roller and the axis line deflection of rotary kiln.

IV. CONCLUSION

In this paper, the fatigue reliability of the roller in the crack initiation stage is investigated. In the crack initiation stage, fatigue damage estimation of the roller is based on Miner’s ruler, and used the $S-N$ curve approach to determine fatigue strength. The resultant reliability curve of the example roller indicated that its reliability is decreased, approximately linearly, after operating 3 years. Therefore, crack detection is quite important and can be performed better at that time based on the reliability curve. Theoretically, adjusting the axis line properly can change the loading condition, which can help to enhance the reliability of the roller, thus the fatigue lifetime of the roller will be longer. The mathematical relationship, between the reliability about each roller and the axis line deflection of one kiln, needs further detailed study.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of the National Hi-tech Research and Development Program of China (No.2007AA042415) and the National Natural Science Foundation of China (No. 50675066).
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