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THEORETICAL AND EXPERIMENTAL RESEARCH ON STRESSES OF A KILN RING

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ABSTRACT

In this paper the stresses in the riding ring of cement rotary kiln are discussed from both theoretical and experimental approach. These stresses are alternating in nature and are caused by forces acting on the ring and by thermal gradients. The most significant stresses are caused by Hertzian contact pressure between the ring and supporting roller. Their highest value is not on the surface but slightly below it. These stresses are responsible for subsurface cracking and pitting damage of kiln ring and roller. In the ring, the bending stress and stress due to temperature gradient along the section height also exists.

Theoretical value of stresses will be compared with experimental ones, obtained for the most loaded, middle ring in Cement factory in Kakanj..

Keywords: rotary kiln, riding ring, Hertz contact stress

1. INTRODUCTION

The riding ring is supporting element of rotary kiln and is subjected to dynamic stresses (Fig. 1). Most significant are contact stress and bending stress. Thermal stress is caused by temperature difference between the inner and outer fiber of ring and this stress can significantly reduce fatigue strength and can not be influenced by proper dimensioning like other two stresses. Contact stress is significant for all rotary parts, because it causes three-dimensional state stress below the surface and highest values of equivalent and tangential stress are slightly below the surface where cracks are supposed to initiate.

2. STRESSES DUE TO VERTICAL LOAD

2.1 Bending stress

The riding ring rests on two rollers. Due to kiln loads and support reactions, ring is subjected to bending (Fig. 1). Ring can be considered as a thin curved beam. The calculation of bending moment distribution can be considered as statically indeterminate problem. Detailed analysis, using e.g. Castigliano's Theorem, shows that maximum bending moment occurs in the contact area and depends on the contact angle. For the worst case when no clearance exists between ring and furnace (which never occurs in practice) maximum bending moment is:

$$M_{\max} = 0.086 Q \cdot R \quad (1)$$

Maximum bending stress is:

$$\sigma_{bend\ \max} = \frac{M_{\max}}{W_x} \quad (2)$$

where

Q is total kiln load, R is mean radius of riding ring, $W_x = B \cdot H^2/6$ section modulus.

On the outside fiber bending stress varies four times along the circumference from tension to compression.

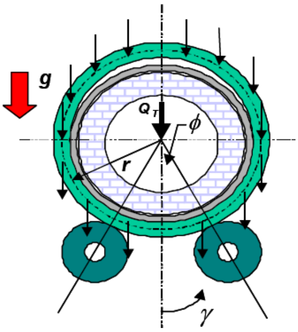

Figure 1. Ring and rollers [1]

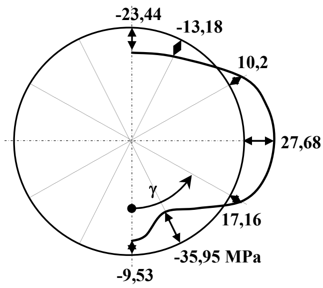

Figure 2. Bending stress in the outer fiber

For the middle ring in cement factory in Kakanj (Q=3412 kN, R=2513mm , H=374 mm, B=880mm) maximal bending stress is $\sigma_{bend\ max}$= -35,95 MPa (Fig. 2). Sign '-' means that outer fibers of ring, where contact with rollers takes place, are in compression.

2.2 Surface contact stress

Between the riding ring and the supporting roller a contact stress is produced by normal component of the vertical load (Fig. 3). The pressure within each body has semieliptical distribution. Maximal pressure occurs at the center of the contact area: $\sigma_{h\max} = \dfrac{2Q_N}{\pi a^2 B} = -363,7\,\text{MPa}$ . ... (3)

where Q_N is normal component of vertical load, a is half–with of the contact area $a = \sqrt{\dfrac{4Q_N R}{\pi B E^*}} = 3.89\,\text{mm}$, R is equivalent radius $R=(1/R_1+1/R_2)^{-1}$=617.1 mm, E^* is equivalent modulus of elasticity $E^*=((1-\mu^2)/E_1+(1-\mu^2)/E_2)^{-1}$=115385 N/mm^2. Indices 1 and 2 relate to ring and roller, respectively, B is a face width.

Due to contact stress at the surface, triaxial-state stress is produced below the contact surface. Fig. 4 shows normal stresses σ_z , σ_y , σ_x , as well as equivalent stress σ_{ekv} and shear stress τ. Equivalent stress, in accordance with the distortion energy theory, reaches maximum value which can be expressed as a function of $\sigma_{h\ max}$: $\sigma_{ekv\ max} = 0,55\ \sigma_{h\ max}$. Maximal shear stress is: $\tau_{max} = 0,304\ \sigma_{h\ max}$. These two stresses reach maximal values slightly below surface, and it is believed that at this depth, they initiate cracks that spread to surface [2].

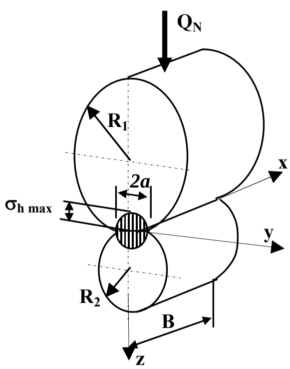

Figure 3. Contact between roller and ring

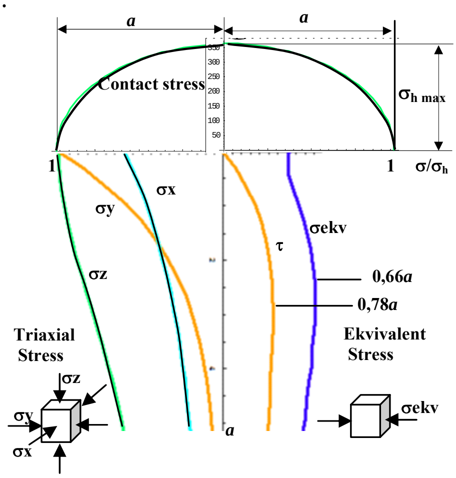

Figure 4. Stresses below the contact surface

3. STRESSES DUE TO TEMPERATURE GRADIENT

As riding ring allies on rotary furnace, there always exists temperature difference between inner and outer fibre. The temperature gradient along section height is: $\Delta T = T_I - T_A$. For the middle ring in Kakanj, the temperature of inner fibre is T_I =290 ºC, and temperature of outer fibre is T_A =190 ºC. Temperature gradient is ΔT =100 ºC.

Outer tangential stress (tension) is:

$$\sigma_{TA} = \frac{E \cdot \alpha_T \cdot \Delta T}{3} \frac{m+2}{m+1} = 122{,}9 \text{ MPa} \text{ ....(4)}$$

Inner tangential stress (compression) is:

$$\sigma_{TI} = -\frac{E \cdot \alpha_T \cdot \Delta T}{3} \frac{2m+1}{m+1} = -129{,}11 \text{ MPa} \text{ .....(5)}$$

where α_T is expansion coefficient, $m = R_A / R_I$ is radius ratio of outer and inner fibre.

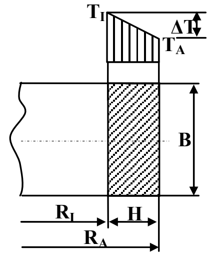

Figure 5. Temperature gradient along section height

4. ALTERNATING STRESS

Alternating stress (Fig. 9) is created by the three principal stresses:

- bending stress σ_{bend} , which alternates four times from positive to negative value (Fig. 6),
- contact stress σ_h , which is negative (Fig. 7),
- thermal stress σ_T , caused by linear temperature gradient along the section height (Fig. 8).

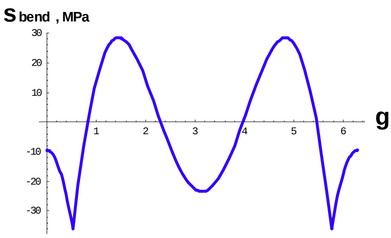

Figure 6. Bending stress

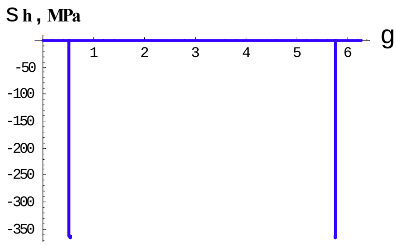

Figure 7. Hertian pressure

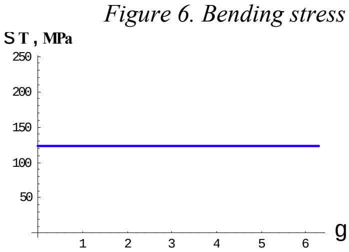

Figure 8. Thermal stress

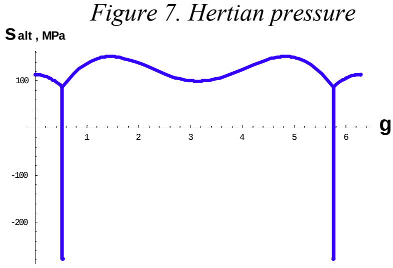

Figure 9. Alternating stress

The critical area of riding ring is outer fiber; therefore the determination of alternating stress has to be related to this area.

Alternating reference stress can be divided on static component: mean stress σ_m = - 63 MPa and stress amplitude: σ_a =213,75 MPa, i.e. $\sigma_{alt} = \sigma_m$ +/- σ_a = - 63 +/- 213,75 MPa.

The alternating reference stress provides valuable information about fatigue load to which riding ring is subjected. During one revolution the stress alternates four times from tension to compression. As ring has 2 revolution per minute, this means that during one year the ring has 4 204 800 cycles, if short breakages are neglected. According to S-N diagram, the infinite strength of steel begins at approximately 10 million cycles, corresponding to fatigue strength of app. $\sigma_E = 0{,}4 \cdot \sigma_U$ (σ_U is ultimate tenssile strength).

5. EXPERIMENTAL RESEARCH ON STRESSES OF THE RING

In order to obtain contact and bending stress during one quarter revolution of the ring, a strain gauge was bonded on the vertical side of riding ring, near the contact surface. It had possibility to determine stresses in two directions vertical and horizontal. The bad surface condition of the roller and the ring was the cause that the contact was reduces to 55% of possible contact area (in figure 10 a bright areas on roller surface show reduced contact length). Outer, edge fiber, nearby strain gauge was bonded, had clearance toward roller of app. 5 mm, so it was impossible to record true contact stress. On figure 11 these values are around zero. Only possibility was to record bending stress. Theoretically, in the interval when γ have value form 0 to 0.8 radians (app. $\pi/4$), the gauge should give compression stress with the maximal value for γ=0.52 ($\pi/6$). But recorded diagram on Fig. 11 have positive value. This means that when no contact on the edge of ring is achieved, bending moment in those fibers will have different bending stress distribution. However, maximal value will remain the same i.e. 40 MPa.

Figure 10. Strain gauge bonded on the ring

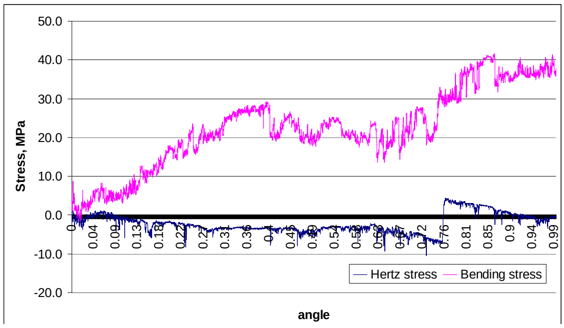

Figure 11. Bending and contact stress

6. CONCLUSION

Riding ring is subjected by three types of stresses: bending, contact and thermal. Bending stress is determined using Nies formulae [1], contact stress is calculated according Hertz theory and thermal stress is determined using compatibility equation.

Outer fibers are the most stressed part of the ring. Figure 9 shows alternating stress, calculated for the middle ring in cement factory in Kakanj. This stress changes four times from tension to compression, and with 2 rev/min, ring has 4 million stress cycles per year.

Experimental determination of contact and bending stress didn’t give correct values because the existing clearance between outer fibers of ring and roller surface. Reduced area of contact means that contact stress has higher value than that calculated. Bending stress in outer fiber, when the clearance exists, has different distribution than theoretical one.

7. REFERENCES

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