Coming out prevention by stopper for the shrink fitted sandwiched shaft from the ceramic sleeve

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Coming out prevention by stopper for the shrink fitted sandwiched shaft from the ceramic sleeve

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Abstract : Ceramic roller can be used in the heating furnace conveniently because of its high temperature resistance. The roller consists of sleeve and steel shaft connected only under a small shrink fitting ratio because of the brittleness. However, the coming out of the shaft may often happen from the ceramic sleeve under repeated bending load. Therefore, how to prevent the coming out failure becomes an important issue. Based on the previous study, a two-dimensional shrink fitted structure is considered by replacing the shaft with the inner plate and by replacing the sleeve with the outer plate. Then, this research focuses on preventing the inner plate coming out from the outer plate by introducing a newly designed stopper on the outer plate. The simulation results shows that the coming out phenomenon can be prevented effectively due to the contact between the inter plate and the stopper installed on the outer plate. In order to evaluate the contact force between the inner plate and the stopper, the coming out mechanism is clarified. To prevent the coming out by stopper safely, the effects of the magnitude of repeated load and the friction coefficient upon the contact compressive force are investigated under large number of loading cycles by using 2D simulation.

1 Introduction

Steel conveying rollers are used in the heating furnace for producing high-quality steel plates for automobiles. The conventional roller material is steel with ceramic spray coating on the outside of sleeve. To reduce the temperature, inside of the roller is cooled by water. However the thermal expansion mismatch may exceed the adhesion strength of the ceramic layer and causes failure on the roller surface such as crack, peeling, and wearing [1]. Therefore, the life of the roller becomes quite short.

Figure 1 shows a new ceramic roller consisting of steel shaft at both ends and ceramic sleeve having high heat resistance, high corrosion resistance and high wear resistance [2, 3]. Several previous studies suggested that the shrink fitting system may be the most suitable joining method for cylindrical structures to reduce the maintenance time and cost for the shaft replacement [4-8]. However, since only a small shrink fitting ratio can be used because of the ceramic brittleness [9-15], the coming out of the shaft from the sleeve

may happen during operation. In our previous studies, therefore, the coming out simulations are performed by using the finite element method [4, 5] for this kind of roll. Suryadi [4] et al built 3D FEM model to simulate the coming out but only until N = 5 loading circles because of the large calculation time. Therefore, Xu [5] et al developed 2D model as shown in Figure 2 to reduce the calculation time and obtained the results until N = 40 circles or more. Those studies [4, 5] have proved that the coming out behavior can be realized in the 2D and 3D simulations. In this paper, how to prevent the shaft from coming out will be newly discussed when the shrink fitting ratio is smaller and the load is larger.
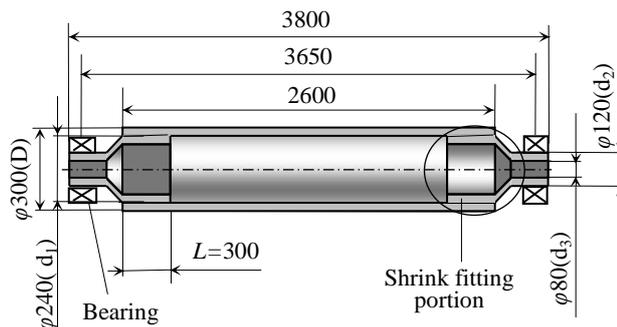

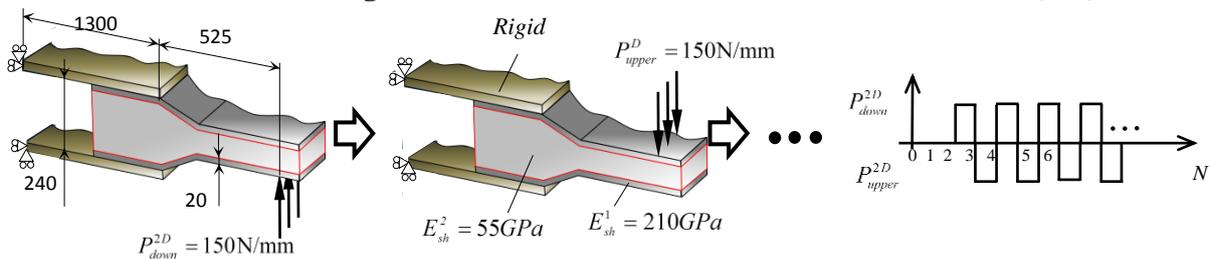**Figure 1**.Structure and dimensions of a real ceramic roller (mm)

Figure 2. Two-dimensional alternate loading model (Model 2D-alt.)

This paper considers the shrink fitted sandwiched shaft and the newly added stoppers to simulate the prevention of coming out from the roller sleeve as an innovation solution. The two dimensional model will be considered instead of the three dimensional model subjected to rotary bending, which can save much computational time[5]. Here, the inner plate and outer plate will be considered by replacing the shaft and sleeve as shows in Figure 2. The finite element method is applied to simulating the behavior; then several mechanical factors is considered to explain the mechanism of coming out and also to prevent the coming out of the inner plate.

2 Analysis condition

Figure 3 illustrates a new simplified 2D model with the stopper against the old one. Table 1 shows the material properties of the models. For 3D model, the shaft material was steel. For 2D model, the material of 2D shaft assumed to be the composite as described in the literature[5], and the outer plate (Ceramic sleeve) is assumed to be rigid.

Regarding the 2D model, the point load in the 3D model is replaced by the distributed load as shown in Figure 2. Here, the 2D model has a unit thickness which corresponds to 120mm width and the standard load 18KN is represented by 150N/mm considering the diameter of the shaft.

The purpose of this study is to realize the coming out prevention by the stopper for large number of cycles by the numerical simulation to find out the mechanism. In this study, the simulation is considered under room temperature because the coming out occurs more easily. Here, static structural analysis is

performed to the models by using MSC. Marc/Mentat 2012 with the Full Newton-Raphson method. A half model is considered due to the symmetry.

Table 1 Material properties

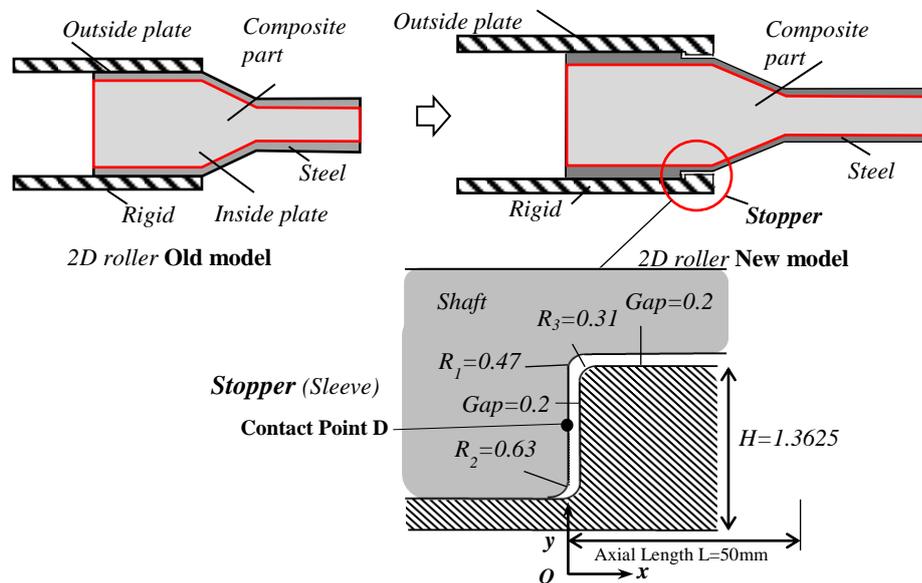| Model	3D－alt., 2D－alt.			3D－rot.	
	Sleeve	Shaft		Sleeve	Shaft
	Rigid	Steel	Composite part	Ceramics	Steel
Young's modulus [GPa]	∞	210	55	300	210
Poisson's ratio	1	0.3	0.3	0.28	0.3
Tensile strength [MPa]	∞	600	—	500	600
Mass density [kg/m³]	0	7800	7800	3200	7800

Figure 3. New simplified 2D model with the stopper against the old model of the roller

Equivalent shrink fitting ratios as the roller in the heating furnace may be applied by considering the shaft expansion. The shrink fitting ratio δ/d is defined as the height difference δ divided by height $d=240$ mm. The shrink fitting is considered in the range $\delta/d=0.01\times10^{-3} \sim 0.4\times10^{-3}$. Then, the ratio 0.2×10^{-3} is used as a reference value.

3 Contact condition between the inner plate and the stopper installed on the outer plate under different shrink fitting ratios and bending loads

In order to investigate the contact status between the inner plate and the outer stopper, Figure 4 (a) shows the displacement u_{xD} in the x-direction at Point D when load P=150N/mm is repeated N times for the fixed shrink fitting ratio from $\delta/d=0.01\times10^{-3} \sim 0.4\times10^{-3}$. It can be seen that the smaller shrink fitting ratio causes the contact between the inner plate and the stopper easily under small N. If there is no stopper, the shaft continues coming out as have been discussed in the previous research [5]. After the coming out is prevented by the stopper, a constant amplitude of the displacement can be seen when $\delta/d = 0.01\times10^{-3}$ and $\delta/d =0.03\times10^{-3}$.

To find out the effect of magnitude of loads on the contact status, Figure 4(b) shows the displacement u_{xD} in the x-direction at Point D for the fixed fitting ratio $\delta/d=0.2\times10^{-3}$ with fixed friction coefficient $\mu=0.3$. From Figure 4(b), it can be seen that P=600N/mm is the threshold value of the contact and below
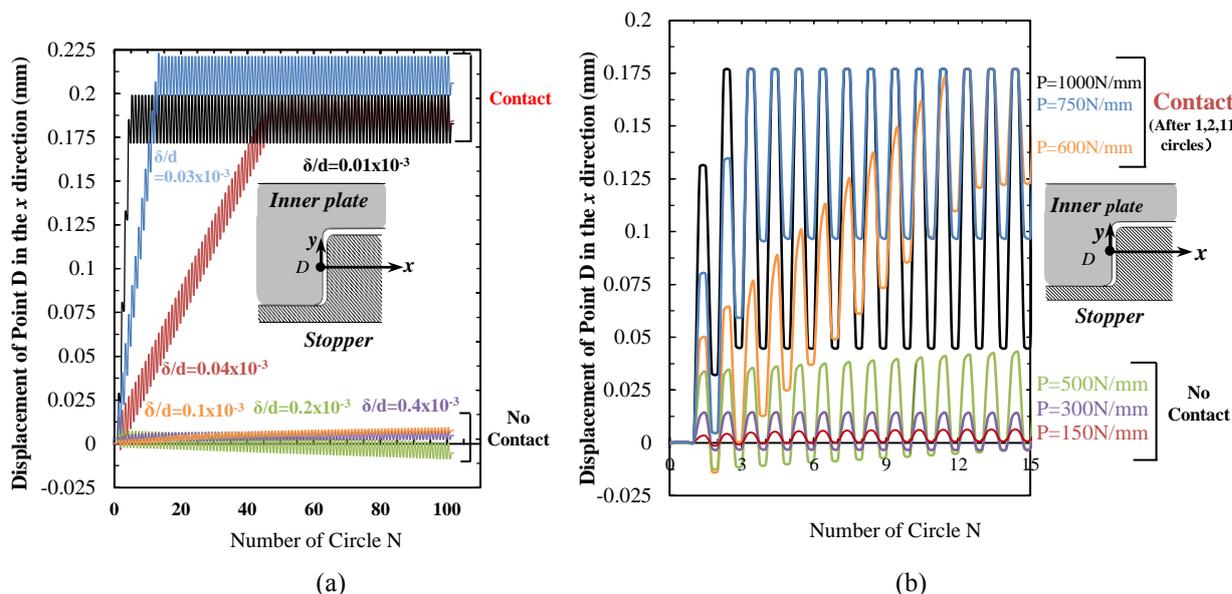

(a)   (b)

Figure 4. (a) Displacement u_{xD} vs number of cycle N under fixed load P=150N/mm. (b) Displacement u_{xD} vs number of cycle N under fixed δ/d =0.2×10^{-3} and μ=0.3

which no contact anymore. When load is smaller than the threshold, even after several circles N the displacement u_{xD} does not increases and therefore there is no contact. In other words, the relative position between the inner plate and the stopper is almost steady from the beginning of N. It should be noted that the displacement for P=150, 300, 500N/mm is far less than the gap distance G=0.2mm in Figure 3. On the contrary, when load P= 750N/mm, only after N = 3 circles, the shaft has contacted with the sleeve stopper. The contact appears after for P=600N/mm at N = 11 circles, for P=1000N/m at N = 2 circles, and for P=2000N/mm at N = 1circle. It may be concluded that with increasing load P, the coming out speed increases and the number of cycle until the contact deceases when load P is smaller than 2000N/mm.

4 Coming out mechanism and how to prevent the inner plate from coming out

The simulation is performed to investigate the contact force F_x appearing on the stopper. The contact force F_x may be regarded as the driving force for the coming out. Therefore, to obtain the reaction F_x at the stopper may be useful for understanding the coming out mechanism and finally for preventing from coming out.

Figure 5 shows the contact force F_x when upward load is applied with varying the magnitude of loads P and friction coefficients μ under fixed δ/d =0.2×10^{-3}. In Figure 5, it is seen that with increasing the magnitude of the applied load P, the compressive force F_x increases. It is also seen that with increasing the friction coefficient μ, the compressive force F_x increases.

Due to the shrink fitting and the applied load P, the inner plate is contacting with the outer plate at several portions such as the upside portion, the downside portion and the stopper. It should be noted that the reactions from those contacted portions should be balanced because the coming out behavior is quasi-static. As an example, when the load P =600N/mm is in the upward direction, the shrink fitting ratio δ/d=0.2×10^{-3}, the friction coefficient μ=0.3 and N≥11, the downside inner plate contact with the stopper,

the upside does not contact. As shown in Figure 6 ，from the shear stress distributions , the shearing force at the upward part can be obtained as $F_{\tau u}$=1165.7N, and the shearing force at the downward part can be calculated as $F_{\tau d}$=-931.1N. Then we have:

$$F_s = F_{\tau u} + F_{\tau d} \tag{1}$$

Substituting $F_{\tau u}$=1165.7N, $F_{\tau d}$=-913.1N into Eq.(1) we have F_s=252.6N as the driving force for coming out. The compressive force F_x on the stopper is calculated by FEM as F_x= -240.3 N[16]. Then we have $F_s + F_x \doteq 0$ within 5%. It may be concluded that the shear force F_s balanced with the compressive force F_x in the *x*-direction.
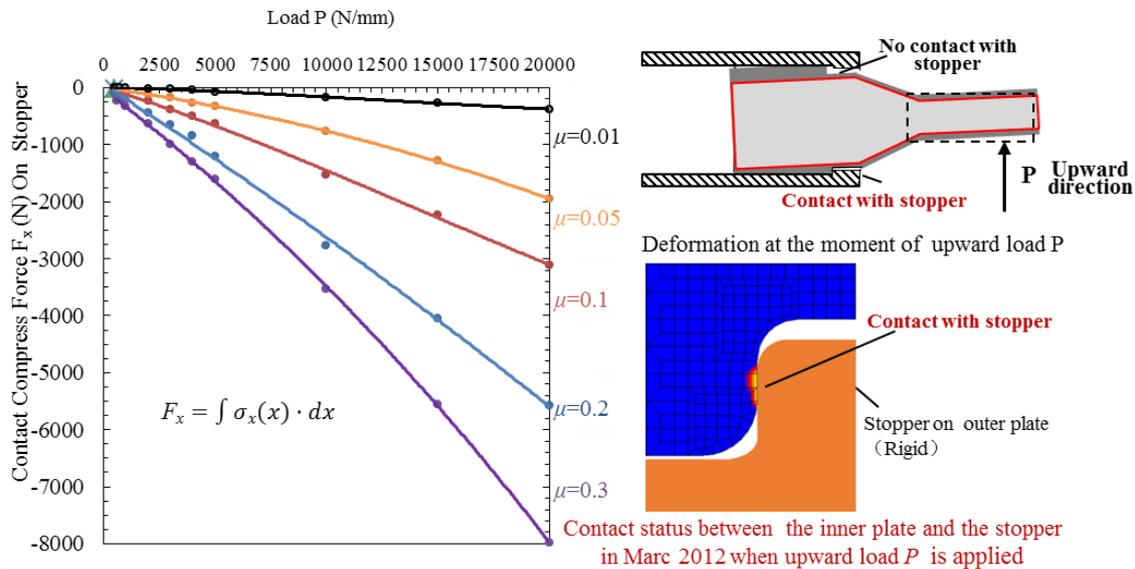

Figure 5. Relation between different load *P* and compressive contact force F_x on the stopper under different friction coefficient μ when δ/d =0.2×10⁻³and upward load *P* is applied

5 Conclusions

In this study, a newly designed stopper is considered to prevent the inner plate from coming out. In order to evaluate the contact status between the inner plate and the stopper, a simulation has been conducted. The effect of the magnitude of applied force on the coming out of the inner plate has been discussed. The conclusion can be summarized in the following way.

(1) The analysis results shows that the several portions of the inner plate contact with the outer plate due to the repeated load *P* after shrink fitting. At that time, two shearing forces are generated at the upward portion and at the downside portion of the inner plate.

(2) The resultant force $F_s = F_{\tau u} + F_{\tau d}$ can be obtained from the shearing force at the upward portion F_τ and the shearing force at the downside portion $F_{\tau d}$. This resultant force F_s can be regarded as the driving force of coming out. Here, the positive direction is defined as the coming out direction. Due to this positive driving force, the inner plate is coming out.

(3) To prevent the inner plate from coming out can be achieved by applying a negative force to the inner plate. This force can be provided as a contact force F_x appearing at the stopper. Numerical simulation demonstrated that the contact force F_x and the driving force of coming out F_s are almost equal within 5% error. In other words, it is confirmed that the shearing force at the upward portion F_τ and the shearing force at the downside portion $F_{\tau d}$ and the contact force F_x are balanced.

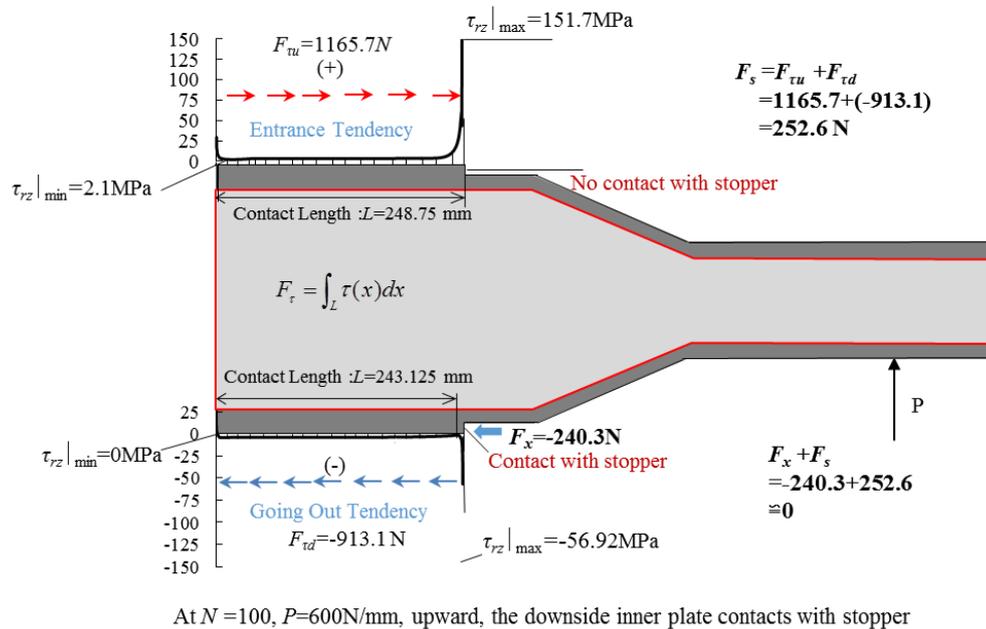Figure 6. Shear stress distribution on inner plate at the moment of upward load P=600N/mm is applied when circle *N*=100

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