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Study on coming out of the shaft from ceramic sleeve in terms of the residual displacement

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Study on coming out of the shaft from ceramic sleeve in terms of the residual displacement

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Abstract. Ceramic roller can be used in the heating furnace conveniently because of its high temperature resistance. However, the coming out of the shaft may often happen from the ceramic sleeve under repeated load. In this paper, 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. Based on the model with stopper, the FEM simulation is performed under alternate loading with certain intervals newly added. The analysis results show that the coming out failure can be explained from the residual displacement accumulation during these intervals.

1. Introduction

In order to produce high-quality steel plates for automobiles as is shown in figure 1, steel conveying rollers with high temperature resistance working in furnace have been developed. Usually, the conventional roller material is composed by steel and ceramic spray coating on the outside of sleeve. However the thermal expansion mismatch may exceed the adhesion strength of the ceramic layer, which causes failure on the roller surface such as crack, peeling, and wearing [1].

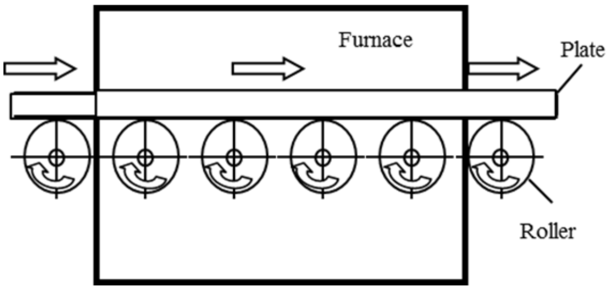

Figure 1. Layout of rollers in heating furnace.

Figure 2 shows a new ceramic roller consisting of steel shaft at both ends and ceramic sleeve with high corrosion resistance and high wear resistance [2,3]. The inside of the roller is usually cooled by water. The method of joining the steel with the ceramic sleeve is an important issue. The previous studies suggested that the shrink fitting system may be the most suitable joining method for cylindrical ceramic structures, which can reduce the maintenance cost and the shaft replacement time [4-10]. However, the coming out of the shaft from the sleeve happens during operation since only a small shrink fitting ratio can be used because of the ceramic brittleness [11-17]. Previously the coming out simulations are performed by using FEM, which can be applied many industrial problems conveniently [4-17]. Suryadi [4] *et al* built 3D FEM model to simulate the coming out but only until 5 loading circles because of the large calculation time. Therefore, Xu [5] *et al* developed 2D model as shown in figure 3 (2D roller old model) to reduce the calculation time and obtained the results until 40 circles or more. As a further study, authors designed a new simplified 2D model with stopper to prevent the coming out behavior as shown in figure 3 [6]. Those studies [4-6] have proved that the coming out behavior can be realized in the 2D and 3D simulation and it can be prevented by the stopper. This paper considers 2D coming out problem under alternate loading with a certain interval, by taking account of the influence of intervals in alternate loading. And try to explain the coming out mechanism in detail with the help of the stopper. Then the coming out failure can be considered from the residual stress displacement during these intervals. Here, the inner plate and outer plate will be considered as the shaft and sleeve as shown in figure 3. The finite element method is applied to simulating the prevention of the coming out behavior in terms of the residual displacement.

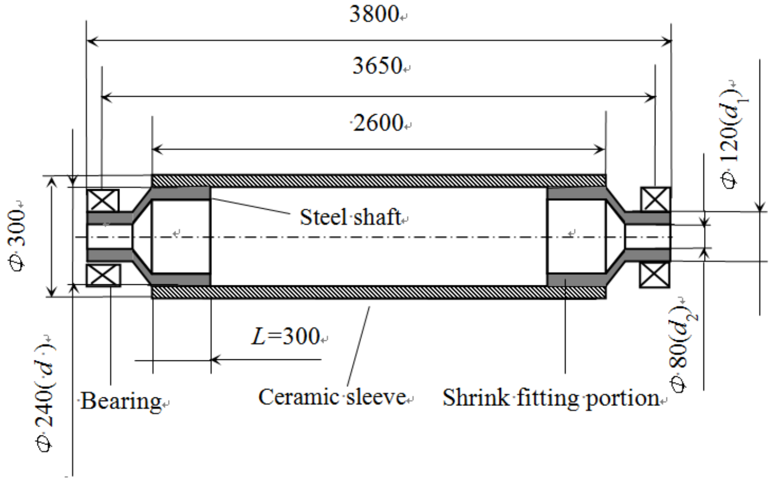

Figure 2. Structure and dimensions of a real ceramic roller (Unit: mm).

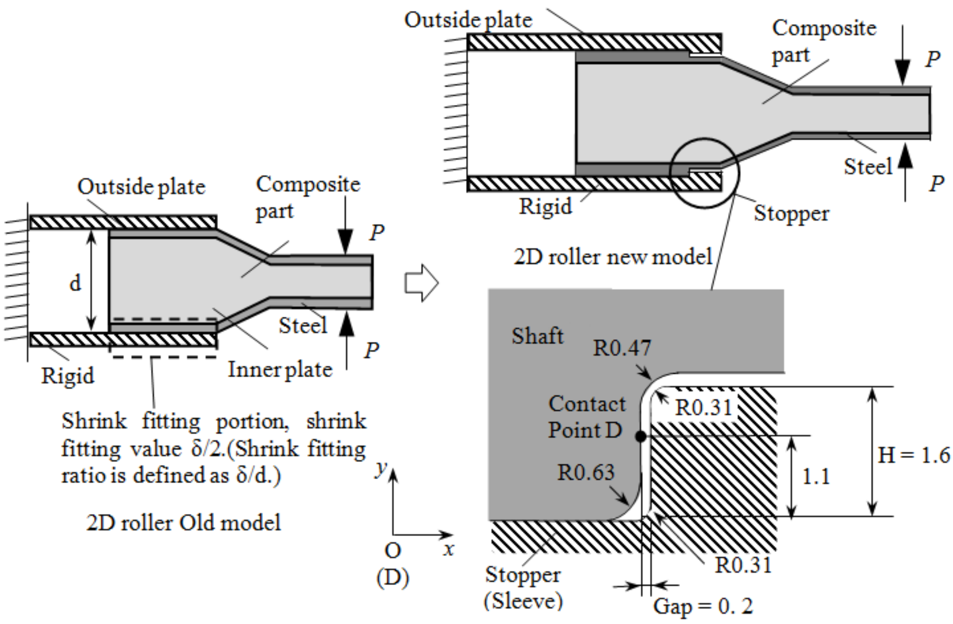

Figure 3. New simplified 2D model with stopper (Unit: mm).

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2. Analysis method

Figure 3 illustrates the structure of the newly designed stopper installed on the outer plate and the boundary condition. Figure 4 shows the previously used loading pattern which does not contain intervals between the loading [4-6]. Figure 5 shows the new loading pattern including intervals denoted by Step II and step IV between the loading periods as Step I and step III, where the temporary no-load condition during roller conveyance of the iron plate has been taken account into practically. Table 1 shows the material properties of the models. In this 2D model, the 2D solid inner plate and the 2D rigid outer plate are considered to simplify the model and to reduce the calculation time as described in the literature [5,6].

Table 1. Material properties.

Model	2D－alt.		
	Sleeve	Shaft	
	Rigid	Steel	Composite part
Young's modulus [GPa]	∞	210	55
Poisson's ratio	—	0.3	0.3
Tensile strength [MPa]	∞	600	—
Mass density [kg/m^3]	0	7800	7800

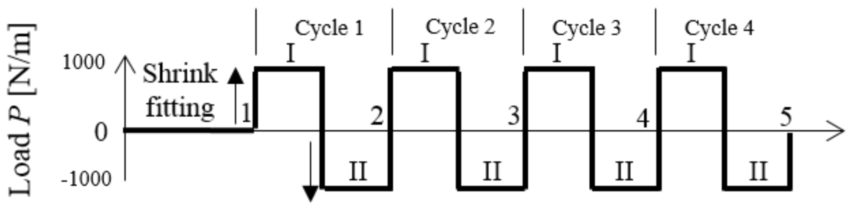

Figure 4. Alternate loading pattern without intervals.

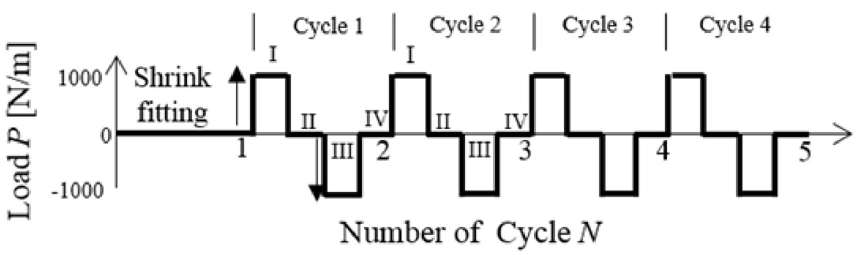

Figure 5. New alternate loading pattern with intervals.

To express the roll rotation, the point load is shifted in the circumferential direction in the 3D roll simulation [4]. This load shifting is replaced by the alternate loading in the 2D simulation [5]. Here, the 2D model has a unit thickness which corresponds to 120 mm width and the standard load 18 KN is represented by 150 N/mm considering the diameter of the shaft.

In this simulation, room temperature is assumed where the coming out occurs more easily. Then, static structural analysis is performed to the models by using MSC. Marc/Mental 2012 with the Full Newton-Raphson iterative sparse solver of multifrontal method [18]. A half model is considered due to the symmetry. Quadrangular contact element under axial symmetry has been used, the number of elements is 24546. Considering analysis accuracy, a minimum element size is 0.15625 mm×0.15625 mm around the part comes into contact with stopper. The shrink fitting ratio δ/d is defined as the height difference δ divided by the inner plate height d = 240 mm. Then, the shrink fitting ratio $\delta/d = 0.2\times10^{-3}$, friction coefficient μ = 0.3, load P = 1000 N/mm are used as reference values.

3. Residual displacement of the inner plate

In this section, Point D in figure 2 is focused on representing the contact part. To find out the contact condition between the inner plate and the stopper, the coming out is represented by the displacement u_{xD} in the x-direction at Point D under the alternate loading in figure 6(a).

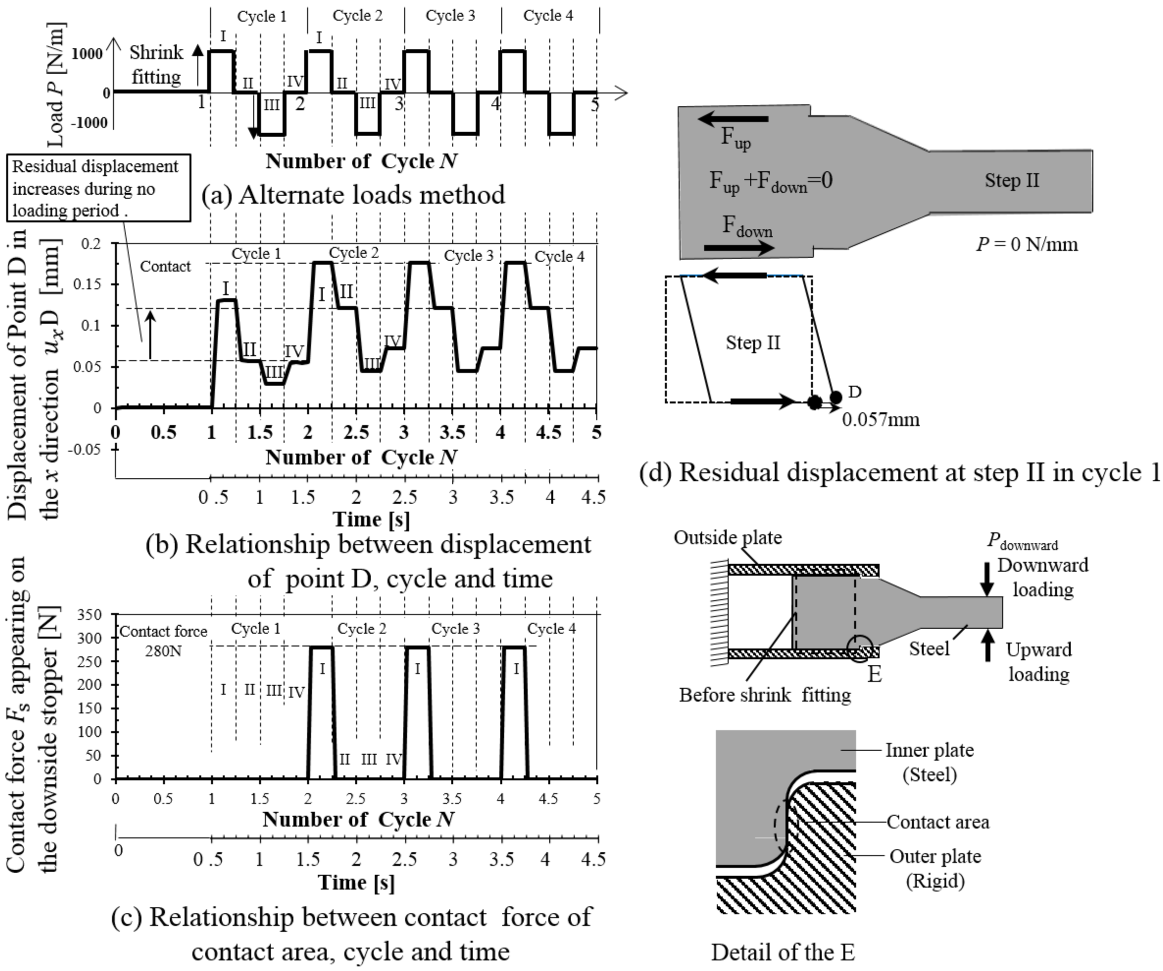

Figure 6. Displacement of Point D and contact force of the downside stopper vs loading time when load P = 1000 N/mm under new alternate loading pattern with intervals.

Figure 6(b) shows the displacement u_{xD} in the *x*-direction at Point *D* when load P = 1000 N/mm is repeated 5 times. From the 2nd cycle I, the displacement u_{xD} becomes stable independent of the cycles with the maximum displacement u_{xD} = 0.176 mm at Step I. Note that u_{xD} = 0.176 mm is smaller than the original gap 0.2 mm. In the case of dealing with the contact problemp [19] as in this research, it is necessary to take as much as 1/2 or more of the fitting value as the contact determination amount for calculation, $\delta/d = 0.2 \times 10^{-3}$, the inner diameter d = 240 mm, since $\delta = 0.2 \times 10^{-3} \times 240 = 0.048$, $0.048 \times 1/2 = 0.024$ mm is taken as the contact determination amount. Therefore, in this simulation, u_{xD} = 0.176 mm (0.2 mm - 0.024 mm) can be regarded as the contact distance between the inner plate contact with the stopper.

Figure 6(c) shows the contact force appearing at the stopper under the alternate loading. It can be seen that the inner plate end (part E in figure 6) is in contact with the stopper from the 2nd cycle I. Then, the resultant contact force becomes stable as shown in figure 6(c) independent of the cycles with the value of 280 N. If there is no stopper, the shaft will gradually come out as discussed in the previous papers [4,5]. After the coming out is prevented by the stopper, a constant amplitude of the displacement with the contact force can be obtained as shown in figure 6.

During every step II and step IV, the contact force is zero but the displacement is neither zero nor the maximum. During step II, no load is applied after the upward load is removed and also during step IV, no load is applied after the downward load is removed. The displacement during those periods can be regarded as a residual displacement. Therefore, figure 6(b) indicates that the residual displacement increases from u_{xD} = 0.057 mm in cycle 1 to u_{xD} = 0.121 mm in cycle 2, then becomes stable from cycle 2 after the inner plate is in contact with the stopper.

Figure 6(d) shows the detail of the residual displacement at step II in cycle 1. During this no loading step in cycle 1, it should be noted that shear forces F_{up} and F_{down} are balanced. Here, F_{up} and F_{down} represent the shear forces applied along the upside and downside of the inner plate. Therefore, although the coming out does not progress during this no-loading step II, the residual displacement appears due to this balanced frictional forces. During step II in cycle 2, the residual displacement accumulates and increases until the inner plate contact with the stopper. The accumulation of the residual displacement can be regarded as a coming out process. In other words, the coming out phenomenon can be explained from the residual displacement accumulation during the intervals.

4. Conclusions

In this study, the finite element method was applied to simulating the coming out behavior of the shaft which was connected to the sleeve by shrink fitting. To clarify the coming out mechanism, a new alternate loading pattern was applied where intervals was included. The conclusion can be summarized in the following way.

- The design of stopper and the newly loading pattern is helpful to understand the coming out problem.
- The residual displacement can be seen in the intervals that were newly considered during the alternate loading. The residual displacement accumulates and increases by repeating the loading cycle until the shaft contacts to the stopper.
- The accumulation of the residual displacement causes the shaft coming out. In other words, the coming out phenomenon can be explained from the residual displacement accumulation.

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