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INVESTIGATION ON COMING OUT PHENOMENON OF THE SHAFT FROM THE SLEEVE BY 2-D PLATE MODEL APPROACH

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Abstract: The ceramics roller can to be used in the heating furnace because of high temperature resistance. The roller consists of ceramics sleeve and steel shaft connected by shrink fitting. Since ceramics is brittle, it should be noted that only low shrink fitting ratio can be applied for the connection. Therefore, coming out of the shaft from the sleeve during rotation should be investigated in this study. In this study, the finite element analysis is applied to simulate this phenomenon. In the previous study, mechanism of coming out has been considered by using 3-D model. However, since 3-D model analysis needs large computational time, only small number of cycle can be considered, and therefore, the coming out phenomenon cannot be predicted easily. In this research, the 2-D plate model approach is proposed in order to reduce computational time, considering the upper and lower alternate load, repeatedly. Then, the effects of the magnitude of the load and shrink fitting ratio are investigated systematically. Finally, the simulation of the coming out phenomenon can be carried out for much larger number of cycles.

Keywords: Ceramics Roller, Coming Out, Shrink Fitting, 2-D Plate Model, Finite Element Method

1 INTRODUCTION

Steel conveying rollers are used in the heating furnace for producing high-quality steel plates for automobiles. Recently, the conventional roller has been used in the heating furnace which consists of sleeve and shaft. They are connected by shrink fitting. The roller material is steel with ceramics spray coating on the outside of sleeve. The coated sleeve and shaft are bonded by welding. To reduce the temperature, inside of the roller is cooled by water. However the thermal expansion mismatch may exceed the adhesion strength of the ceramics layer and causes failure on the roller surface such as crack, peeling [1], wearing, and shortens the life of the roller.

A new ceramics roller consists of steel shaft at both ends and ceramics sleeve having high heat resistance, corrosion resistance and wear resistance [2]. The ceramics sleeve may prevent defects caused by coating, and therefore, the roller life can be extended significantly. The shrink fitting may be the most suitable joining method for cylindrical ceramics as discussed in Refs. [3,4]. By using shrink fitting connection, the maintenance cost and replacement time of the shaft can be reduced. On the other hand, the thermal expansion coefficient of steel is about four times larger than that of ceramics. Since the fracture toughness of ceramics is lower than the value of steel, attention should be paid to the ceramics sleeve at joint portion.

In the previous study, the influence of the shrink fitting ratio and the friction coefficient upon the coming out behavior of the shaft was analyzed by using 3-D model [5]. And the mechanism of coming out has also been considered by using 3-D model. However, since the 3-D model analysis takes very large computational time. It is nearly impossible to calculate when cycle number N larger than 10.

In this paper, the 2-D model has been used instead of the 3-D model, so that the computational time can be greatly reduced and the model can be calculated until a large cycle number N (N=40). In this way, the coming out behavior of the shaft can be accurately evaluated by using the result of a large cycle number N 2-D model rather than a small cycle number N 3-D model. The finite element method is applied to simulate the behavior. Then, several mechanical factors will be considered to understand the coming out of the shaft.

2 ANALYISIS CONDITIONS

2.1 Analysis Model

Figure 1 shows dimensions of the real roller. In this paper, in order to reduce computational time, the 3-D model is simplified to a 2-D model. Here, the sleeve is modeled by rigid body, while hollow shaft is modeled by a composite shaft as shown in Fig.2.

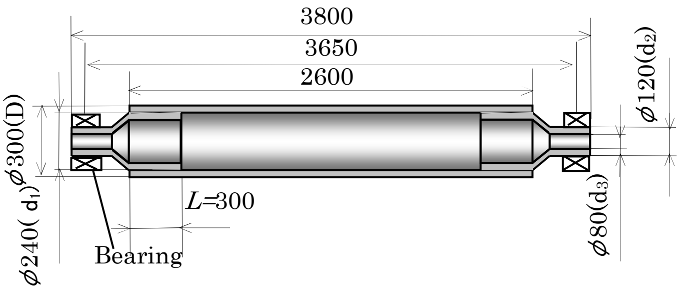


Fig. 1 Structure and dimensions of a real ceramic roller (mm).

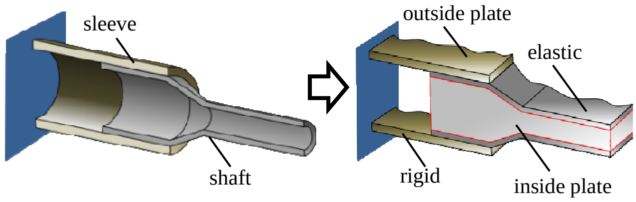


Fig. 2 Simplification from 3-D model to 2-D model

The rule of mixture is applied to obtain the average Young's modulus of the hollow shaft. Then, the average Young's modulus is given by using following equation.

$$E_{comp} = E_1 \frac{A_1}{A_1+A_2} + E_2 \frac{A_2}{A_1+A_2}$$

$$= E_1 \frac{A_1}{A_1+A_2} = 51.55MPa$$

Here, E_1 devotes the Young's modulus of the shaft, E_2 devotes the Young's modulus of the hollow portion of the shaft (E_2=0), A_1 devotes the cross-sectional area of the peripheral portion shaft and A_2 devotes the cross-sectional area of the hollow portion of the shaft (see Fig.3).

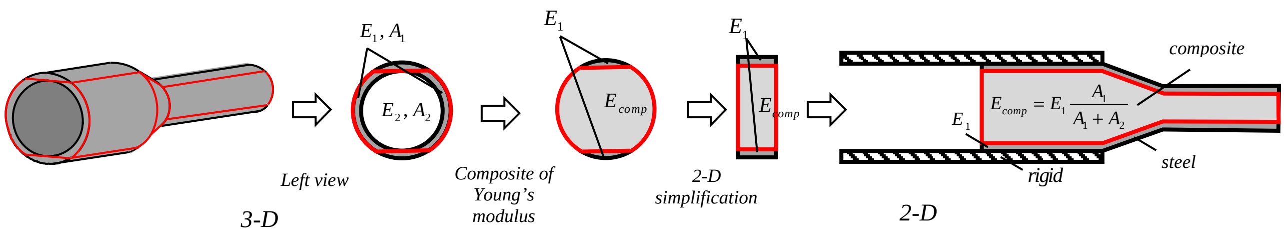


Fig. 3 Simplification from 3-D shaft to 2-D inside plate

2.2 Analysis Method and Boundary Conditions

In this study, the coming out of the inside plate in Fig.2, will be realized by the simulation. Then, the fundamental several important factors will be discussed. First, the coming out at room temperature is considered because the coming out easily occurs. Here, the shrink fitting ratio between outside and inside plates is defined as δ/d, where δ is the width difference (see Fig. 7.a) and d is the width of the inside plate d=240 mm. In this study, the shrink fitting ratio is considered in the range δ/d=0.01x10^{-3}-0.4x10^{-3}.

In this study, three models will be considered, that is, the 3-D real model (a), 3-D alternate load model (b) and 2-D alternate load model (c). In the previous studies, the half model of roller was used in the simulation. The roller is subjected to distributed load w=30N/mm due to the weight of the conveyed steel. In order to simulate the rotational behavior of the model, the distributed load on the sleeve part *w* is shifted repeatedly at certain time interval of the rotational angle θ_0 in circumferential direction in Figure 4.

In the first place, as shown in Fig.5, in this paper, in order to reduce the computational time, the 3-D rotation load is simplified as an alternate load model. The ceramic sleeve is simplified as a rigid sleeve and the left end of the sleeve has been completely fixed. And the load changes as shown in Figure 5.

Figure 6 shows the loading condition of the 2-D alternate load model. The distributed load is determined to satisfy the effectiveness of concentrated load applied upon per millimeter diameter length of the shaft. And the distributed load changes alternatively as shows in figure 6. Plane strain assumption is used.

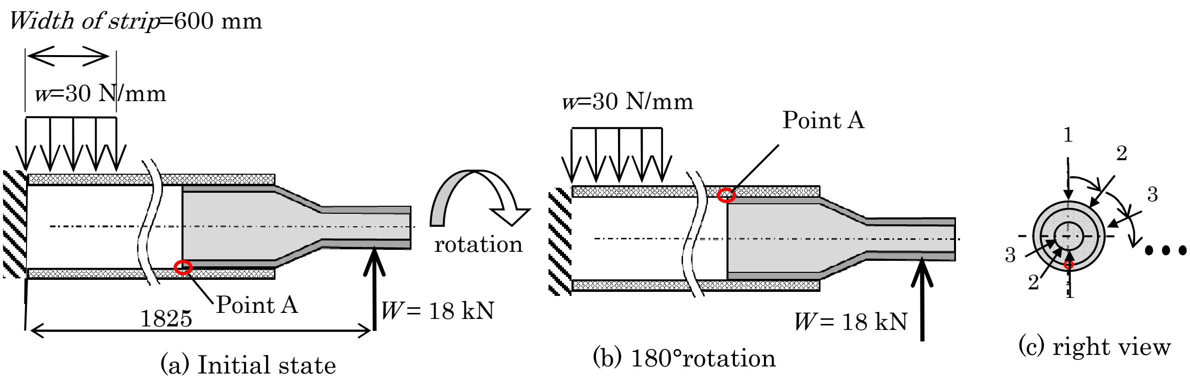


Fig. 4 Three-dimensional real roller model

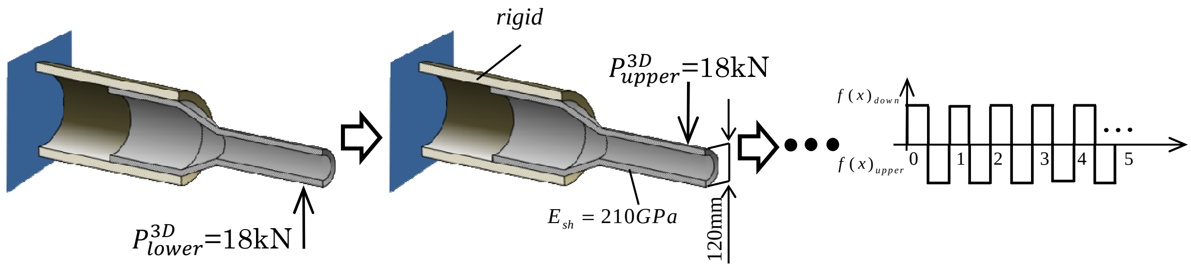


Fig. 5 Three-dimensional alternate loading model

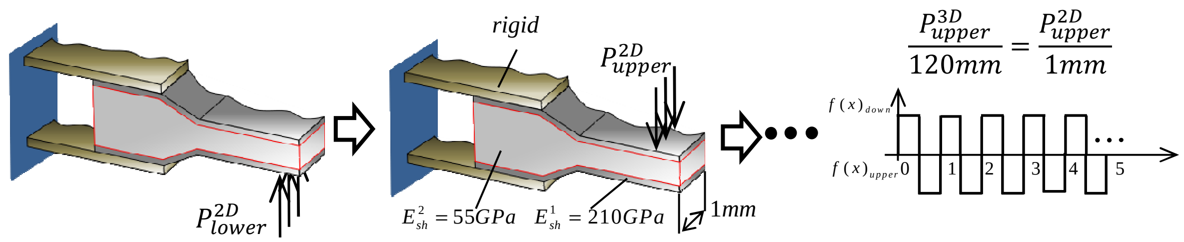
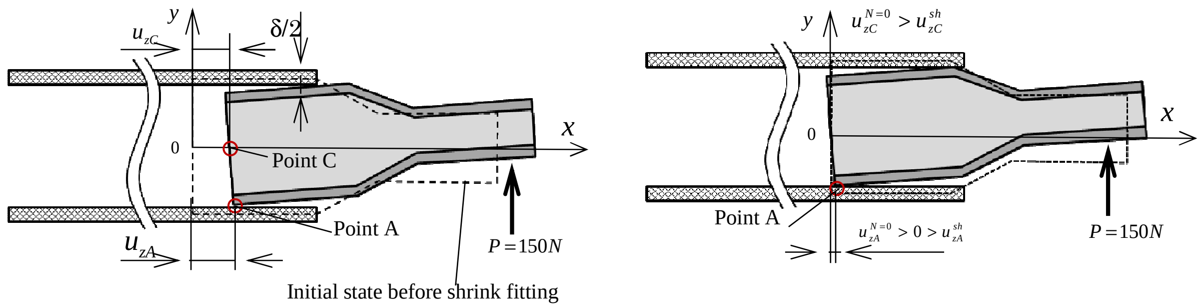


Fig. 6 Two-dimensional alternate loading model

3 EVALUATION METHOD FOR THE COMING OUT AND DEFLECTION OF THE SHAFT DUE TO THE DISTRIBUTED LOAD AND SHRINK FITTING RATIO

Deformation of the shaft due to initial load is considered. Figure 7(a) shows definition of coordinates (r,z) on the position of the shaft at before shrink fitting. Here, the relative displacement u_{zC} from initial position is focused. The displacement direction $u_{zC}^{N=0}$ (>0> u_{zC}^{sh}) at point C initiates coming out by initial load as shown in Figure 7(b). The displacement of the inner plate goes to negative direction by shrink fitting and it goes to positive direction due to the load. Moreover, point C is focused. The $u_{zC}^{N=0}$ is put as the initial displacement at number of cycle N=0.



(a) Definition of displacement u_{zC}, u_{zA} (b) Definition due to shrink fitting and initial load (N=0)

Fig. 7 Displacement of the shaft due to bending

4 COMPARISON OF THE RESULTS OF THREE MODELS

To confirm the usefulness of simplified 2-D model, three models are compared under the shrink fitting ratio δ/d=0.2×10^{-3} in Fig.8. The results for 3-D real roller (model A), 3-D alternate load model (model B) and 2-D alternate load model (model C) are compared focusing on u_{zC}. It is seen that the u_{zC} of model A increases at N=0~2. Then, it becomes constant at N=2~3. Since 3-D real model (model B) needs very large computational time, the simulation is carried out only until N=3. Therefore, it is hard to judge whether the coming out of the shaft occurs or not from this model. Further, the u_{zC} of the model B increases at N=1~6. However, the speed of the coming out of the shaft decreases gradually, therefore, the possibility of coming out of the model B looks very small. For the model C, the number of cycle can be reached until N=40. Here, the u_{zC} increases with increasing number of cycle N=0~5 and becomes constant after N=5, therefore, the coming out of Model C does not occur. From Fig.8, it is seen that model C is useful to judge whether the coming out occurs or not.

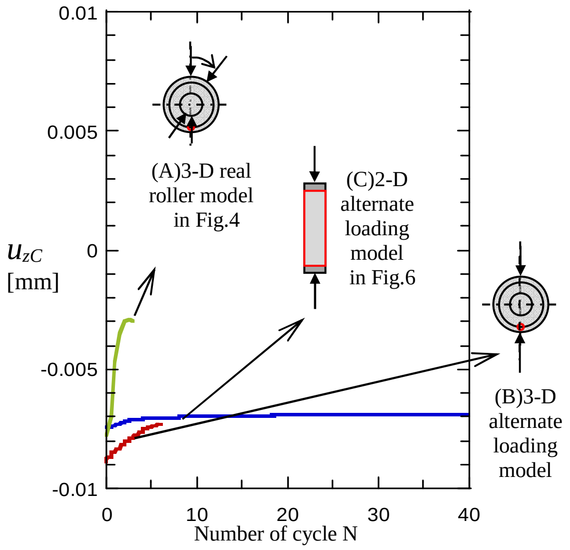


Fig. 8 The displacement u_{zC} vs. number of cycle N for 3-D real roller model, 3-D alternate loading model and 2-D alternate loading model with δ/d =0.2×10^{-3}

5 THE COMING OUT CONDITIONS DUE TO LOAD AND SHRINK FITTING RATIO

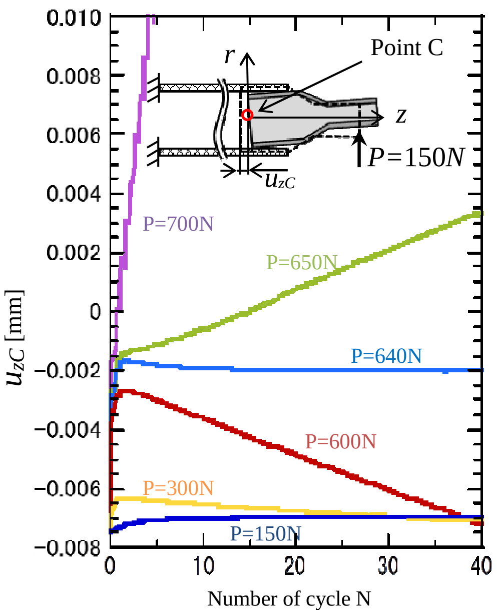


Fig. 9 The displacement u_{zC} vs. number of cycle N for different load P when δ/d =0.2×10^{-3}

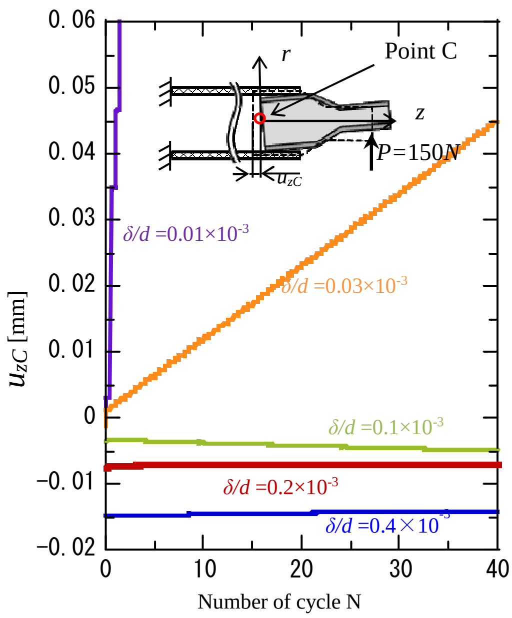


Fig. 10 The displacement u_{zC} vs. number of cycle N for different load δ/d when P=150N

Figure 9 shows the effect of the magnitude of alternative load upon u_{zC} under the shrink fitting ratio δ/d=0.2×10^{-3}. From the graph, the large load P causes large z-displacement u_{zC}. The u_{zC} tends to increase at N=0-4 independent of the magnitude P. Then, after N=4, it is seen that for P≥650N, the u_{zC} increases significantly, and the coming out occurs. After N=4, it is seen that for P≤640N, the u_{zC} becomes constant, which means that the coming out does not occur.

Figure 10 shows the effect of the shrink fitting ratio upon the u_{zC}. The large shrink fitting ratio causes negative u_{zC} at N=0 due to compressive stress. For N=0~40, the u_{zC} increases significantly with increasing N under the low shrink fitting ratio δ/d =0.01×10^{-3} and δ/d =0.03×10^{-3}, therefore, the coming out of the shaft occurs easily. On the other hand, the u_{zC} becomes constant under the shrink fitting ratio δ/d $=0.1\times10^{-3}$, δ/d $=0.2\times10^{-3}$ and δ/d $=0.4\times10^{-3}$, therefore, the coming out of the shaft does not occur. Fig.9 and 10 show the usefulness of the 2-D alternate load model because the results for large N can be obtained easily.

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