◉ 硏究論文

# DIMENSIONAL CHANGES AND REDISTRIBUTION OF RESIDUAL STRESSES DUE TO INNER LAYER REMOVAL OF RESIDUALLY STRESSED CYLINDRICAL COMPONENTS

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# 잔류 응력이 내재하는 원통형 부품의 내면 가공에 따른 치수 변화와 잔류 응력의 재분포

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**Key words** : Residual stress, Layer removal, Autofrettage process, Redistribution of residual stress

## Abstract

잔류 응력이 존재하는 부품의 가공 시에는 잔류 응력 상태가 새로운 평형 상태를 이루기 위해 재 분포되며 이는 가공 자체에 따른 변형 이외의 부가적 변형을 초래한다. 고도의 정밀도를 요하는 가공에는 이러한 잔류 응력에 의한 부가적 변형을 고려하여야 하며, 가공 후의 잔류 응력의 재 분포 상태는 가공 후 부품의 물질적 성능을 결정하는데 중요한 요소이므로 이를 예측할 수 있어야 한다.

본 연구에서는 잔류 응력에 의한 부가적 치수 변화를 고려한 가공 후의 부품의 내경·및 두께와 잔류 응력의 재 분포를 예측할 수 있는 이론적 수식을 제시하고 유한요소법에 의한 시뮬레이션의 결과와 비교하였다. 초기 잔류 응력의 분포는 autofrettage process 에 의해 유도되었다.

## NOMENCLATURE

- $r$ Radial coordinate, mm
- $a_o$ Original inner radius, mm
- $b_o$ Original outer radius, mm
- $t_o$ Original thickness of the cylinder, mm
- $a_1$ The radial location where machining is to be reached, mm
- $a$ New inner radius after machining, mm
- $b$ New outer radius after machining, mm
- $t$ Thickness of the remaining cylinder after machining, mm
- $u_r$ Radial displacement, mm
- $\sigma_{ro}$ Original radial residual stress, Mpa
- $\sigma_{\theta o}$ Original tangential residual stress, Mpa
- $\sigma_r'$ Radial stress resulting from applied

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stress, Mpa

$\sigma'_\theta$ Tangential stress resulting from applied stress, Mpa

$\sigma_r$ Redistributed radial residual stress, Mpa

$\sigma_\theta$ Redistributed tangential residual stress, Mpa

$E$ Youngs modulus, Mpa

$\upsilon$ Poisson′ s ratio

$\sigma_y$ Yield stress, Mpa

## INTRODUCTION

Residual stresses are self−equilibrated internal stresses remaining in a component after non−uniform plastic deformation. Residual stress system are probably revealed most dramatically in the form of distortion or dimensional change when residually stressed material is removed by machining. Dimensional instability arising from machining of residually stressed components is one of the main consumer complaining regarding manufactured products.

One of the most frequently utilized techniques for characterization of residual stresses in cylindrical bodies of elastically isotropic materials is the Sachs boring out method[1]. However, though it is important to predict the dimensional changes in order to machine cylindrical components to close tolerances, means for determining the dimensional changes due to machining have not been discussed.

Honda et al.[2] investigated the distortion of three holes drilled around a center−welded part of a circular plate utilizing numerical as well as experimental techniques. In their investigation, they demonstrated the interaction of residual stresses with material removal by studying the dimensional changes of three circular holes drilled in a residually stressed region. Fujiwara et al.[3] showed that a circular disk deforms into elliptical shape when it is cut out from the center of a rectangular plate containing biaxial residual stresses. They also investigated residual stress redistribution and dimensional changes of a circular plate containing an axisymmetric residual stress pattern utilizing experimental technique, due to material removal from the outer region of the circular plate using Electrical Discharge Machining.

Given the magnitude and distribution of residual stresses in a hollow cylinder, the purpose of this study was to formulate a procedure for the determination of the dimensional change resulting from removal of a cylindrical layer from the inner surface of a cylinder. The material for the cylinder was assumed to be isotropic. Utilizing ABAQUS Finite Element code[4], the original distribution of residual stresses was induced by simulating the autofrettage process of a cylinder using elastic−perfectly plastic material model and plane stress conditions.

## SOURCE OF ORIGINAL RESIDUAL STRESSES

In order to start with a known pattern of residual stresses, the autofrettage process of a hollow cylinder (inner radius=38 mm, outer radius=60 mm) was simulated to induce the original residual stresses in the cylinder. Finite element simulation for the autofrettage process was conducted utilizing the ABAQUS Finite Element code. Plane stress condition was assumed during the simulation. A 2D finite element model consisting of second order isoparametric 8−node elements was used. The metal plasticity models in ABAQUS use the Mises stress potential with yield flow stress $\sigma_y$=275.8 Mpa. The Young's modulus was assumed to be

E=68950 Mpa. The autofrettage process was simulated by specifying a radial displacement for all nodes at the inner surface of the cylinder. The nodes making the inner surface of the cylinder were displaced outwards in 200 increments making the total radial expansion of the inner wall equal to 5 % of the inner radius of the cylinder. The above loading scheme resulted in permanent expansion on the inner wall by 4.466 % of the inner radius. The inner and outer radii of this new configuration with the residual stresses became $a_o$=39.697 mm and $b_o$=61.874 mm (i.e., $t_o$=21.537 mm). The resulting residual stress distributions in radial and tangential directions are shown in Figures 1 and 2, respectively.

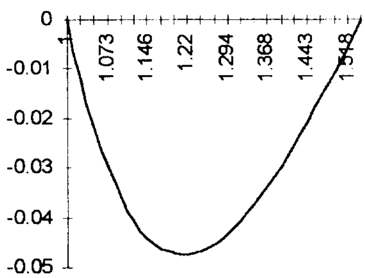


**Fig. 1 Original radial residual stress distribution**

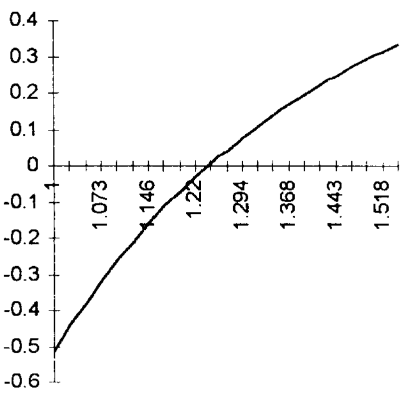


**Fig. 2 Original tangential residual stress distribution**

## DEVELOPMENT OF ANALYSIS OF THE LAYER REMOVAL

In this study it was assumed that the relaxation of the residual stresses is a linearly elastic process, and that the material was removed without creating appreciable residual stresses at the exposed material surface.

As material is removed from the inner surface of the cylinder, the remaining body changes its dimension in order to maintain the equilibrium of forces. Similar to original inner surface, the radial residual stress at the new inner surface would be also equal to zero. Therefore, the layer removal process can be simulated by superposition of an equal but opposite radial stress to the residual radial stress at the radial location where the layer removal operation is to be reached.

Assume that the inner surface of the cylinder is to be machined from a radius of $r=a_o$ to $r=a_1$, where $a_o$ is the original inner radius. The layer removal process can be thought of as superposition of a radial stress, , to the original radial residual stress at $r=a_1$, $\sigma_{ro}|_{r=a_1}$, such that the radial residual stress at the new inner surface is equal to zero. Thus, the radial displacement of the remaining body would be equal to that experienced by a cylinder with inner radius of $a_1$ and outer radius of $b_o$ subjected to an internal pressure $p=\sigma_{ro}|_{r=a_1}$. The radial displacement throughout the remaining material due to the internal pressure, $p=\sigma_{ro}|_{r=a_1}$, is given by [5] ;

$$u_r=\frac{b_o p c^2}{E(1-c^2)}\left[(1-\nu)\left(\frac{r}{b_o}\right)+(1+\nu)\left(\frac{b}{r}\right)\right] \qquad (1)$$

where $p=\sigma_{ro}|_{r=a_1}$, $c=a_1/b_o$ .Therefore, the new inner and outer radii of the cylinder due to layer removal up to $r=a_1$ can be written as;

$$a = a_1 + u_r|_{r=a_1} \quad (2)$$

$$b = b_0 + u_r|_{r=b_1} \quad (3)$$

where $a$ and $b$ are the new inner and outer radii after the layer removal, respectively.

In finite element analysis, material removal can be accomplished by removing the corresponding elements. The stiffness of the elements that are removed will be reduced gradually to about zero and remain inactive.

The new state of residual stresses in the remaining cylinder can be obtained by the superposition of the stresses resulting from the application of internal pressure $p = \sigma_{ro}|_{r=a_1}$ to the original residual stress distribution. The stresses caused by the application of the internal pressure $p = \sigma_{ro}|_{r=a_1}$ to the cylinder are given by [6] ;

$$\sigma_r' = \frac{pc_1^2}{1-c^2}\left[1-\left(\frac{r}{b_o}\right)\right] \quad (4)$$

$$\sigma_\theta' = \frac{pc_1^2}{1-c^2}\left[1+\left(\frac{r}{b_o}\right)\right] \quad (4)$$

where $c_1 = a/b$

Thus, the redistributed residual stresses in the remaining cylinder can be expressed as ;

$$\sigma_r = \sigma_{ro} + \sigma_r' \quad (6)$$

$$\sigma_\theta = \sigma_{ro} + \sigma_\theta' \quad (7)$$

## RESULTS AND DISCUSSION

Let us assume that the original inner radius of the autofrettaged cylinder is to be extended to the value $a_1 = 46.472$ mm. Obviously, due to presence of residual stresses, the actual inner radius of the cylinder after machining will be different than the value of $a_1$. The actual values of inner and outer radii of the cylinder after the layer-removal can be predicted by the developed equations (2) and (3). The redistributed residual stresses through the thickness of the cylinder due to the layer-removal can also be predicted by the equations (6) and (7).

Figures 3 and 4 show the variations of the inner radius and the thickness after corresponding layer removal. It can be clearly seen that the dimensions of the remaining body after the layer removal of residually stressed body will be different from those we can predict in the case of the body without residual stresses. The redistributed residual stresses from analytical solutions and numerical simulations are also shown in Figures 5 and 6.

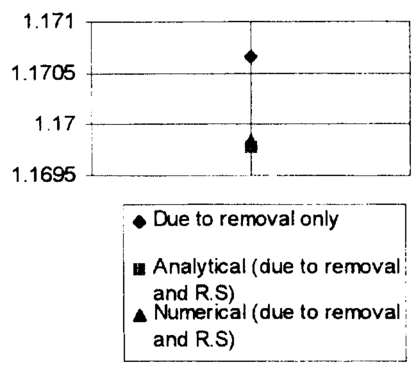


**Figure 3. Inner radius after the removal up to a1**

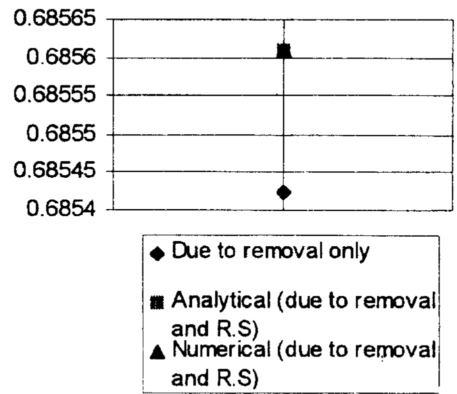


**Figure 4. Thickness after the removal up to a1**

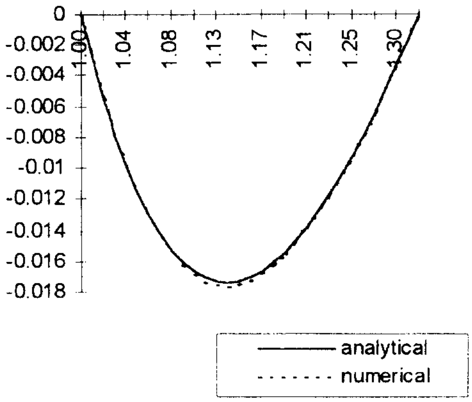


**Fig. 5 Redistributed radial residual stress after the removal up to a1**

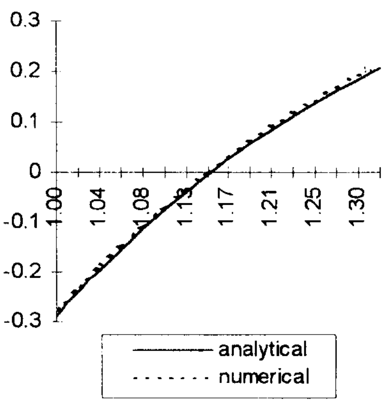


**Fig. 6 Redistributed tangential residual stress after the removal up to a1**

## CONCLUSION

The object of this study has been to develop the methodology of predicting dimensional change and post-machining state of residual stresses due to machining of an elastically isotropic cylindrical components containing axisymmetric, radial and tangential residual stresses.

There have been well agreements between closed-form solutions and finite element results. It is interesting that the dimensional changes and the post-machining state of residual stresses depend only on the initial radial residual stress at the radial point to which the material removal process is to be reached. Although, in this research, the initial state of residual stresses was induced by autofrettage process, it should be noted that the results of this work is applicable to any axisymmetric residual stress state as a result of various metal forming of manufacturing practices. The results of this study are specially useful in cases where original residual stress distribution has been obtained by a nondestructive technique such as neutron diffraction method with no information on the effect of material removal operation on dimensional and residual stress changes in a component.

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