Numerical Analysis and Experimental Research of Autofrettaged Shrink-fitted Three-layer Extrusion Cylinder

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Abstract: Multilayer cylinder is a commonly used structure of ultra-high extrusion cylinder. In order to increase the load carrying capacity and durability of a shrink-fit three-layer extrusion cylinder, the paper proposed the multiple autofrettage process based on analysis of simulation. Firstly, A 3-D finite element contact model of the extrusion cylinder has been constructed in the ANSYS environment; The element used here is 3D SOLID 186, and using a bilinear isotropic hardening model approximating the real material behaviour. Then, we have used the model to simulate processes of fitting, autofrettage and boring of extrusion cylinder by multi-step load and birth and death element techniques, then comes to the residual stresses of different times autofrettaged cylinder. The results show multiple-autofrettage can increase hoop compressive residual stress. The extrusion cylinder was made three times autofrettage processes and boring machining, its actual elastic operating pressure is consistent with finite element analysis results and it's strength is improved significantly.

1 INTRODUCTION

Hydrostatic extrusion technology is a new type of material processing method, and it can extrude the materials, which are difficult to use conventional deformation process to machining, such as hydrostatic extruding tungsten alloy materials, etc, their strong toughness can be greatly improved[1-4]. Hydrostatic extrusion pressure of high strength material as high as 1000 MPa to 1500 MPa, so the design of extrusion cylinder strength is particularly important [2, 3]. If the design is careless, the bore area will cause plastic deformation even burst. For example, in a research institute, the pressure of a three-layer shrink-fit extrusion cylinder(TSEC) was designed to be 1500MPa, according to the theory of maximum tensile stress theory, however, when extrusion pressure had not reached 1500MPa, the bore area of the cylinder appeared plastic deformation, which leading to squeeze rod difficult to move and hard to be sealed, until it didn't work.

Ultra-high pressure extrusion cylinder mostly is adopted multi-layer cylinder structure, and strength design used elastic failure criterion. AA Miraje, SA Patil[5, 6] and Shildip D Urade [7] had researched the residual stress distribution through the cylinder thickness of multi-layer shrink-fit cylinder(MSC) based on the theory of maximum tensile stress theory; Yuan Gexia et al.[8] had researched optimization design of MSC based on the theory of the maximum shear stress theory using analytical method and finite element method. Yuan Gexia and Liu hongzhao[9,10] had researched residual stress of shrink-fitted and autofrettaged double cylinder. Cylinder is usually made of plastic material, and it is in the three direction stress state, so designing strength according to the maximum shear stress theory is more close to actual value.

In this paper, according to the actual tensile compressive stress-strain curve of material, using a bilinear isotropic hardening model approximating the real material behaviour, and applying 3D SOLID 186 element, We have constructed a 3-D finite element contact model for the extrusion cylinder in the ANSYS environment to simulate processes of shrink-fitting, autofrettage and boring of the extrusion cylinder. The simulation results show that Multiple-autofrettage processes can effectively generate favorable compressive residual stresses to increase strength of shrink-fitted cylinder. Then, three times autofrettage process and boring machining to the extrusion cylinder were carried out, and test its strength. The tested results are consistent with the finite element simulation results.

2MODELING OF THE EXTRUSION CYLINDER

2.1 Cylinder Material Model

The stress-strain curve of the material is shown in Figure 1. It clearly demonstrates the Bauschinger-effect. Analysis procedure for autofrettage process involves overstrain which is typically based on Tresca or Von. Mises failure criteria. Here, using a bilinear isotropic hardening model approximating the real material behaviour is shown in Figure 1; has been used in which E1 is the slope of the linear line in the tensile elastic region (modulus of elasticity), H1 is the slope of the linear line in the tensile plastic region, E2 is the slope of the linear line in the compression elastic region (modulus of elasticity), and H2 is the slope of the linear line in the compression plastic region. This material's constants are as follows: E1=206GPa; H1=2GPa; E2=207GPa; H2=57GPa; □□□□□□□□□σy1 =1103 MPa, σy2 =1100 MPa, where, v, σy1, and σy2 are the Poisson's ratio , tensile yield stress, compression yield stress, respectively.

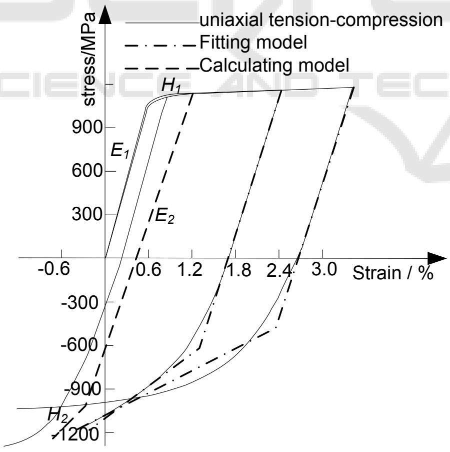


Figure 1: Material strain-stress curve.

2.2 Finite Element Model

The finite element model of TSEC has been constructed in ANSYS APDL 15.0. The geometric model is 1/4 of circumference of the cylinder, and the element used here is 3D SOLID 186, and mapped mesh method be used for easy simulation of boring bore.

The cylinder body is mainly subjected to radial force. During shrinking and autofrettage, the contact surfaces are all one-way contact behaviors between the surfaces, and the material of the three-layer cylinder is also the same, so the contact can be regarded as the "surface to surface" contact model of the "Flexible-Flexible". The target surface is the inner surface of the middle layer and the outer layer; The element type used is Target170. The contact surface is the outer surface and middle surface, the element type is Contact174. The geometric dimensions of every cylinders was the actual dimensions, including the initial mutual penetration, and penetration tolerance was 0.0001 mm, and the contact algorithm was chosen to be the Augmented Lagrangian Method.

2.3 Boundary Conditions

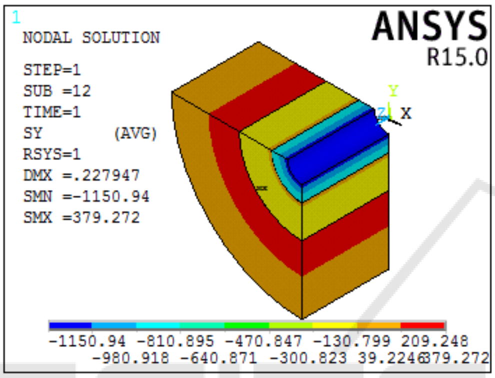
Analytical model was the 1/4 of the extrusion cylinder, so it is necessary to apply symmetry B. C. on the corresponding surface. For easy solution, assuming that the extrusion cylinder was in the plane strain state, then axial displacement constraints has been applied the both ends of cylinder.

3 SIMULATION AND RESULT ANALYSIS

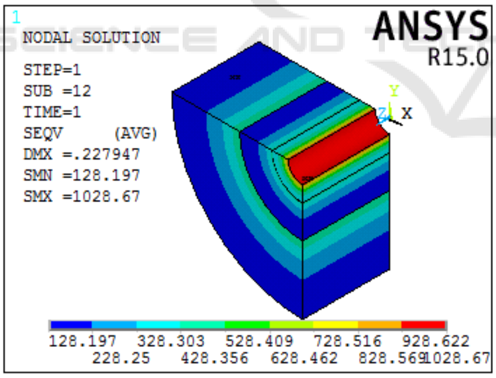
In the ANSYS environment, a number of simulations have been performed on the shrink-fit, autofrettage, boring and loading processes of cylinder to calculate the residual stress distribution in the shrink-fitted and multiple autofrettaged compound cylinder and the maximum elastic pressure capacity. Here the autofrettage pressure was 1800 MPa (pressurized system up to maximum pressure).

First, having simulated the shrink-fit process of the three-layer cylinder, residual hoop stress(RHS) is shown in Figure 2(a). It reveals that the inner layer is subjected to compressive stress with a large value,and stress at the inner bore area (working area) is 1150.94MPa, and the inner part of middle cylinder is subjected to tension, and the outer part is subjected to compression, and the stress value is small, and the outer layer is subjected tension. Mises stress is shown in Figure 2(b), and the maximum stress is 1028.67MPa, and it is lower than compressive yield limit of material, on this condition, the entire cylinder is in elastic state.

After the autofrettage process, the RHS of the cylinder is shown in Figure 3(a), compared with the stress after the shrink-fit, the residual compressive stress of the inner cylinder is significantly increased, and at the inner bore area is as high as 1638.07MPa. The Mises stress is shown in Figure 3(b), and the inner wall is up to 1409.59MPa, the inner part of the inner cylinder has undergone reverse yield. after the boring, the RHS of the cylinder wall is shown in Figure 4, compared with the stress after once autofrettage, the residual compressive stress is reduced and it is reduced to 1594.32MPa. After calculation [11], the elastic pressure of the cylinder is 1553MPa.

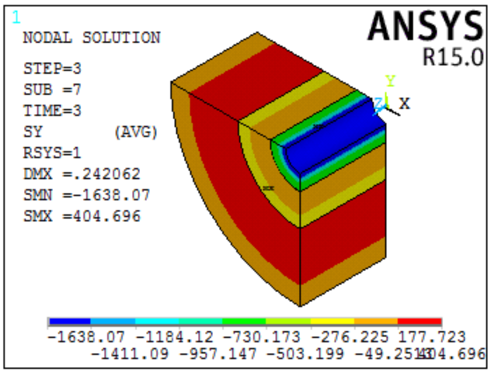


（a）Hoop stress

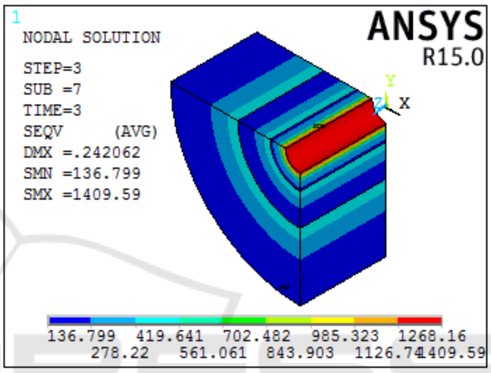


（b）Mises stress

Figure 2: Residual stress of the shrink-fitted cylinder.



（a）Hoop stress



（b）Mises stress

Figure 3: Residual stress of once autofrettaged cylinder.

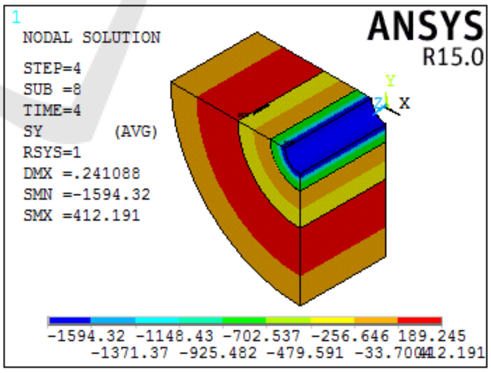


Figure 4: Residual hoop stress of once autofrettaged and boring cylinder.

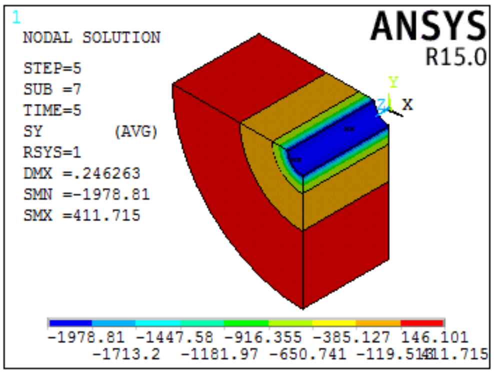


Figure 5: Residual hoop stress of double autofrettaged cylinder .

In order to further enhance pressure capacity of the cylinder, we investigated double and triple autofrettage processes for the cylinder. The HRS of double autofrettaged cylinder is shown in Figure 5, compared with the stress of once autofrettaged cylinder, the residual compressive stress of the bore area increases significantly, with an increase of 340.74MPa. After the secondary autofrettage simulation, the boring machining has been simulated , the hoop compressive stress is 1870.75MPa , with an increase of 276MPa, as shown in Figure 6.

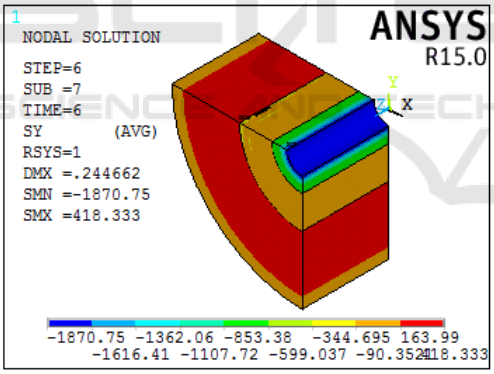


Figure 6: Residual stress of double autofrettaged and boring cylinder.

The elastic pressure capacity(EPC) of the different times autofrettaged cylinder is shown in Table 1. EPC of the two times autofrettaged and hole boring cylinder is 1710 MPa, EPC of three times autofrettaged and hole boring cylinder is up to1853 MPa. Since the strength is calculated by the linear elasticity, the calculated value is slightly lower than the actual value. It can be seen from Table 1 that as the number of autofrettage increases, the cylinder strength increases, but increment is reduced.

Table 1: The RHS and EPC of different times autofrettaged cylinder.

process	RHS /MPa	EPC /MPa
Shrink-fit	1150	1300
Once autofrettage	1638	1578
Once autofrettage and boring	1594	1553
Double autofrettage and boring	1870	1710
Triple autofrettage and boring	2120	1853

4 EXPERIMENTAL VERIFICATION

The shrink fit process had been accomplished. The cylinder was triple autofrettaged under pressure 1800MPa; Finally the inner hole was bored by 2mm. when the operating pressure is 1800MPa, after the pressure is released, the internal wall of the cylinder can be fully recovered. It means that extrusion cylinder elastic operating pressure can be up to 1800MPa, compared with the simulation value, and the error is about 3%; Taking all differences of every simulation value , the maximum error is about 5%, which proves that the method and model in the paper is correct.

5 CONCLUSIONS

Performing the autofrettage process to the shrink-fit cylinder can increase hoop compressive residual stress.

Multiple-autofrettage can further increase hoop compressive residual stress, but as the number of autofrettage increases, its increment is reduced.

Using the finite element model in the ANSYS environment may better predict the residual stresses of shrink-fit and autofrettage compound cylinder.

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