A study on a bolt fastening structure of a plastic valve body for CVTs

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Summary

It is becoming increasingly important to reduce the weight of automotive parts in order to improve the energy efficiency of vehicles. Lighter weight is also required for the control valve that serves as the mechanism for supplying hydraulic pressure in continuously variable transmissions (CVTs). One weight reduction approach is to apply plastic materials. The control valve body is fastened with bolts, and it is necessary to prevent fluid leakage while suppressing bore deformation. However, because plastic has low stiffness, the design method used for aluminum materials cannot be applied to a plastic control valve body. This article presents a study in which a simple finite element method model was used to confirm the influence of certain variables on bolt tightening force. It was verified experimentally that a plastic control valve body can satisfy the required hydraulic pressure performance while suppressing deformation.

1. Introduction

The automotive industry is facing strict environmental regulations in every country around the world, and vehicle exhaust emission and fuel economy standards are continually being tightened. In order to cope with this situation, technologies for reducing the vehicle weight are becoming increasingly important. Studies are being conducted on ways of reducing the weight of the components of the automatic transmission that is a key vehicle part.

The control valve, one of the internal parts of an automatic transmission, optimally controls the pressure and flow rate of the hydraulic flow produced by the oil pump for supply to the working elements. It has been increasingly desired to reduce the weight of the control valve because it accounts for approximately 10% of the total weight of the internal parts, excluding the housing. Except for the high-pressure hydraulic circuit and the bore hole into which the valve is inserted, research is already underway to change the material of the valve body, which secures electric and other components, from aluminum to plastic.

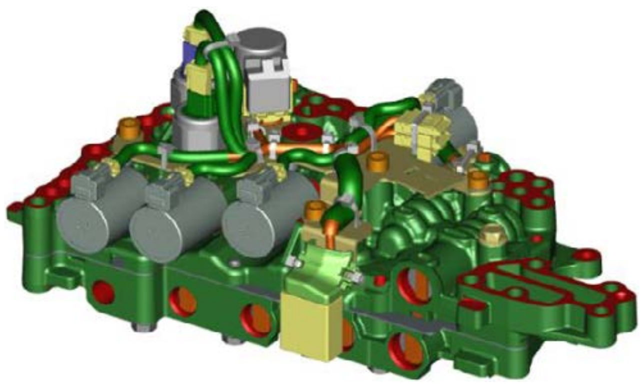

Fig. 1 Structure of control valve

In order to manufacture the bore of plastic, it is necessary to satisfy the performance required of the transmission fluid while suppressing any deformation from external forces such as the bolt tightening force. Because plastic has less stiffness than aluminum, it is difficult to use the same design method as that applied to the aluminum valve body geometry.

In this study, a method was extensively examined for simulating and predicting deformation of a plastic control valve body induced by the bolt fastening structure. A prototype control valve body was manufactured and tested to verify that it satisfied the required hydraulic performance.

2. Structure of control valve body and issues involved in applying plastic

The configuration of the control valve is shown in Fig. 1, and the functions of its component parts are explained below.

1) Valve body: It consists of passages that supply hydraulic pressure and the bore that regulates the pressure together with the spool valve. It serves as the body for assembling the valve parts.
2) Spool valve: It moves reciprocally under the input hydraulic pressure and spring force to regulate the

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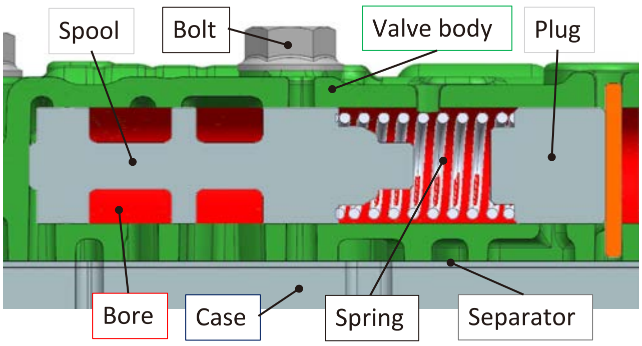

Fig. 2 Structure of spool valve

pressure according to the opening/closing of the passages.

3) Separator plate: It connects the fluid passages between multiple valve bodies and also provides a sealing function between parts to prevent fluid leakage.

4) Electric components (solenoids, sensors, distribution board, etc.): These parts actuate the control valve using electric signals and detect the operating conditions.

5) Bolts and nuts: They fasten together the component parts of the control valve and fasten the control valve to the case.

The parts to be made of plastic in this study included the valve body and spool valve, as shown in Fig. 2. The functions that would be influenced are described below.

1) Hydraulic pressure control and distribution: The reciprocal motion of the spool valve in the axial direction generates and distributes hydraulic pressure passing through the opening and closing of the entry/exit ports of the passages and supplies transmission fluid to parts requiring it.

2) Assurance of flow rate: The sealing force between parts must be maintained to prevent fluid leakage.

2.1 Vulnerability and issues of a plastic control valve

In general, plastic has only 6% of the stiffness of aluminum, so it is susceptible to deformation caused by input loads. Accordingly, the following two concerns must be carefully considered when designing a plastic control valve.

1) Excessive valve body deformation induced by bolt tightening force: The tightening force of the bolts used to fasten the control valve can induce deformation in the valve body when the bolts are tightened. The bore with its hollow structure especially undergoes relatively large deformation. Excessive bore deformation makes it impossible to ensure the necessary minimum space for the sliding of the spool valve. That inhibits movement of the spool valve, which can cause pressure adjustment failure or abnormal pressure distribution.

2) Insufficient sealing performance due to inadequate bolt tightening force: Bolts not only serve to fasten valve parts, they also have the function of ensuring sealability between parts by using the surface pressure produced between them at the time of tightening. Insufficient bolt tightening force can result in large gaps between the valve body and the case and the separator plate. Transmission fluid can leak through such gaps, causing the required flow rate to parts to be insufficient.

Abnormal hydraulic pressure and insufficient flow rate are serious problems that can affect the entire functionality of an automatic transmission, so it is essential to ascertain the relationship between the bolt fastening structure and tightening force.

3. Simulation study of valve body deformation

3.1 Range of influence of axial force

The axial force produced by bolt tightening torque is one cause of valve body deformation. The range of influence of bolt axial force on valve body deformation can be calculated with a method for determining the spring constant between the fastening bolt and the fastened valve body. With Shigley's method, the spring constant of the fastened body can be calculated with Eq. (1) in the manner illustrated in Fig. 3. This calculation is based on the range of influence of axial force on the stiffness of the fastened body at the time of fastening.

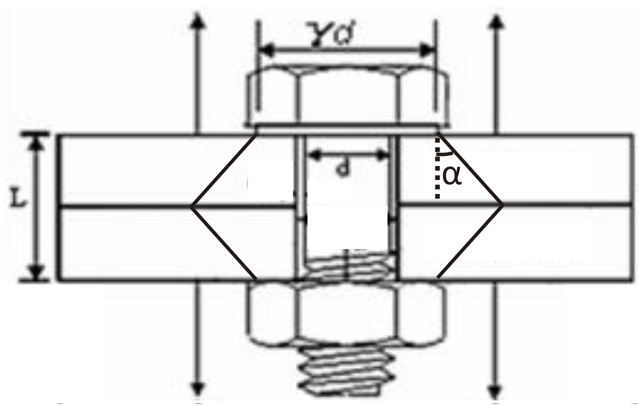

Fig. 3 Shigley's method for tightening structure

$$k_f = \frac{\pi d E \tan(\alpha)}{2\ln\left(\frac{(L\tan(\alpha)+\gamma d-d)(\gamma d+d)}{(L\tan(\alpha)+\gamma d+d)(\gamma d-d)}\right)} \qquad (1)$$

where k_f in the equation is the spring constant of the fastened body, γd is the diameter of the bolt seating surface, d is the diameter of the bolt shank, L is the valve body

Table 1 Condition of simulation model

Part	Material	Mesh
Body	Plastic/Aluminum	3D/Tet
Separator	Steel	3D/Tet
Case	Aluminum	3D/Tet
Bolt/Nut	Steel	1D

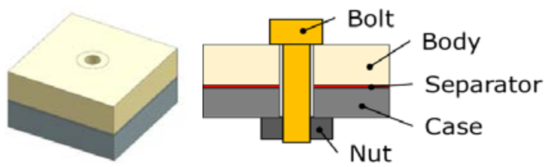

Fig. 4 Simple model for simulating tightening

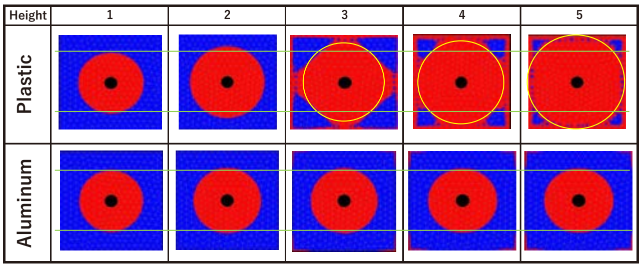

Fig. 5 Comparison of surface pressure of simple models

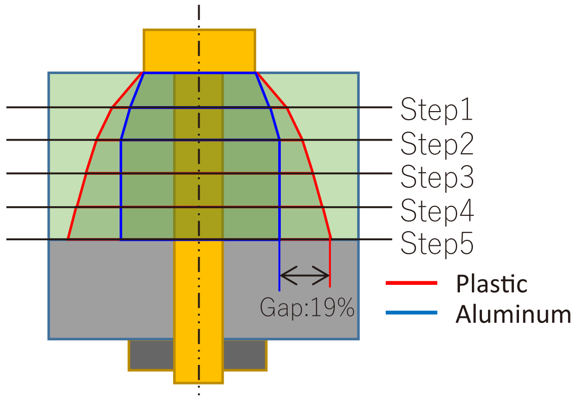

Fig. 6 Surface pressure range for different materials

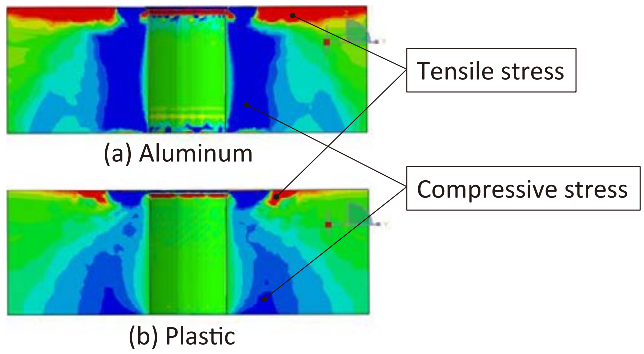

Fig. 7 Comparison of stress distribution

thickness and α is the range of influence on the stiffness of the fastened body at the time of fastening. E is Young's modulus.

In general, it is assumed that 30° represents the value of the spring constant α of the fastened body. However, if the fastened body is thick and has a complicated shape, it is difficult to apply the formula above to the calculation.

3.2 Simulation of range of influence of axial force using a simple model

A parametric simulation was conducted to ascertain the relationship between the bolt fastening structure and valve body deformation. First, a comparison was made of the range of influence of axial force for different valve body materials. That was done using a simple rectangular model consisting of the body, separator plate and the case, as shown in Fig. 4.

In order to investigate the surface pressure distribution corresponding to the body thickness, five levels of thickness were defined for a regular hexahedron model having an ample area. The shapes of the other parts were defined in the same way. A simulation was performed for plastic and aluminum valve bodies having five levels of height. Table 1 lists the materials and meshes of the simulation model.

As shown in Fig. 5, the simulation results confirmed that the area influenced by the bolt tightening force became increasingly larger as the body thickness increased.
Figure 6 presents a cross-sectional view of the simulation results for the surface pressure distribution of the model having varied heights. It is seen that above a certain body thickness the surface pressure region expanded in the shape of a second-order curve, which differed from the linear distribution indicated by Shigley's method. For the thickest model, the surface pressure area of the plastic material was 19% larger than that of the aluminum material.

It will be noted that the stress distribution of both materials also displayed a second-order curve as shown in Fig. 7. Although the stress values generated in the two different materials differed, it was confirmed that the compressive stress distribution of the plastic material increased over a wider area than that of the aluminum material.

Surface pressure is a parameter showing the contact pressure produced by the compressive deformation of two fastened members. The above-mentioned range of influence can be seen as the deformation distribution of

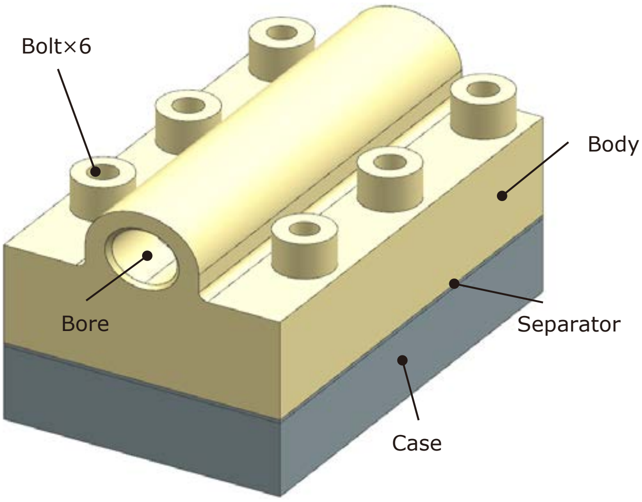

Fig. 8 Simulation model with shape of bore

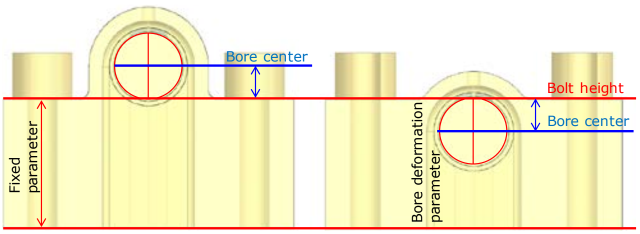

Fig. 9 Bore deformation parameter

the fastened valve body induced by the bolt axial force. By comparing the results for the surface pressure and the stress distribution, it is possible to predict the range of influence of the bolt tightening force on valve body deformation. Deformation of the bore can influence the movement of the spool valve. Defining the position of the bore away from this range of influence is one way of reducing the amount of bore deformation.

3.3 Simulation of range of influence of axial force using a bore model

A parametric simulation was conducted to ascertain the bolt fastening structure for creating the necessary surface pressure between parts while suppressing bore deformation. That was done by using a simple bore model to predict the range of influence of axial force on bore deformation when the bolts were tightened.

1) Simulation model and methodology

As shown in Fig. 8, the simulation model replicated the valve body by taking into account a single hollow bore and the bolt fastening structure. The number of bolts, the body length and the distance between bolts were defined using

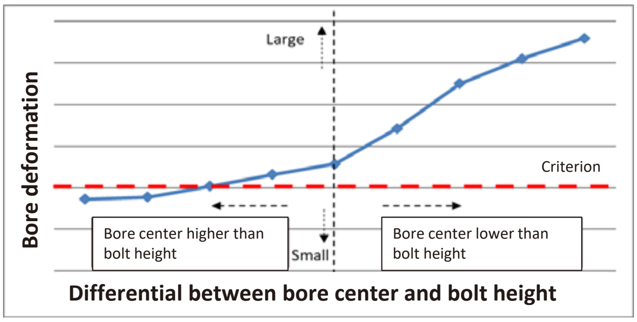

Fig. 10 Simulation results for bore deformation

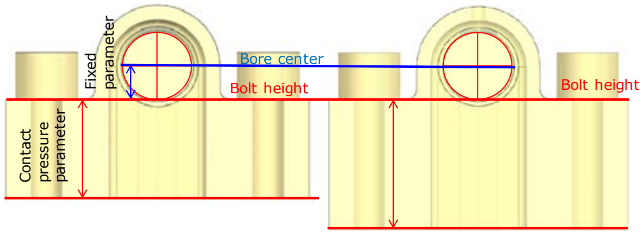

Fig. 11 Contact pressure parameter

simulation results obtained with the simple model and considering the influence of fastening on sealability.

Plastic material was specified only for the valve body containing the bore, and other parts were defined in the same way as in the simple model.

The amount of bore deformation and the contact pressure produced between two fastened members were confirmed while varying two parameters of the simulation model as indicated in Figs. 9 and 11.

Bore deformation parameter: The amount of bore deformation was confirmed by varying the relationship between the bore center position and the bolt height for a fixed body thickness (Fig. 9).

The simulation results for the bore deformation parameter are presented in Fig. 10. It is seen that bore deformation increased sharply when the bolt height was higher than the bore center position and that it was reduced when the bolt height was lower than the bore center.

Contact pressure parameter: The radius of the contact pressure range relative to changes in the valve body thickness was confirmed for a fixed relationship between the bore center position and the bolt boss height (Fig. 11).

The simulation results for the contact pressure parameter are presented in Fig. 12. It is seen that the range of effective contact pressure increased with a thicker valve body.

The sensitivity graphs in Figs. 10 and 12 confirmed the sensitivity of bore deformation and the radius of the effective contact pressure range. That made it possible to determine a bolt fastening structure for satisfying both of these required characteristics.

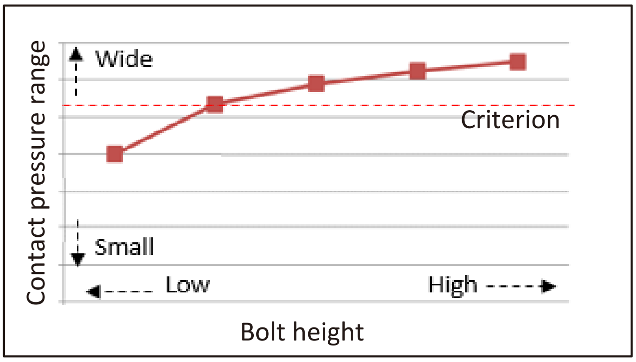

Fig. 12 Simulation results for contact pressure range

4. Experimental validation

The simulation results revealed that bore deformation decreased with a higher bore center position and that the range of effective contact pressure widened with a thicker valve body. However, the weight also increased, so a simulation model for comparison with experimental data was created using specifications from among the results that satisfied both criteria and reduced the weight the most. This model was used to simulate bore deformation for making a comparison with the experimental results.

4.1 Comparison of simulation and experimental results for bore deformation

Using a plastic valve body having the same geometry, bore deformation was measured for various levels of bolt tightening torque. The experimental and simulation results are compared in Fig. 13. Although the simulated bore deformation differed from the experimental results by 61.7% and 63.4% under low and high tightening torque conditions respectively, the results confirmed that both sets of data show the same tendencies.

4.2 Validation of plastic control valve hydraulic pressure performance

An experiment was conducted with the same model to validate the hydraulic pressure performance. As the first step, the indicated current and hydraulic pressure were

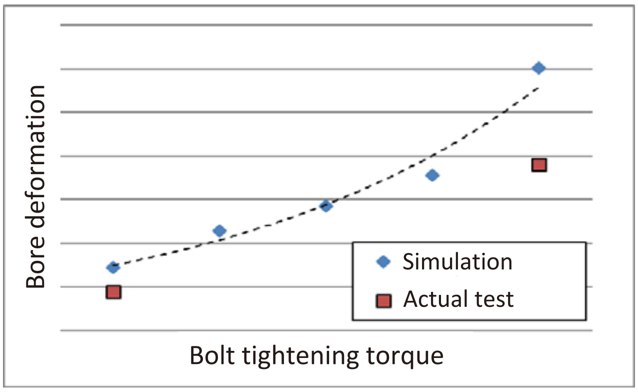

Fig. 13 Comparison between simulation and experiment

measured in relation to time. As confirmed by the results in Fig. 14, the hydraulic pressure reached the necessary level within the target time following the issuance of the current command.

Hydraulic hysteresis was also measured under the application of a pressure change at a certain level. The results in Fig. 15 confirm that the pressure fluctuation was below the target level.

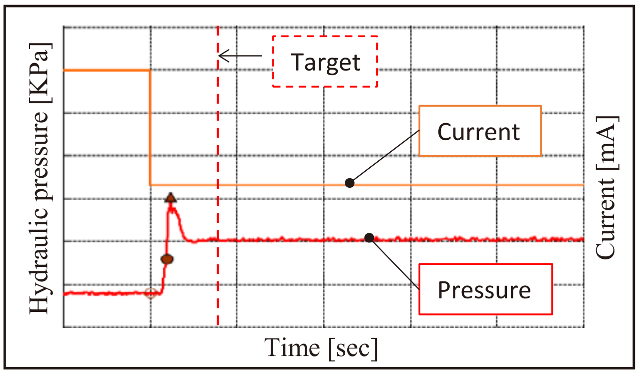

Fig. 14 Hydraulic response

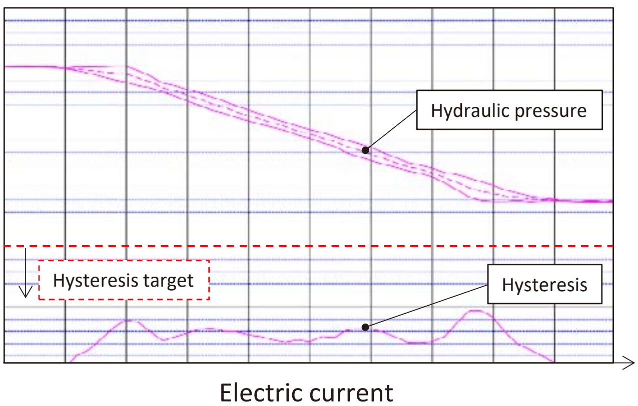

Fig. 15 Hydraulic sweep characteristic

5. Conclusion

This study analyzed the bolt fastening structure in conjunction with the application of plastic to the control valve body. The following conclusions were drawn from the results.

1) It was confirmed that the transmission range of bolt axial force varied with the material of the fastened valve body and that it can be predicted by simulation.
2) It was found that bore deformation of a plastic valve body can be predicted, confirming that even the sliding part of the spool valve can be made of plastic, in addition to component parts that are simply fastened.
3) Based on parametric simulations of a plastic valve body, a bolt fastening structure was proposed that satisfies the criteria for bore deformation suppression and hydraulic pressure performance.

6. References

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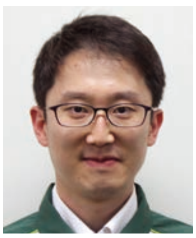
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