

When the control pressure (P_c) supplied by the servo valve increases relative to the source pressure (P_s), the servo piston (cylinder) reduces the swashplate inclination angle. Conversely, when the control pressure decreases relative to the source pressure, the swashplate inclination angle increases.[5,6]

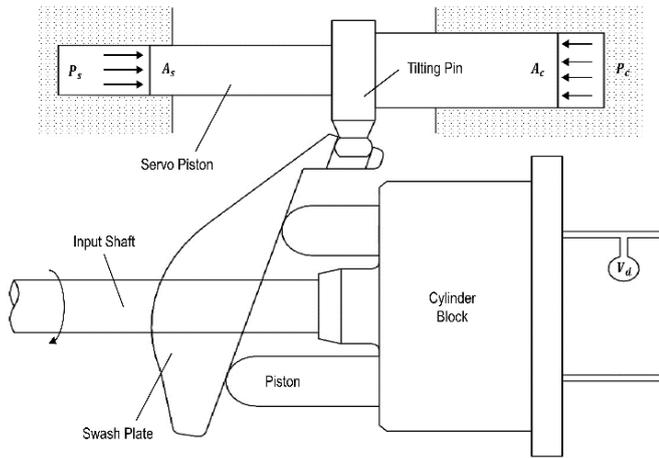


Fig. 2 Structure of the Regulator.

3D Design of the Tilting Pin

Fig. 3 represents the modeled shape of the tilting pin proposed by M Corporation, created using Autodesk Inventor software. The tilting pin consists of three main parts: the cantilever, the servo piston coupling section, and the head. The tilting pin is made of SACM 645 material, with the head undergoing gas carburizing and nitriding treatment. The chemical composition and mechanical properties of SACM 645 are presented in Tables 1 and 2.[7]

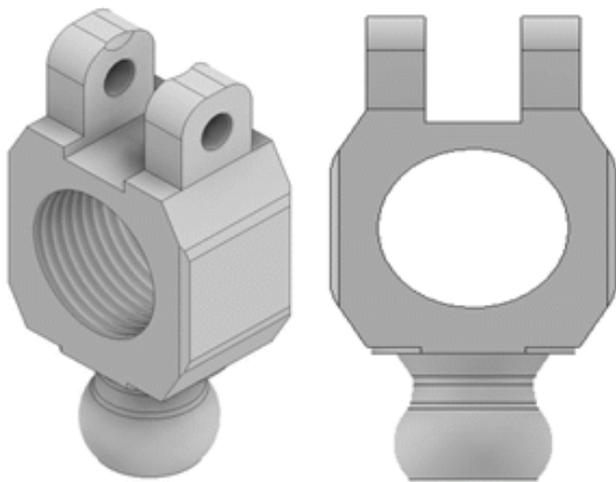


Fig. 3 3D Design of the Tilting Pin.

Table. 2 Comparison of Mechanical Properties: SACM 645 vs Nitrided SACM 645.

| Mechanical Property | Base-Metal | Nitriding |
|----------------------|------------|-----------|
| σ_y (MPa) | 923.50 | 889.69 |
| σ_{uts} (MPa) | 1094.67 | 943.69 |
| σ_b (MPa) | 818.08 | 853.52 |
| E(GPa) | 224.48 | 224.22 |
| Elongation(%) | 17.05 | 7.99 |
| H_v | 318.6 | 971.0 |

Principle and Conditions of FEA

Finite Element Analysis (FEA) is a computational method that divides a mechanical structure into small elements, analyzing them collectively as a single structure. This technique utilizes computer simulations to predict and evaluate the responses of an object to applied loads, vibrations, and thermal effects. The FEA process consists of three main stages: preprocessing, analysis, and visualization. During the preprocessing stage, material properties, boundary conditions, and loads are defined before performing the analysis to obtain results. In this study, SACM 645 and gas-carburized and nitrided SACM 645 were selected as the materials. The applied load is based on the rated pressure of the hydraulic pump in which the tilting pin is used, set at 32.9 MPa.

RESULTS AND DISCUSSION

Axial Load on the Cantilever

To minimize stress concentration and enhance the stability of the tilting pin under axial load on the cantilever, modifications were made by expanding the stress concentration area and incorporating an arch-shaped support structure. Fig. 4(a) visualizes the stress distribution of the original tilting pin, where a peak stress concentration of 348.5 MPa is observed. In Fig. 4(b), the angle between the cantilever and the lateral section was reduced from 120° to 105°, effectively expanding the surface area. This design modification, which results in a 1.56% increase in weight, successfully reduces the stress concentration by approximately 2% compared to the original model. Fig. 4(c) presents the stress distribution after introducing an arch-shaped support between the two cantilever sections. This design, which adds only 0.7% to the weight, leads to a 3% reduction in stress concentration. Finally, Fig. 4(d) illustrates a comprehensive approach, combining both lateral angle reduction and support structure addition to further induce stress redistribution. This optimized design achieves a 6% reduction in stress concentration with only a 2.26% increase in weight. The stress concentration values corresponding to each structural modification are summarized in Table 3.

Table. 1 Chemical Composition of SACM 645.

| Element | C | Si | Mn | P | S | Cr | Mo | Al |
|---------|------|------|-------|-------|-------|------|------|------|
| (%) | 0.40 | 0.15 | ≤0.60 | ≤0.03 | ≤0.03 | 1.30 | 0.15 | 0.70 |
| | ~ | ~ | | | | ~ | ~ | ~ |
| | 0.50 | 0.50 | | | | 1.70 | 0.30 | 1.20 |

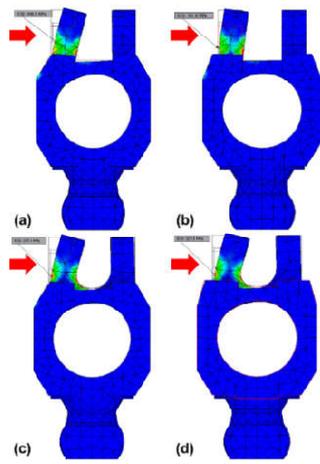


Fig. 4 Structural Modifications of the Tilting Pin Under Axial Load on the Cantilever.

(a) Basic, (b) Expansion Area, (c) Add Support, (d) Synthesis.

Table. 3 Weight-to-Stress Reduction Effect Under Axial Load on the Cantilever.

| | Additional Weight (%) | Maximum Concentration Stress (MPa) | Reduction Stress (%) |
|--------------------|-----------------------|------------------------------------|----------------------|
| (a) Basic | 0 | 348.5 | 0 |
| (b) Expansion Area | 1.56 | 341.8 | 1.92 |
| (c) Add Support | 0.7 | 337.1 | 3.27 |
| (d) Synthesis | 2.26 | 327.5 | 6.03 |

Lateral Load on the Cantilever

To mitigate stress under lateral load on the cantilever, a fillet was applied to the edge between the main body and the cantilever. Fig. 5(a) illustrates the application of lateral load on the original model, while Fig. 5(b) presents the results after applying a 5mm fillet. This modification, which adds only 0.3% to the weight, effectively reduces stress concentration by 38.3%. The changes in stress concentration values due to structural modifications are summarized in Table 4.

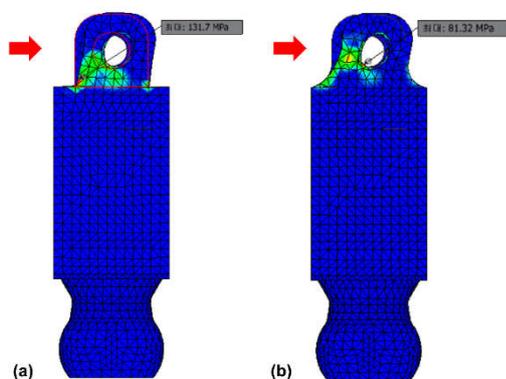


Fig. 5 Structural Modifications of the Tilting Pin Under Lateral Load on the Cantilever.

(a) Basic, (b) Fillet

Table. 4 Weight-to-Stress Reduction Effect Under Lateral Load on the Cantilever.

| | Additional Weight (%) | Maximum Concentration Stress (MPa) | Reduction Stress (%) |
|------------|-----------------------|------------------------------------|----------------------|
| (a) Basic | 0 | 131.7 | 0 |
| (b) Fillet | 0.01 | 81.32 | 38.3 |

Lateral Load on the Head

To reduce stress concentration in the Neck section of the head, the Neck was thickened in the redesigned model. Fig. 6(a) illustrates the stress distribution in the original model, where a maximum stress of 2207 MPa is observed. Fig. 6(b) visualizes the stress distribution after increasing the Neck curvature radius from 2mm to 4mm, effectively thickening the structure. The curvature modification is further detailed in the sketches presented in Fig. 7(a) and Fig. 7(b). As a result of this design change, the maximum stress was reduced to 1897 MPa, representing an approximate 14% decrease compared to the original model. The variations in weight and stress due to structural modifications are summarized in Table 5.

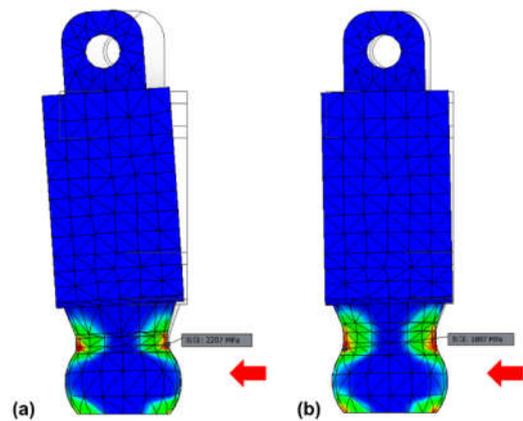


Fig. 6 Stress Concentration Under Lateral Load on the Head.

(a) Basic, (b) Increasing Thickness

Table. 5 Weight-to-Stress Reduction Effect Under Lateral Load on the Head

| | Additional Weight (%) | Maximum Concentration Stress (MPa) | Reduction Stress (%) |
|--------------------------|-----------------------|------------------------------------|----------------------|
| (a) Basic | 0 | 2207 | 0 |
| (b) Increasing Thickness | 1.1 | 1897 | 14 |

CONCLUSION

This study investigated the structural optimization of a tilting pin used in hydraulic pump regulators to enhance durability and reduce stress concentration. Finite Element Analysis (FEA) was conducted to evaluate stress concentration under axial and lateral loads on the cantilever as well as lateral load on the head. Key structural modifications were introduced to mitigate stress concentration. Reducing the cantilever side angle from 120° to 105° increased the stress distribution area, resulting in a 2% reduction in stress with a 1.56% weight increase. Adding an arch-shaped support reduced

stress by 3% with a 0.7% weight increase. Combined modifications led to a 6% reduction in stress with a 2.26% weight increase. Under lateral load on the cantilever, applying a 5 mm fillet at the cantilever-body intersection reduced stress concentration by 38.3% with only a 0.3% increase in weight. Increasing the neck thickness from 2 mm to 4 mm reduced maximum stress from 2207 MPa to 1897 MPa, representing a 14% reduction. Furthermore, reinforcing the head under lateral load resulted in additional stress reduction and enhanced structural stability. These targeted structural improvements effectively enhanced the fatigue resistance and durability of the tilting pin while maintaining minimal weight gain. The findings provide a systematic approach to improving the performance and reliability of hydraulic pump regulators. This study demonstrates that strategic design modifications can significantly enhance structural integrity and extend the service life of hydraulic components.

Acknowledgements

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