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ABSTRACT

Improvement of the energy efficiency of home appliances has been a very important topic in industry and academia for the past few decades due to global warming and the limitation of energy resources. Household refrigerators are considered as one of the necessities of human life in our current century, and hermetic compressors have the most important role in their energy efficiency. Although a ball joint piston has more economical advantages, most reciprocating compressors with high performance adopt pin joint pistons because a ball joint mechanism has a large friction loss in areas where the ball and socket contact during the early operation stage.

In this paper, the friction loss in a ball joint mechanism is analyzed experimentally, and the aging mechanism in a ball joint piston is investigated. A low friction ball joint piston with higher reliability was developed. Experimental results showed that the compressor performance with a new ball joint piston was improved and that the compressor durability was also enhanced. It suggests that a new ball joint piston be used in high performance reciprocating compressors.

1. INTRODUCTION

A ball and socket joint mechanism is mainly used in part connections which require 3 rotational degrees of freedom. Compared with a universal joint mechanism, it needs smaller installation space and lower manufacturing costs so that it has many applications in engineering field. Typical application examples are the joint in parallel mechanisms with 6-dof, in supporting struts of auto vehicles and in pistons used in small hermetic compressors.

A ball joint piston is shown in Fig. 2.1 which consists of a piston body, a steel ball and a PTFE (polymerpolytetrafluoroethylene) buffer ring manufactured by the powder molding process. The PTFE buffer ring is placed between the steel ball and the constraining wall. The ball is pre-stressed between the required minimum and maximum stress levels in order to obtain the long term reliability. Though non-conformal contact between the ball and socket reduces the friction loss, it still is a drawback of ball a joint mechanism. The required performance levels of hermetic compressors are going up to satisfy energy efficiency regulation of household refrigerators. As a result of that, most high performance compressors adopt pin joint type pistons in spite of their high manufacturing costs.

An aging period is needed until friction torque in a ball joint piston has become stabilized after manufacturing. There is a performance difference between new compressors and aged compressors. The difference is about 3 ~ 7% of COP, which is a major drawback of a compressor using a ball joint type piston. A few days are needed to have the ball joint stabilized. Once it is stabilized, the friction loss in a ball joint type piston maintains constant and becomes comparable to the pin joint friction loss.

Many engineers are mainly interested in the lubrication characteristics of the contacting area of a steel ball and a socket. Their investigations are based on the theoretical analysis using FEA. [2, 3, 4] But it is not easy to get the reliable friction data from those investigations because their main concerns are the lubrication characteristics. From the many experiments with ball joint pistons, it is known that there are metal contacts in the ball joint mechanism under the normal operating condition.

In this study, we analyzed the friction loss in a pre-loaded ball joint piston and measured the friction loss change before and after the aging. We developed a new ball joint piston of which aging period is within few hours, and we investigated the wear progress of the ball and the socket with the durability test.

2. THEOREOTICAL ANALYSIS

2.1 Analysis of a Ball Joint Piston

Fig. 2.1 shows the forces and moments on the connecting rod which connects the rotating crank shaft and the reciprocating piston. The forces and the moments can be expressed as shown in equations (2.1) and (2.2).

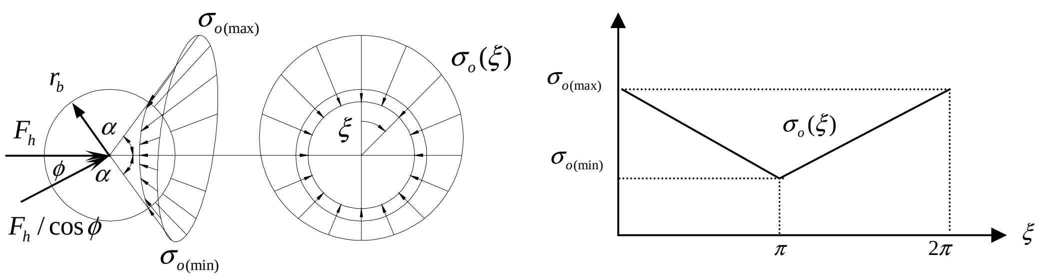
$$\overline{F}_o + \overline{F}_r = m_c \overline{a}_c \tag{2.1}$$

$$\overline{r}_o \times \overline{F}_o + \overline{r}_r \times \overline{F}_r + \overline{T}_o + \overline{T}_r = I_c \overline{\alpha}_c \tag{2.2}$$

(a) A 3-D cad image of a ball joint piston (b) FBD of a connecting rod

Figure 2.1 A ball joint type piston

During the compression process, the steel ball experiences compression stress at the contacting area between the ball and the socket. The stress around the ball surface, σ_o, varies according to the angle, ξ, and it is assumed that the stress varies linearly between the maximum ($\sigma_{o(\max)}$) and minimum ($\sigma_{o(\min)}$)values for simplicity, which are shown in Fig. 2.2.



(a) Stress distribution on the steel ball surface (b) Stress variation

Figure 2.2 Stress distribution on the ball surface

With the linearity assumption, $\sigma_o(\xi)$ can be expressed as shown in Equation (2.3).

$$\sigma_o(\xi) = \frac{F_h(\phi)}{4 \cdot b \cdot r_b \cdot \sin\alpha} \left(\frac{2}{\pi \cos\alpha} + \frac{\pi \tan(\phi)}{2 \sin\alpha} - \frac{\tan(\phi)}{\sin\alpha} \xi \right) \tag{2.3}$$

Friction loss, W_{b-loss}, in ball joint can be calculated using the friction coefficient, k_p, and $\sigma_o(\xi)$. Equation (2.4) shows the friction loss.

$$W_{b-loss} = C_1 \int_0^{\pi} \sqrt{(\cos^2 \alpha + \sin^2 \alpha \cos^2 \xi)}\, \sigma_o(\xi) d\xi \tag{2.4}$$

where $C_1 = \left| 2 \cdot r_b^{\ 2} \cdot b \cdot \omega_b \cdot \sin\alpha \cdot k_p \right|$ and b is the width of contacting band.

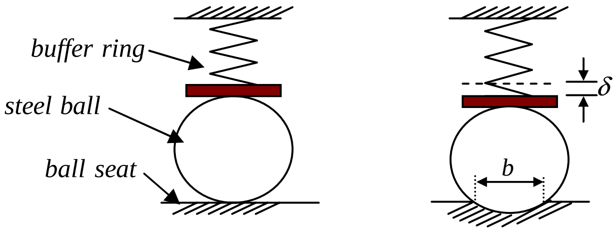
In the case of the friction loss, W_{t-loss}, between the PTFE buffer ring and the steel ball, a similar approach can be used. The total friction loss in the ball joint can be expressed in Equation (2.5).

$$W_{total} = W_{b-loss} + W_{t-loss} + W_{pre} \tag{2.5}$$

where W_{pre} is the friction loss due to the pre-loading.

2.2 Aging Process of a Ball Joint

There is a line contact theoretically between the steel ball and the socket. The buffer ring behaves like a compression spring so that the ball and the socket are pre-loaded. The stress due to the pre-loading can be very high because of the non-conformal contact. The surface conditions are not perfectly smooth. Therefore, the wear at the contact area with high stress is unavoidable. Fig. 2.3 shows the simplified configuration of a ball joint.



(a) Initial condition (b) Aged condition

Figure 2.3 Ball joint configurations before and after the aging

The wear occurred in the initial operation stage reduces the amount of the pre-loading stress on the ball. The pre-loading stress depends on the buffer ring compression force which is generated in the manufacturing process. As the wear continues, the compression stress is released and the width of the contacting band becomes wider until the lubrication is stabilized. The width of the band depends on the operating condition and the mechanical properties of the compressor. The amount of the released stress on the ball surface can be calculated with Equation (2.6).

$$\sigma_{released} = k_{buffer\ ring} \delta / A \tag{2.6}$$

where $k_{buffer\ ring}$ is the spring constant of the PTFE buffer ring.

2.3 Low friction ball joint piston

A piston with a band on the ball seat surface was developed. The socket and the steel ball have partially conformal contact at the banded area. By using this design change, the amount of pre-loading can be reduced significantly. The aging period to get constant compressor input power was also reduced to within few hours. 70 ~ 80% reduction of friction loss due to the pre-loading effect can be obtained with the new piston. Friction losses in a ball joint are calculated with a 1/5hp grade compressor. The results are shown in Table 2.1.

Piston type	W_{b-loss}	W_{t-loss}	W_{pre}	W_{total}
Old	10.8W	0.4W	4.7W	15.9W
New	9.5W	0.4W	1.1W	11.0W

Table 2.1 Friction losses in a ball joint piston

3. EXPERIMENTS

3.1 Friction measurement

Friction coefficient of the ball and the socket is needed to calculate the ball joint friction loss. Fig. 3.1 shows the friction measuring equipment. Friction torque due to the pre-loading is measured while the external force is applied axially. Fig. 3.2 shows the friction torque with respect to the angle. It shows that friction torque depends on the orientation and it changes periodically.

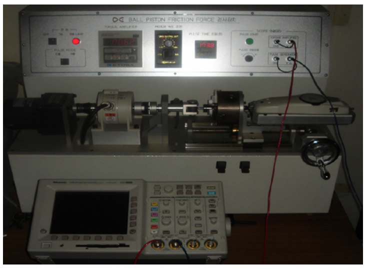


Figure 3.1 Friction torque-meter

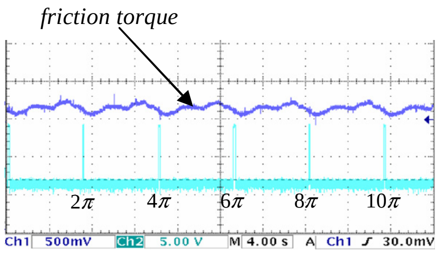


Figure 3.2 Friction torque

Friction coefficient of the steel ball and the ball seat can be obtained from the relationship between the external force applied and the friction torque without contacting the ball and the buffer ring. Pre-loading force on the ball is obtained by checking the external tensile force when the ball joint looses the metal contact between the ball and the ball seat. Once the friction coefficient between the ball and the ball seat and the pre-loading force are known, the friction coefficient of the ball and the buffer ring can be calculated.

Compressor performances are measured with aged and new pistons using a calorie-meter. R-134a is used as a refrigerant. The same compressor parts except the piston assembly are used for the experiments to get the effect only from the ball joint friction. There are only friction torque differences so that it can be considered that the input power difference of the test compressors is directly related to the ball joint friction loss difference.

3.2 Aging test

The compressor durability test device is shown in Fig. 3.3. Discharge and suction pressures are 25 ~ 30 kgf/cm^2 and 1.0 kgf/cm^2. Wear progress of the ball joint was investigated by measuring the width of the contacting band. The wear test was performed until the durability test ended. The band on the ball seat surface after 1,000 hour durability test is shown in Fig. 3.4. We assumed that the initial aging stage ends when the width of the band on the ball seat keeps constant.

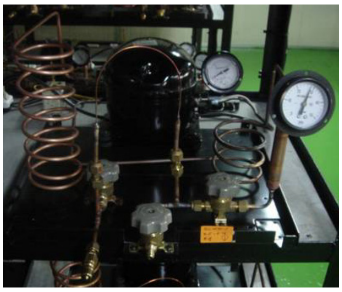


Figure 3.3 Durability test device

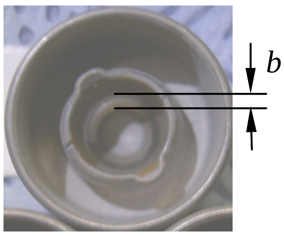


Figure 3.4 Band on the ball seat

4. EXPERIMENTAL RESULTS

4.1 Measurement of friction coefficients

Friction torque of a ball joint is measured with the friction torque-meter. Fig.4.1 shows the relation between the friction torque and the applied force. The slope, m, is used for the calculation of the friction coefficient. The results are listed in Table 4.1. The friction coefficient of the steel ball and the socket decreases slightly after the aging. It is expected that the surface condition of the socket surface, such as surface roughness and the width of contact band, becomes favorable to the lubrication. In the case of the contact between the steel ball and the PTFE buffer ring, there is no significant change in friction, and the measured friction coefficient is well consistent with the known values.[1] The friction coefficient of a new piston with a preformed band is similar to that of the aged piston.

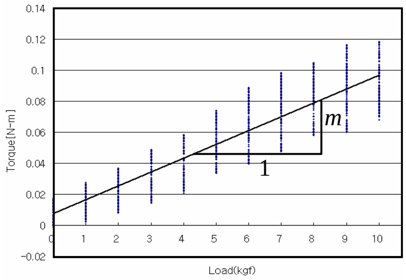


Figure 4.1 Relation between applied forces and friction torques

Parts		Friction coefficient
steel ball	socket	0.17 ~ 0.21
	aged socket	0.14 ~ 0.16
	socket (new)	0.20 ~ 0.23
	aged socket (new)	0.15 ~ 0.16
	buffer ring	0.05 ~ 0.11

Table 4.1 Measured friction coefficients

4.2 Friction loss in a ball joint piston

COPs of non-aged and 3-day aged compressor are measured, and they are listed in Table 4.2. There is about a 5% COP difference before and after the aging. Considering the energy efficiency regulations, 5% is not trivial to be neglected. The compressor with a new piston has about 3% of COP difference, which shows the effect of the released pre-loading. 2% COP difference between the compressors with the new piston and the aged piston still exists. It can be expected that the pre-loading effect still remains in the new piston.

	With old piston (not aged)	With old piston (aged)	With new piston
COP	156%	161%	159%

Table 4.2 Compressor performances with different pistons

4.3 Wear of a ball joint

Fig. 4.2 shows the typical examples of the band generated on the contact area of the steel ball and the socket after 1-day and 3-day normal operations. The band width of the old piston grows for a few days and remains almost constant during the compressor lifetime. The band width of the new piston, however, keeps almost constant. It is expected that the lubrication property at the contact area of a new piston is better than that of an old piston because the change of the band width can be considered as the amount of wear generation, even though it is very tiny.

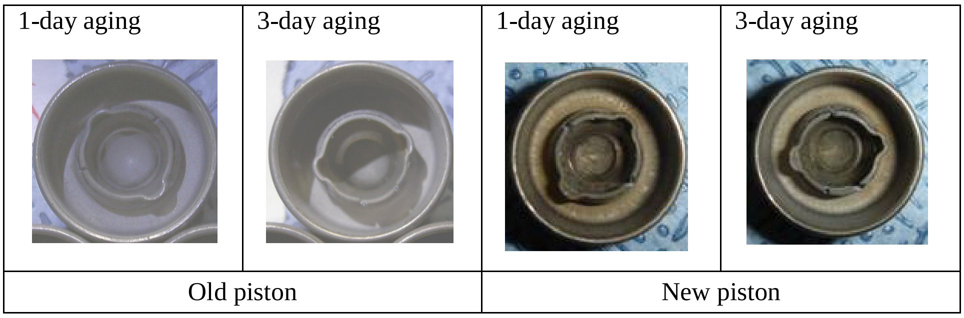


Figure 4.2 Band widths of aged pistons

5. CONCLUSIONS

The friction loss in a ball joint type piston which is used for a small hermetic compressor is analyzed and its effect is evaluated. New ball joint pistons are developed to reduce the friction loss caused from the pre-loading. With this study, the following conclusions are obtained.

1. Friction torque generated at the ball joint assembly process is reduced with the band-formed piston and the loss is reduced by amount of 3% COP.
2. Reliability of a ball joint is enhanced because the wear generated at the initial operation period is reduced.
3. The shape of the ball seat can be easily made by the pressing process so that it can be manufactured at the same cost with the conventional ball joint piston.

As a result, we can expect that ball joint type pistons can be used for high performance hermetic compressors.

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