Evaluation of Reed Valves Using an Impact Evaluation Device that Simulates Operating Condition

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ABSTRACT

In fluid machinery, especially compressors, suction and discharge valves are key components that greatly affect performance, noise, and reliability. The use of reed valves, manufactured through sheet material punching, is prevalent in these applications. While reed valves are often chosen over other types like poppet valves for their cost advantages, they demand high fatigue strength and impact resistance, necessitating a high level of quality and reliability.

One of the challenges in using reed valves is evaluating their durability in real-world conditions due to their robust fatigue strength and impact resistance. This report introduces a novel approach to impact resistance testing that closely simulates the operational conditions of compressors. The study focuses on constructing and implementing a methodology for this form of testing, ensuring a more realistic evaluation of the valves in conditions similar to actual use.

A specific aspect of compressor reed valves is that the fluid forces acting on them primarily consist of gaseous refrigerants in refrigerant compressors. When the load is gaseous, its low density presents challenges in conducting tests under sufficiently high loads. To address this, the report details the development of an impact resistance tester using refrigeration oil as the working fluid. By controlling the load on the reed valve through variations in the flow rate of the refrigeration oil, and intermittently flowing a denser fluid through the valve, the report successfully replicates the valve's operational behavior for impact resistance testing. The tests revealed that different materials exhibit varying impact resistance performances. This finding is crucial for selecting suitable materials for compressor reed valves and provides valuable data for material selection.

1. INTRODUCTION

In recent years, energy-saving in fluid machinery has become a significant challenge towards reducing CO_2 emissions[i]. Many fluid devices utilize reed valves punched out of sheet metal for their intake/exhaust valves due to their cost advantage, and the characteristics of these reed valves greatly affect the performance of fluid machinery[ii]. However, since many fluid machines are used over long periods once put into operation, reed valves require high fatigue strength and impact resistance, demanding high quality and reliability in their materials[iii, iv]. Especially in compressors used for refrigeration and air conditioning, where valves open and close at high frequencies and operate under various temperature and pressure conditions, the impact resistance of the material is an important performance indicator. Using materials with insufficient impact resistance can lead to unexpected failures and performance degradation, potentially affecting the reliability of the final product. Therefore, accurate evaluation of impact resistance performance can provide a foundation for better material selection and product design, ensuring long-term product reliability and efficiency.
The material of reed valves inherently possesses very high fatigue/impact resistance, and measuring these characteristics under actual use conditions is extremely challenging. This is because if the fatigue/impact resistance is only confirmed to the extent that damage is observable under actual use conditions, there is a significant risk of reed valve failure during long-term use in the market. Therefore, this report developed a test machine that subjects the valves to excessively high loads by changing the working fluid from gas to liquid, allowing for the evaluation of impact resistance performance under actual operating conditions.

2. IMPACT FATIGUE TEST METHOD

2.1 Evaluation Method for Impact Fatigue

To evaluate the impact resistance of valve materials, the following two points are essential:

- It is necessary to damage the valve with movements identical to those in a compressor, ensuring a configuration as close as possible to the actual usage condition and making the fluid flow around the valve equivalent to that in real usage situations.
- A device configuration capable of applying a load that can reliably damage the valve.

To meet these requirements, the basic configuration of the evaluation device is structured as shown in Figure 1. When the operating fluid acting on the valve is gas, valve damage rarely occurs, posing a challenge that requires significant time and effort for material evaluation. Therefore, in this study, instead of using refrigerant gas, refrigeration oil used in compressors was flowed as the load on the reed valve. To replicate the intermittent operation of the reed valve, a disk with six slits was rotated to simulate the ON-OFF load. Furthermore, to approximate real usage conditions, the reed valve was fixed to the compressor's cylinder head and cylinder (not shown), ensuring that the oil flow was equivalent to the flow in an actual compressor.

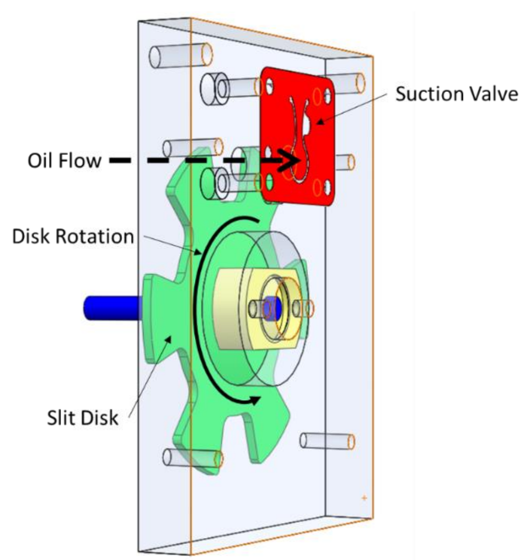


Figure 1: Compressor's Reed Valve Reliability Test Method

2.2 Reed Valve Shape and Materials

Table 1 presents the specifications of the compressor used in this study. The compressor examined was a Panasonic small reciprocating compressor, model TKD91E23DAH. This compressor is an inverter type, with an operational speed range of 1050-4500rpm.

To determine the feasibility of impact resistance evaluation, two types of materials were used: Proterial's high-grade valve stainless martensitic steel, GIN™6 and GIN6H, to assess the differences in impact resistance. (GIN is a registered trademark of Proterial, Ltd., Japan.) The mechanical properties of GIN6 and GIN6H are as shown in Table 2.

For the experiment, reed valves of the shape shown in Figure 2 were first manufactured from each material to serve as test specimens. Although valve prototypes are typically made by wire cutting, this method is unsuitable for reliability evaluations, such as impact resistance, due to the unavoidable heat-affected zone. Therefore, in this study, a mold of the shape shown in Figure 2 was fabricated, and the reed valves were manufactured using the standard industrial process of stamping followed by barrel polishing, which is commonly adopted in product manufacturing.

Table 1: Specification of Tested Compressor

	Reciprocating (Variable Speed)
Model	TKD91E23DAH
Manufacturer	Panasonic
Refrigerant	R600a
Displacement [mL]	9.1
Speed [min^{-1}]	1050-4500
Motor	Ferrite motor
Lubricant	Mineral Oil (VG5)

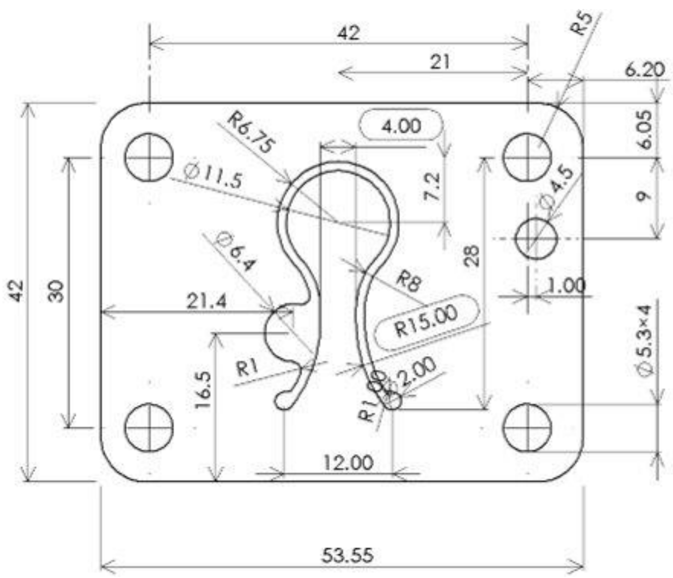


Figure 2: Reed Valve

Table 2 : Material Properties at a Plate Thickness of 0.305mm

	High grade	Middle grade
	GIN6H	GIN6
Hardness (HV10)	599	548
0.2% Proof Stress (N/mm^2)	1422	1462
Tensile Strength (N/mm^2)	2012	1824
Elongation (%)	7.1	6.1
Biaxial Fatigue Limit (50% Probability of Failure at 2×10^6 Cycles, N/mm^2)	1350	1328

2.3 Fabrication of the Evaluation Device

Figure 3 shows an overview of the evaluation device, which was designed to replicate the structure shown in Figure 1 by placing a slit disc structure adjacent to the compressor. Multiple trochoid pumps were used to circulate the oil. The oil circulation path was configured as shown in Figure 4. The oil stored in the test container was in a foamed state due to collisions with the slit and valve material. This foamed oil was sucked up by the trochoid pumps, separated into gas and liquid by centrifugation, and then stored in an oil reservoir. The oil reservoir was maintained with more than 10L of oil at all times, and for example, in tests with an oil flow rate of 10L/min, the oil was left to stand for about one minute for further gas-liquid separation, thereby reducing the impact of foaming.

The defoamed oil in the reservoir was pumped by three trochoid pumps, passed through a flow meter, and then made to intermittently flow through the slit disc before colliding with the valve material. One of the three trochoid pumps was speed-controlled by a PID controller to automatically adjust the flow rate to a preset value based on the output of the flow meter. Figure 5 shows the control panel of the evaluation device. The oil flow rate is set using the PID controller in the lower left, and the operating speed of the pump is set by the motor controller (Pump 3) in the upper right, which receives the output signal from the PID controller. The operating speeds of the other pumps are manually set, defining a rough flow rate with manual speed setting and fine-tuning by the automatic adjustment of Pump 3 to stabilize the oil flow rate.

Figure 6 shows an example of the timer settings in Figure 5. In this device, Omron timers H5CZ-L8 and H5CZ-L8E are combined to stop the test at regular intervals and take photographs of the valve material. Timer 1 sets the test cycle time, oil pumps, etc., are activated by Timer 2, and the oil flow rate adjustment pumps are started 30 seconds later by Timer 3 and Timer 4. Timer 5 triggers Timer 6 to stop the oil pumps, etc., at the designated time. Timer 6 activates air blowing to clear the oil in the camera's field of view and lighting for photography, preparing for photo shooting. The camera control is separately managed by a PC, set to shoot just before Timer 6 turns off.

This configuration allows for the automation of the impact resistance evaluation device and enables the timing of valve material damage to be measured.

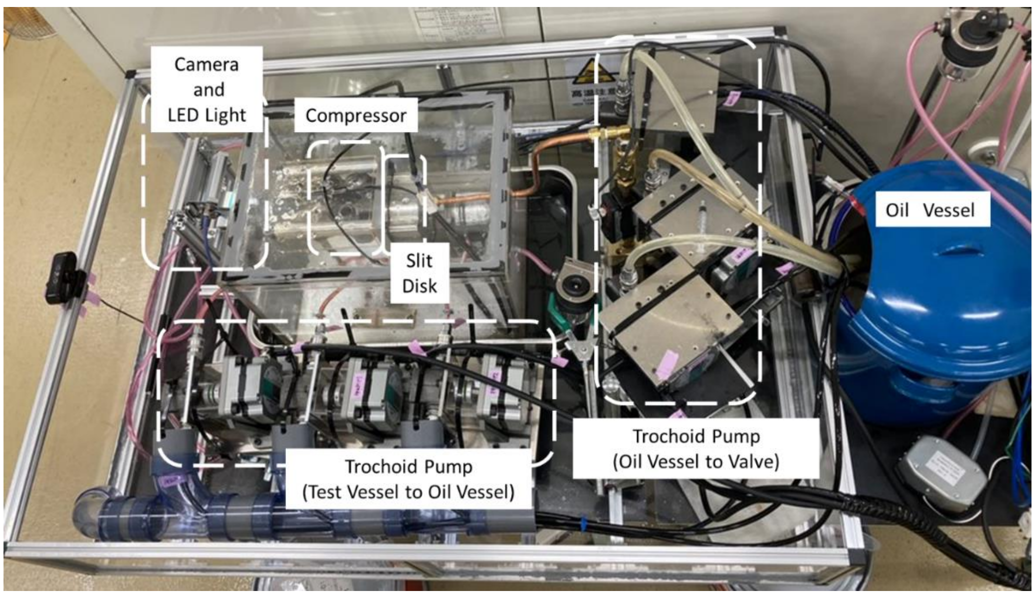


Figure 3: Compressor's Reed Valve Reliability Test Equipment

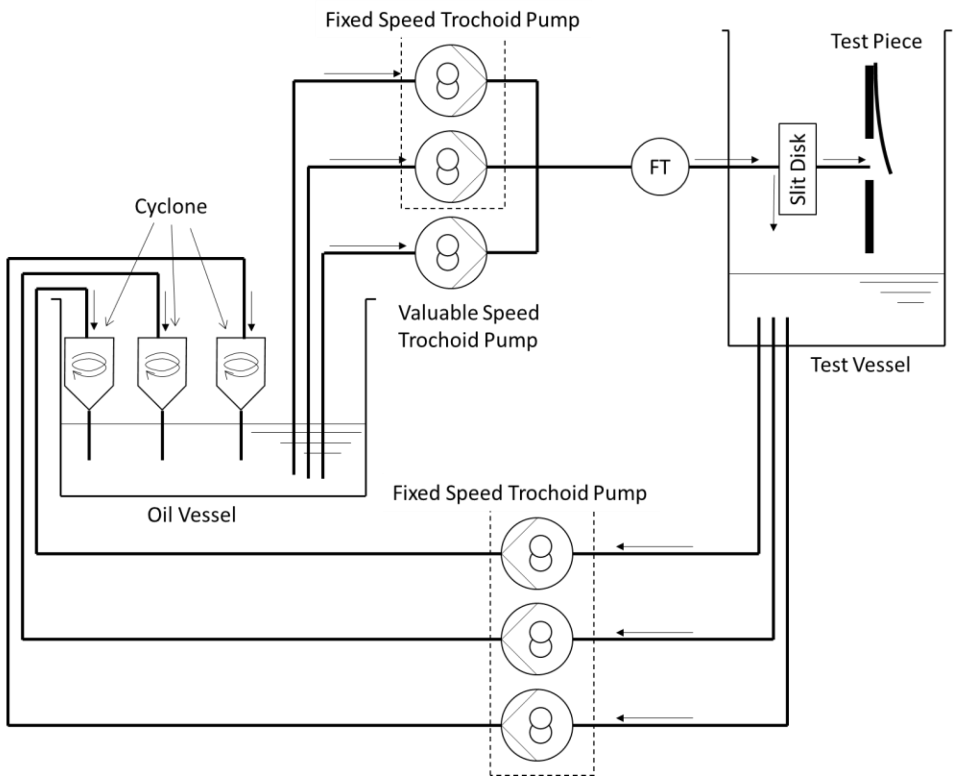


Figure 4: Oil Flow Cycle

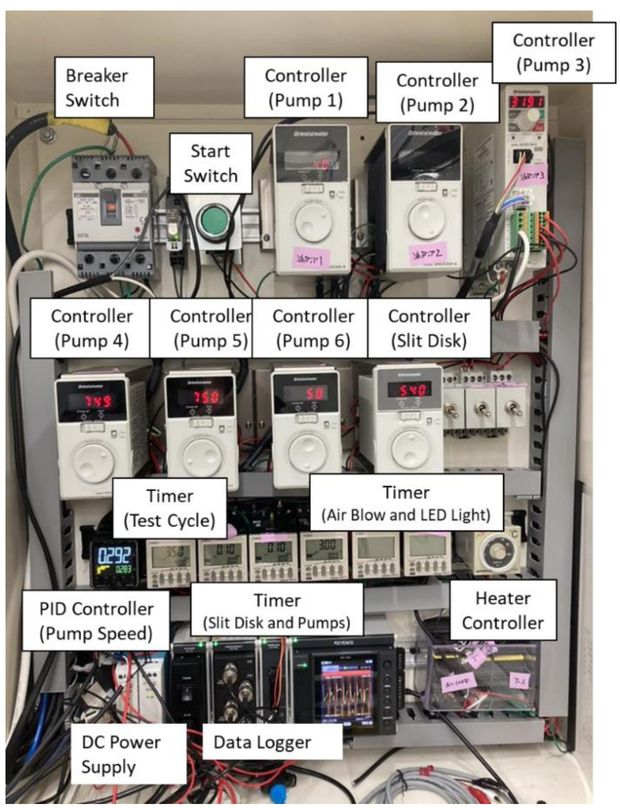


Figure 5: Equipment in the Control Panel

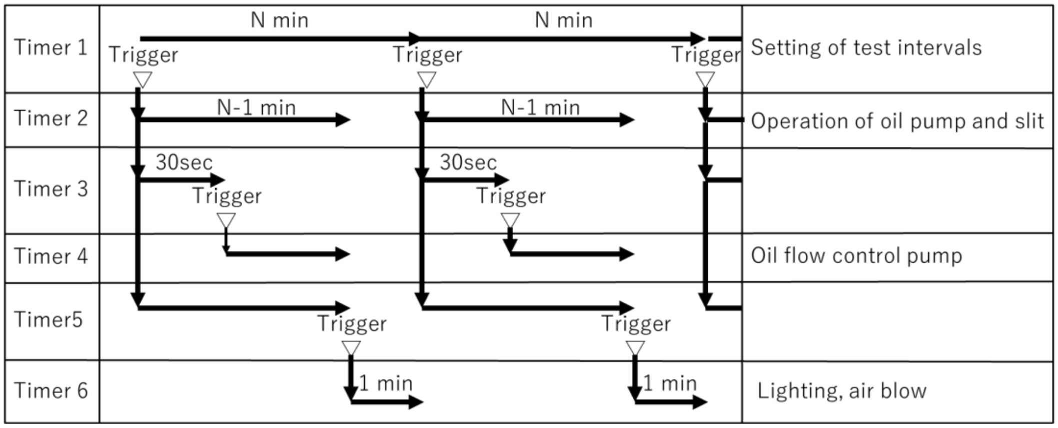


Figure 6: Timer Setting of Reed Valve Reliability Test Equipment

3. IMPACT FATIGUE TEST RESULTS AND DISCUSSION

2.1 Impact Fatigue Test Results

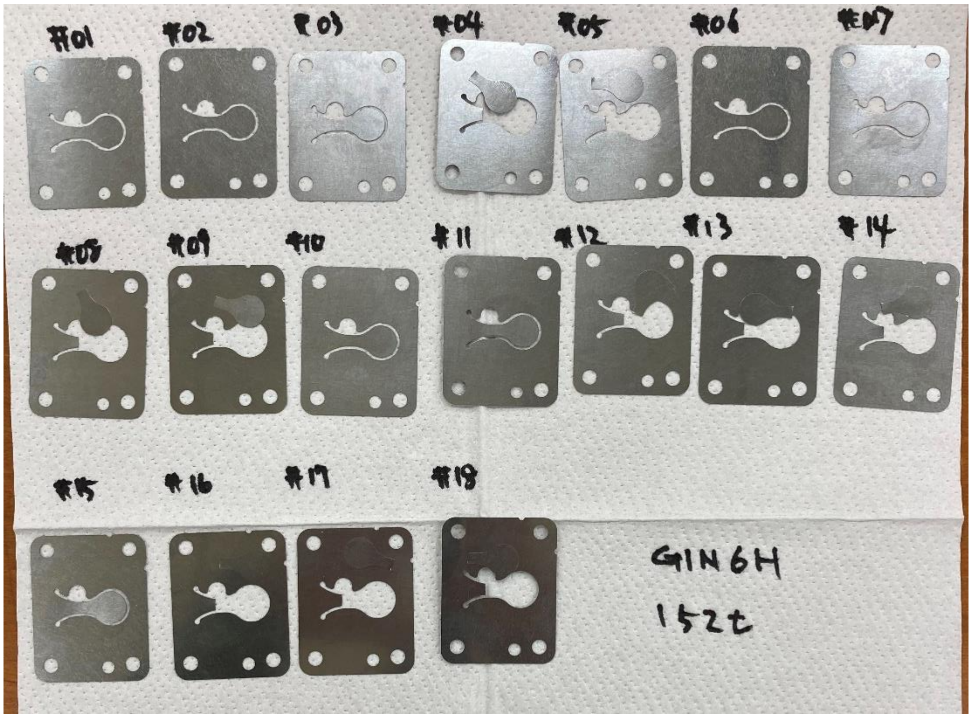
In the statistical fatigue testing method according to the Japanese Society of Mechanical Engineers standards, it is stipulated that approximately 15 specimens should be used for a single S-N curve to determine the curve corresponding to a 50% probability of failure[v]. Thus, in this study, more than 15 valve materials for each type were used to conduct the impact resistance fatigue test. The test procedure was as follows:

(1) Sequentially increase the oil flow rate to find the flow rate at which failure occurs before 10^7 cycles.
(2) If a flow rate causing failure is found, conduct the test at one step lower flow rate to check if it can withstand 5×10^7 cycles. (Generally, the fatigue evaluation of ferrous materials is determined by whether it can withstand 1×10^7 cycles; however, damage can occasionally occur after 1×10^7 cycles. Therefore, this study evaluated based on the ability to withstand 5×10^7 cycles.)
(3) The next test increases the flow rate by one step if the 5×10^7 cycle is cleared, or decreases the flow rate by one step if not. In this study, one step was defined as a 0.5 L/min change in flow rate.
(4) Repeat step 3 until three tests clearing 5×10^7 cycles are obtained. The fatigue limit is determined by the average of these three tests.
(5) Obtain more than ten damage data points at flow rates higher than the fatigue limit flow rate and plot the sloped part of the S-N diagram. From the sloped part plot, calculate the regression line and standard deviation σ.

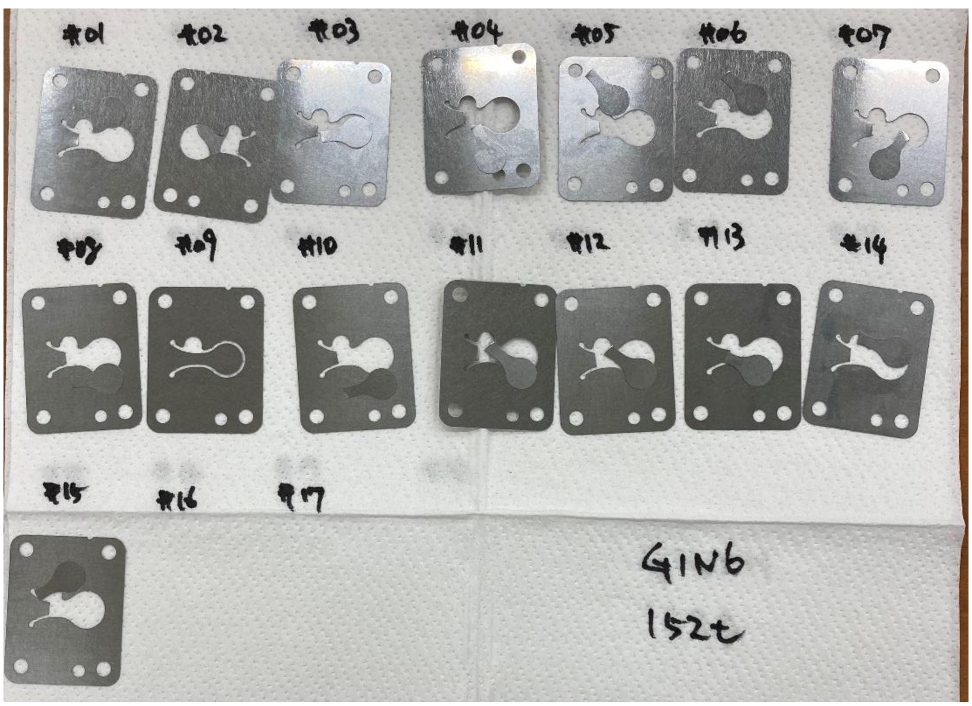
Figure 7 shows a photograph of the reed valve after testing. From Figure 7, it was observed that the damage location of the broken reed valves was exclusively at the 4mm width position shown in Figure 2, regardless of the material. Therefore, it can be said that this test was a condition for evaluating the cantilever bending fatigue of the reed valve.
Figure 8 and Figure 9 show the impact resistance test results for GIN6 and GIN6H, respectively. In the figures, ● indicates a failed result, and ○ indicates a non-failed result. Additionally, the vertical axis represents the oil flow rate converted to fluid force using Equation (1).

$$\boldsymbol{F = \frac{1}{2}\rho u^2 \times S} \qquad (1)$$

Where F is the load, ρ is the fluid density, u is the flow velocity, and S is the pressure area.
Comparing at the 50% failure probability fatigue limit, GIN6 was 1.85N whereas GIN6H was 2.51N, confirming that the fatigue limit was significantly improved. Moreover, focusing on the variability of the test results, the standard deviation was reduced from 0.25N for GIN6 to 0.17N for GIN6H. Analyzing the cause of this from the impact test results is challenging, so this will be discussed in the following sections.



(a) GIN6H



(b) GIN6

Figure 7: Reed Valves after Fatigue Test

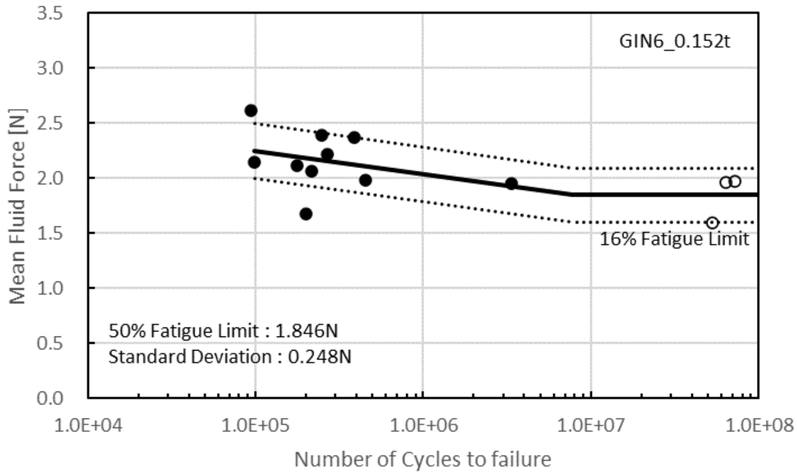


Figure 8: Fatigue Test Result (GIN6, Thickness=0.152mm)

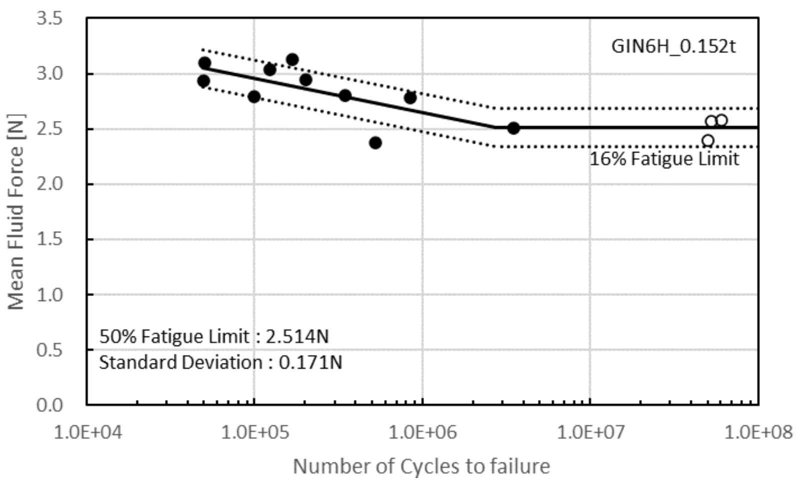


Figure 9: Fatigue Test Result (GIN6H, Thickness=0.152mm)

3.2 Investigation of Variability Factors in Impact Fatigue Resistance

In this study, the reed valves of the reciprocating compressors under consideration are cantilever beam-type reed valves as shown in Figure 2, and the breakage occurs exclusively in the arm portion as depicted in Figure 7. Therefore, this investigation focuses on the stress occurring in the arm part. The maximum stress generated in a cantilever beam is expressed by the following equation:

$$\sigma_{max} = \frac{M_{max}}{Z} = \frac{6Pl}{bh^2} \tag{2}$$

Where σ max is the maximum stress (MPa), M max is the maximum moment (Nmm), Z is the section modulus (mm^3), P is the load (N), l is the length of the beam (mm), b is the width of the beam (mm), and h is the thickness of the beam (mm).

From Equation 2, it can be seen that the stress generated in the beam is inversely proportional to the square of the thickness of the plate, indicating a high correlation with the thickness compared to other parameters. Therefore, the thickness of the reed valves used in the tests was investigated.

Figure 10 shows the locations where the thickness was measured, and Table 3 presents the results of the thickness measurements, organized by average, maximum, minimum values, and standard deviation. Looking at the standard deviation, which indicates variability, GIN6H has a standard deviation of 2.0µm, while GIN6 has 2.2µm, showing that GIN6H has less variability in thickness compared to GIN6.

As the thickness varies, it is assumed from Equation 1 that the breaking load will also vary. Therefore, the effect of thickness on the difference between the regression line and breaking load was investigated. Figure 11 and Figure 12 show the results for GIN6H and GIN6, respectively, with the vertical axis representing the difference between the regression line and breaking load, and the horizontal axis representing the thickness. For both materials, it is evident that as the thickness increases, the plots tend to shift towards the positive side relative to the regression line. These results indicate that the variability in breaking load is due to the variability in thickness, which can be considered the reason why the standard deviation for GIN6H was reduced compared to GIN6 in the previous section's impact resistance evaluation.

From these results, it is clear that the variability in impact resistance performance is due to the variability in the thickness of the valve material. Therefore, in the following section, an evaluation method for impact resistance performance, taking into account the variability, will be discussed.

Figure 10: Thickness Measurement Position

Table 3: Thickness Measurement Results (Unit : mm)

	N	Ave.	Min.	Max	Sta. Dev.
GIN6H_152t	18	0.1558	0.150	0.160	0.00197432
GIN6_152t	15	0.1574	0.148	0.163	0.00224499

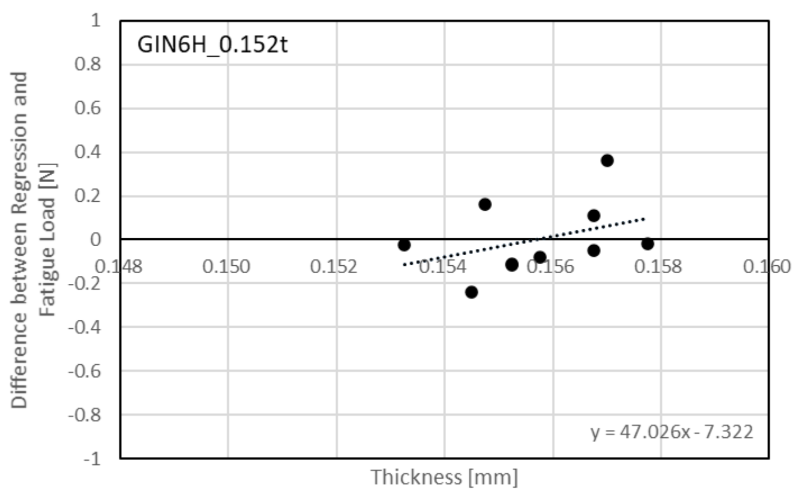


Figure 11: Effect of Thickness for Difference between Regression and Fatigue Load (GIN6H, Thickness=0.152mm)

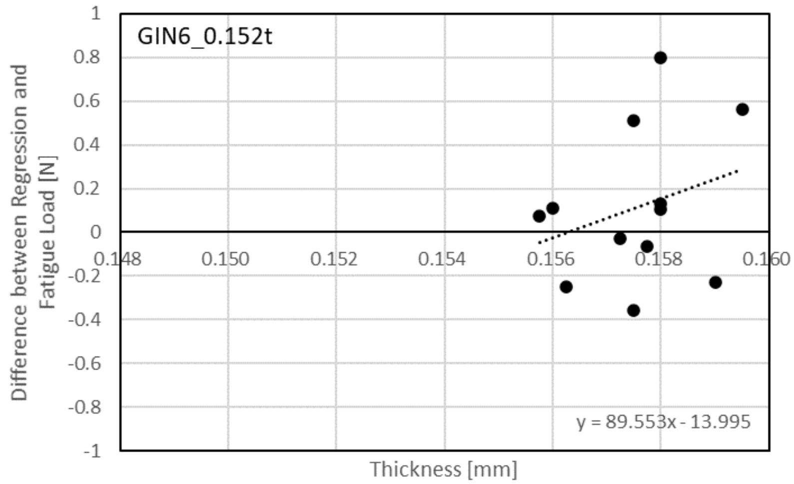


Figure 12: Effect of Thickness for Difference between Regression and Fatigue Load (GIN6, Thickness=0.152mm)

3.3 Evaluation Method Considering Actual Usage Conditions and Variability in Fatigue Limit

When incorporating valve material into a compressor, to avoid compressor failure due to valve material breakage, the stress occurring during actual operation must be lower than the minimum variability of the fatigue limit. The variability of the fatigue limit is generally assessed as a normal distribution, and the relationship between the mean value and the standard deviation σ is as shown in Figure 13. In a normal distribution, 68.2% of all data falls within the range of μ−σ to μ+σ from the mean value μ, and 99.7% of all data falls within the range of μ−3σ to μ+3σ. Figure 14 is an example illustrating the variability state of the fatigue limit on an S-N diagram. The fatigue strength of the test material will vary as shown in the diagram, with the sloped and horizontal sections of the S-N diagram obtained from testing serving as the average value.

The reliability of the compressor valve is designed based on Figure 14, ensuring that the stress falls within the range shown in Figure 15 according to the assumed failure rate. Generally, the failure rate for machinery like compressors is set to be less than 1/1000, and the range of variability is often chosen between 3σ (failure rate of 0.13%) and 5σ (failure rate of 3×10^-5%).

Figure 16 and Figure 17 show the results of illustrating the S-N diagram for GIN6H and GIN6, along with the lower limits of variability for 3σ and 5σ, respectively. Comparing GIN6H to GIN6, it is evident that both the 3σ and 5σ lower limit values are significantly higher for GIN6H, indicating an improvement in fatigue limit. For example, while the 3σ lower limit for GIN6 is approximately 1.1N, it is about 2.0N for GIN6H, which can be said to represent an approximately 80% improvement in fatigue limit.

As a result of this investigation, it has become clear that the fatigue limit of GIN6H is significantly higher than that of GIN6, with an 80% improvement observed at the 3σ lower limit, for instance.

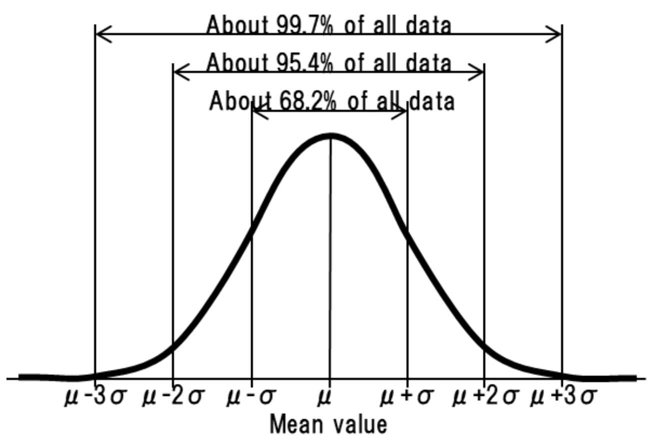


Figure 13: Relationship Between Standard Deviation and Coverage in Statistics

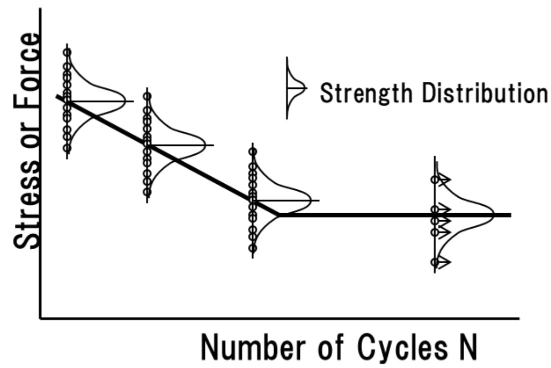


Figure 14: Relationship Between Strength Distribution and S-N Curve

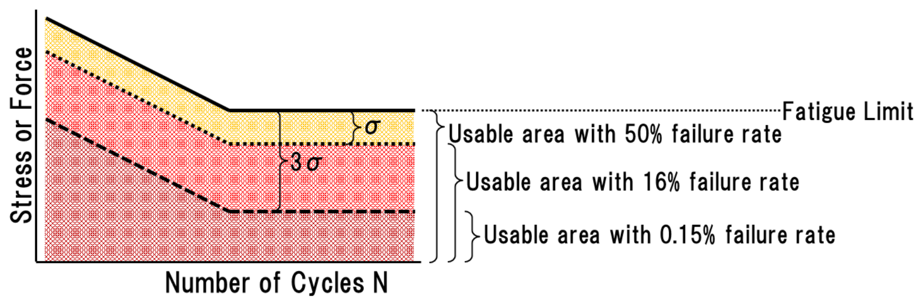


Figure 15: Relationship Between Failure Rate and S-N Curve

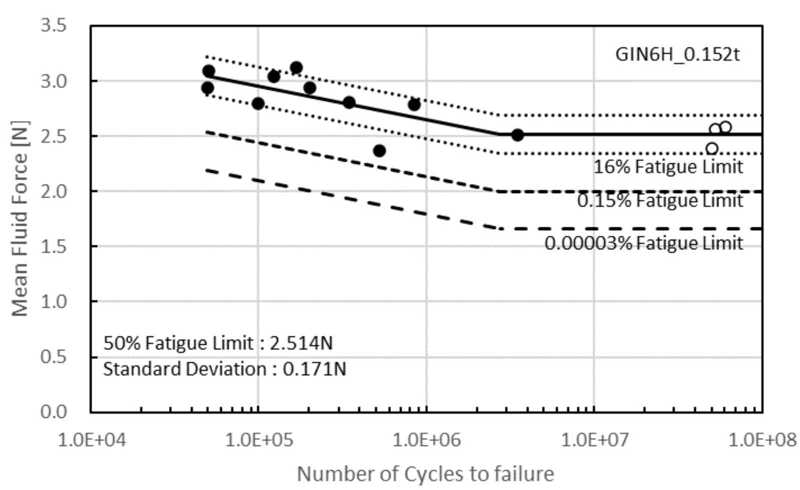


Figure 16: Fatigue Test Results (GIN6H, Thickness=0.152mm)

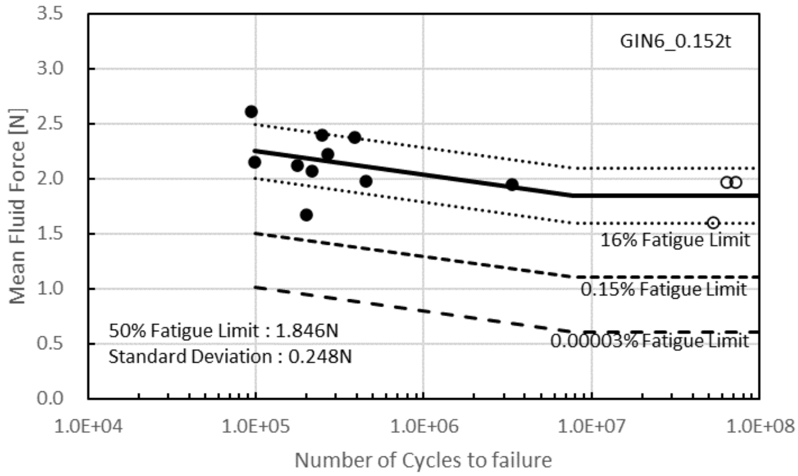


Figure 17: Fatigue Test Results (GIN6, Thickness=0.152mm)

4. CONCLUSIONS

In pursuit of assessing the reliability of reed valves manufactured through sheet metal punching in their actual usage conditions, a reed valve impact resistance tester was developed with the load being refrigerant oil. The results elucidated the following:

- The developed impact resistance tester is capable of evaluating the impact resistance performance of valve behaviors under actual operational conditions.
- The developed tester allows for the quantitative assessment of significant differences in materials, considering the variability in materials.

The methodology examined in this study enables the quantitative reliability evaluation of reed valves in actual compressors, contributing to the enhancement of compressor reliability.

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