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Evaluation of Compressor Valve Stresses by Means of Copper Electrodeposit Technique

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EVALUATION OF COMPRESSOR VALVE STRESSES BY MEANS OF COPPER ELECTRODEPOSITE TECHNIQUE

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Abstract - Repeated bending and impact stresses induced in a suction valve have been examined under compressor operating conditions by using copper electrodeposite technique. A series of rotating-bending fatigue tests were carried out to determine the relationship between the stress level and the appearance of flecks, in which the abrupt change was induced in the copper electrodeposite by cyclic stresses. The suction valve on the surface of which copper was electrodeposited was installed in a hermetic compressor and was operated under compressor operating conditions. Comparing the results of the rotating-bending fatigue tests with the appearance of flecks on the valve surface, the repeated bending and impact stresses are evaluated in conjunction with the valve supporting conditions. Moreover, the generation mechanisms of the repeated bending and impact stresses are clarified.

INTRODUCTION

Demand for experimental analysis did in fact declaine as proponents of the finite-element approach succeeded in convincing program managers that their method could replace all experimental stress anaylsis. As with most new techniques, there is tendendy to attempt to solve all problems with the new tools, and this appears to be the case with the finite-element method. Some disillusionment with the new method is inevitable and thus, there is today a general agreement on a continued need for experimental stress analysis for certain classes of problems.

Stress analysis of compressor valves is one of the reserved problems in the field of experimental stress analysis. This may come from the dynamic analysis of three-dimensional thin structures too complex to be modeled numerically within the limitations of available programs using finite element method. Moreover, it may come from the modeling structures composed of two contact boundary conditions and wave propagating conditions changing with increasing load or deformation.

Papastergiou, Nilsson, Maclaren, and one of authors have already revealed that the finite-element method is powerful for analysis of valve stresses induced by repeated bending.[(1)∿(5)] However, they are not so far reaching as to clarify the generation mechanisms of the impact deformation and stress of suction valves. To cope with these problems, a lot of researchers have carried out the impact fatigue tests.[(6)∿(9)] This means that, at this moment, a combined approach using experimental and numerical approach is a more powerful and useful tool for the prediction of stress and deformation. From the point of view, it is the intent of this paper to demonstrate that an experimental anaylsis using copper electrodeposite technique has been tried to clarify the stress magnitude and deformation of the suction valve under compressor operating conditions.

TEST EQUIPMENT AND VALVE SYSTEM

A hermetic refrigeration compressor was used in this test. Fig. 1 shows a view of construction in the hermetic cell of the tested compressor. Fig. 2 shows an exploded view of the suction valve system. One of the intents in this study is to clarify the effect of the constructions of the suction vlave systems on the stress. Three kinds of suction valve systems as shown in Fig. 3, therefore, were selected in this test. Valve system I has the suction valve supported by the root clamping with the same shape as the cylinder inside wall and installed over the valve refuge cavity which had a large width than that of the suction vlave. Valve system II has the construction in which the clamping portion of the cylinder block is machined out with an inclination angle of 7° within the range of 3.65 mm from the cylinder inside wall. The width of the valve refuge cavity is narrowed below the valve width. Valve system III has the construction in which the root clamping edge has the transversal shape to the valve axis and in which cushion material is installed in this part. The valve refuge cavity is also machined out in the same width as valve system II.

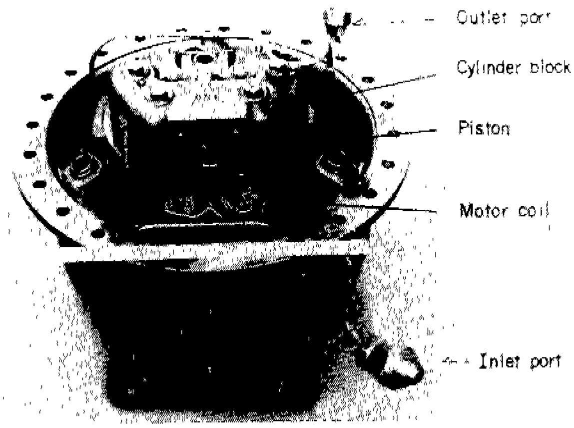


Fig. 1 Allover view of tested compressor

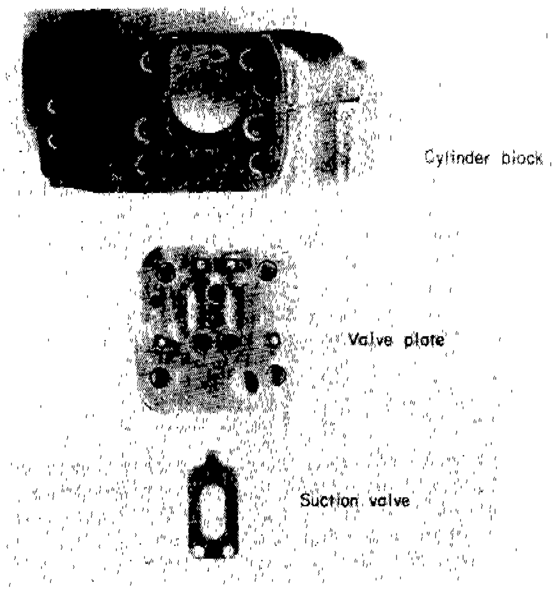
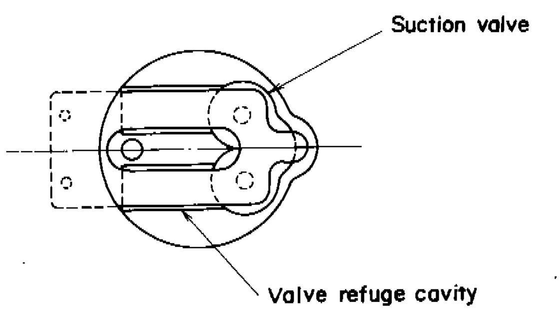
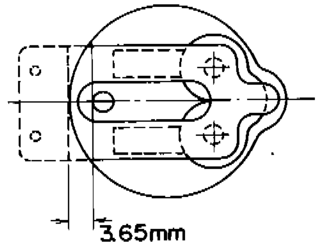


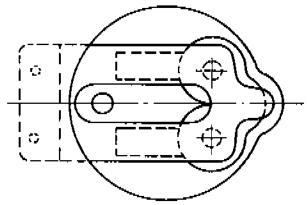
Fig. 2 Exploded view of suction valve system



(a) Valve system I



(b) Valve system II



(c) Valve system III

Fig. 3 Three kinds of valve systems

TEST PROCEDURE

In this study, copper electrodeposite technique was ad pted to the stress measurement. This technique had been proposed by Okubo[10] and developed by Seika,[11]~[14] in which copper coatings electroplated on carbon-steel specimens is found to exhibit flecking when test specimens are subjected to repeated loadings. The valve of the critical stress below which no fleck appears depends on the experimental conditions. Below this stress, the copper coating is unaffected, but above it, the size and density of the flecks increase with increasing load so long as the underlying material of the test specimens remains within the elastic range.

The present work attempts to obtain the suitable valve system and evaluates the repeated bending and impact stresses of the suction valve by showing how grain growth may depend upon the stress conditions to which the copper plating is subjected, thus enabling the state and magnitude of the suction valve stress.

Rotating-Bending Fatigue Test

Rotating-bending fatigue tests were carried out to determine the size and density of the flecks for the stress levels, at which an abrupt change occurs in the appearance of flecks produced by repeated stresses. It is clarified that the effect of the difference in materials for copper to be plated on the size and density of the flecks is neglegible.[10] Conical rods of Cr-Mo alloy steel were used as the test specimens with the dimensions as shown in Fig. 4 for the rotating bending-fatigue test. The use of slightly tapered rods as shown in Fig. 4 is favorable in this experiment, since the appearance of flecks varies continuously along the length of the rod according to the change in the surface of the test specimen. Accordingly, the size and density of flecks may be obtained in conjunction with the corresponded stress level.

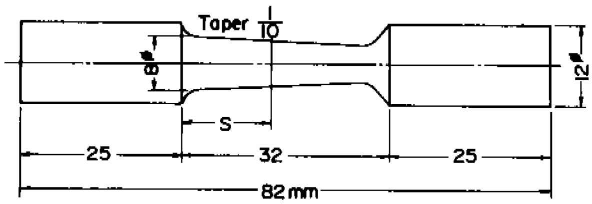


Fig. 4 Test specimen

The conditions for copper electrodeposite are given in Table 1. As given in Table 1, alkaline copper was first plated on the surface of the test specimen and then acid copper was plated on the surface of the alkaline copper plating. The conditions for this copper electrodeposite is similar to those employed by Okubo.(10) The surface of the test specimens was abraded on a series of fine emery papers, rensed successively in trichlore ethylene, acetone, and alcohol, and then given a preliminary strike in copper cyanide solution.

Table 1 Conditions for deposition

	Alkaline plating	Acid plating
Solution	CuCN : 23 grams NaCN : 30 grams Na_2CO_3 : 10 grams H_2O : 1000 grams	$CuSO_4 \cdot 5H_2O$: 250 grams H_2SO_4 : 80 grams H_2O : 1000 grams
Current density	6 A/m^2	300 A/m^2
Temperature	20 °C	20 °C
Voltage	0.35 V	0.5 V
Time	25 min.	20 min.

A rotating-bending fatigue testing machine was used in which the uniform bending moment could be subjected to the test specimen in the repeated rotating manner. This test was carried out at the same temperature of 70°C as that of the suction valve when the tested compressor was in operation under the test conditions described latter.

After repeated loading of a certain number of cycles was acted on the test specimen, the copper electrodeposite on each test specimen was investigated metallographically. This was carried out with a microscope. To observe the appearance of etch pits, the copper electrodeposite was etched with a mixture of equal parts of HCℓ and saturated aqueous $FeC\ell_3 \cdot 6H_2O_3$ solution.

Stress Measurement of Suction valve

The shape and dimension of the suction valve are shown in Fig. 5. It is reported that the critical stress for flecks decreases almost proportionally with increasing temperature and that no fleck appears beyond 100°C. This result means that the limitation to test temperature is about 80°C in application of this technique. Since a temperature in the vicinity of the suction valve becomes about 120°C under normal operation of the compressor because of the compressive action of refrigerant in the cylinder, the copper electrodeposite technique could not apply to the stress measurement of the suction valve in the normal operating conditions.

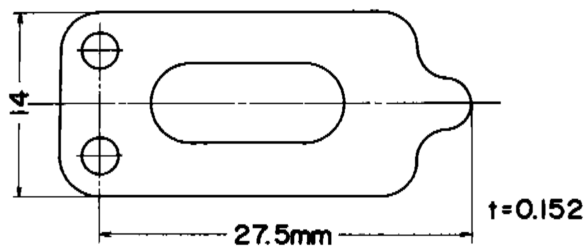


Fig. 5 Tested suction valve

In this test, a consideration was taken to decrease the temperature in the vicinity of the suction valve. Fig. 6 shows the arrangement of test equipment controlling the operating temperature of the tested compressor. As shown in Fig. 6, the tested compressor was dipped in the mixture of compressor oil and dry-ice. The test comditions are given in Table 2. In this test, the compressor was operated at a compressive ratio of 1.7 and a temperature in the vicinity of the suction valve was controlled below 70°C by keeping the temperature rise in suction refrigerant as low as possible. This condition was adjusted by changing setting of the expansion valve and the refrigerant charge in the system. When the compressor is in operation, the suction valve will vibrate several times during each suction stroke. The motion of the suction valve was measured by a displacement pick-up of eddy-current type and a number of cycles was accounted from these data.

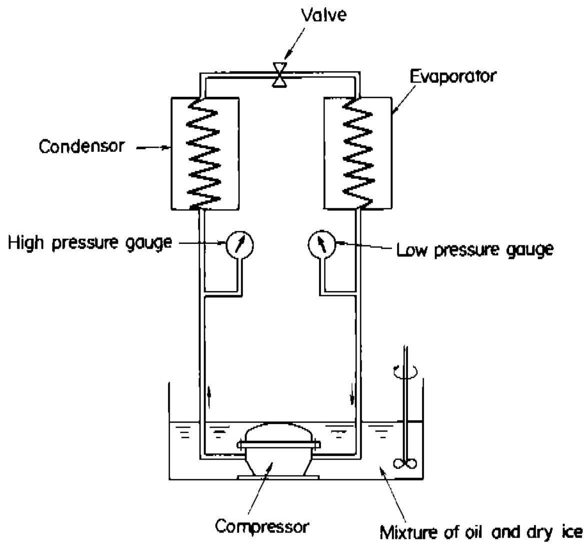


Fig. 6 Schematic diagram of test equipment

Table 2 Test conditions

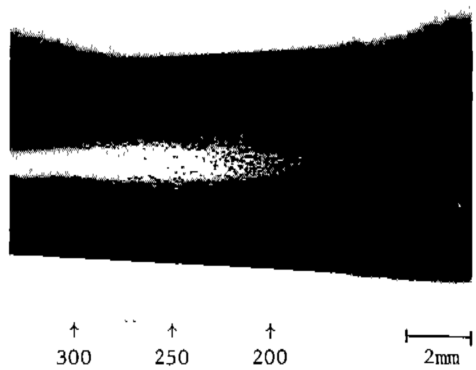
Test No.	Suction pressure (N/cm^2)	Discharge pressure (N/cm^2)	Number of cycles of repeated stress	Valve system
1	53	32	1×10^6	I
2	55	32	1×10^6	I
3	50	30	3×10^5	I
4	55	33	2×10^5	I
5	54	34	1×10^6	II
6	53	32	1×10^6	III

TEST RESULTS AND DISCUSION

Determination of Size and Density of Flecks

Fig 7 shows a test specimen partially changed in colour of flecks after a repeated loading of 2×10^5 was applied. It is clear from Fig. 7 that when the test specimen is subjected to repeated stresses, the appearance of flecks changes sensitively in conjunction with the variation in the stress distributing along the length of the test specimen.

The rotating-bending fatigue tests were carried out for five test specimens. The distance from one end to the point corresponding to the proper stress as shown in Fig. 4 was measured by reading a micrometer observing carefully the surface of the test specimen. This distance is shown with S in Fig. 4. The distance was measured at four counterpoints in every test specimen and their mean valve was calculated. From the bending moment acting on the test specimen and the diameter of the test specimen corresponding to that distance, the induced stress was calculated. In every measurement, the discrepancy between the distances at four counterpoints remained almost within 0.5 mm, which corresponded to an induced stress of 1 N/mm^2. The bending stresses obtained are shown in Fig. 7 in relating to the location of the test specimen. It is noticed from Fig. 7 that the size and density of flecks can be determined in conjunction with the stress level.



Bending stress (N/mm^2)

Test conditions:

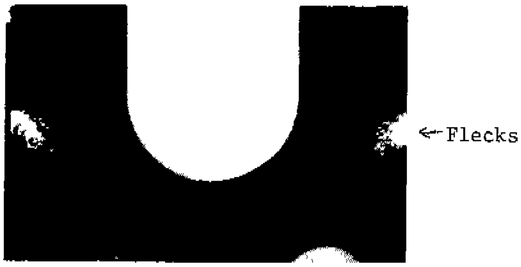
Bending moment : 8.5×10^3 N.mm
Temperature : 70°C
Number of cycles: 2×10^5

Fig. 7 Flecks on test specimens derived from rotating-bending fatigue test

Repeated Bending Stress of Suction Valve

Stress Distribution and Magnitude : The magnitude and distribution of the stress in the suction valve were determined by comparing the microphotographs of the copper electrodeposite on the test specimen with those on the suction valve. When the compressor is in operation, the suction valve will be bent to both piston and valve port sides repeatedly and be under stress conditions for the repeated stress to be piled up the mean stress. The stress amplitude is expressed in this paper with the half value of the peak-to peak stress.

In order to obtain the general knowledge on the stress distribution of the suction valve, a series of tests were carried out on valve system I, in which the repeated stresses with a number of cycles from 2×10^5 to 1×10^6 were subjected to the suction valve. Fig. 8 shows the suction valve partically changed in colour. Table 3 gives the stress distribution of the tested valve. From these figure and table, it is noticed that the stress concentrates at both sides at the edge of clamping. This is caused by cyclic bending deformation in the longitudinal direction of the suction valve.



(a) Valve plate side

(b) Stopper side

Fig. 8 Flecks at clamping portion

Table 3 Test results for valve system 1

Test NO.	Number of cycles	Stress distribution produced in tested valve: Valve plate side	Stress distribution produced in tested valve: Cylinder side
1	10^6	250 N/mm²; 270 N/mm²; 270 N/mm²; 210 N/mm²; 210 N/mm²; Inner periphery of cylinder	270 N/mm²; 270 N/mm²; 210N/mm²; 210N/mm²
2	10^6	250 N/mm²; 270 N/mm²; 270 N/mm²	270 N/mm²
3	3×10^5	250 N/mm²; 270 N/mm²; 270 N/mm²	270 N/mm²; Flecks are not confirmed
4	2×10^5	250 N/mm²; 290 N/mm²; 260 N/mm²	270 N/mm²; Flecks are not confirmed

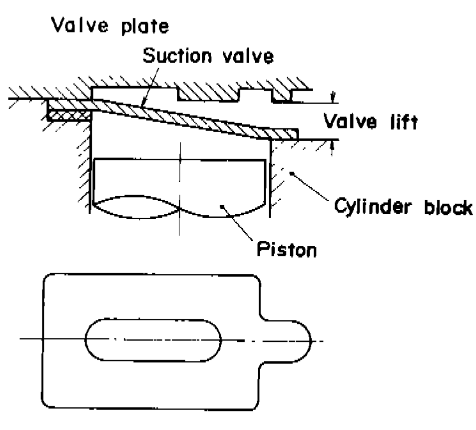
Comparing the microphotographs of the copper electrodeposite on the surface of the suction valve with those of the test specimens, the bending stress of the suction valve is estimated to be about 210~290 N/mm² at both edges of clamping portion.

A series of tests were also carried out on valve systems II and III in the same manner as that in valve system I. The obtained stresses are given in Table 4. The maximum valve stress of about 190∿200 N/mm² is found in valve system II at the same points as valve system I. On the contrary, the bending stresses in valve system III seems to be below 180 N/mm² in all clamping portion.

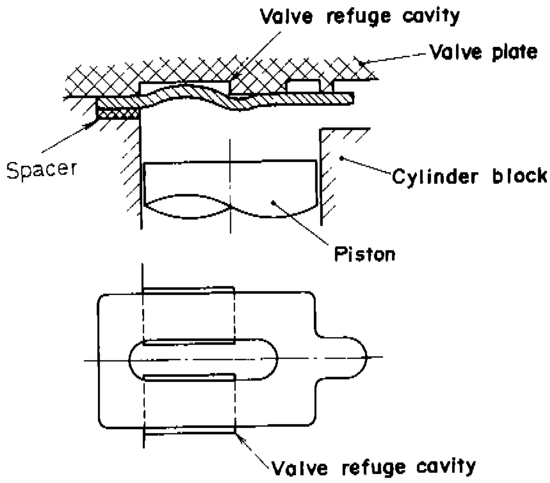
Table 4 Test results for valve system II and III

Test No.	Number of cycles	Stress distribution produced in tested valve: Valve plate side	Stress distribution produced in tested valve: Cylinder side
5	10^6	250N/mm²; Root clamping	200 N/mm²; 190 N/mm²
6	10^6	250N/mm²	Flecks are not confirmed

<u>Generation Mechanism of Repeated Bending Stress</u> : Figs. 9 (a) and (b) show illustrations to explain the relationship between the valve deformation and stress. In valve system I, one end of the suction valve is fixed at the root clamping and the other end is supported at the valve stopper. After the suction valve hits the valve stopper in the suction stroke, suction valve is bent as shown in Fig. 9 (a) and then the stress of the suction valve concentrates at both clamping edges of the suction valve. In the discharge stroke, the suction valve is bent to the valve plate side as shown in Fig. 9 (b) because the width of the valve refuge cavity is larger than that of the suction valve. The stress, therefore, also concentrates at the oposite surface of both clamping edges of the suction valves.



(a) Suction stroke



(b) Discharge stroke

Fig. 9 Schematic valve deformations

The shape of individual grains seems to indicate the direction of the planes of the maximum bending strain. The shape of individual grain, therefore, was examined to obtain some information regarding the cristallographic relationship between grain growth and stress. As a result, it is clarified that the grain orients to the circumferential direction along the cylinder inside wall. This result means that the suction valve is bent in the longitudinal direction and that the stress concentration at the clamping portion is caused by the bending stress during the suction stroke.

On the contrary, the remarkable reduction in the stress is found in valve systems II and III, in which the root clamping has a straight shape by machining the cylinder block out in bevel or inserting a spacer between the cylinder block and the suction valve. This result shows that such construction as valve systems II and III are successful to reduce the stress concentration of the suction valve.

Impact Bending Stress of Suction Valve

Stress Distribution and Magnitude : Fig. 10 shows the free edge portion of the suction valve partially changed in colour on the seat side. The stress distribution is also given in Tables 3 and 4. It is noticed from these figure and tables that the stress concentrates at the center portion at the free edge of the suction valve. The colour change is concentrated at the center portion expanding to the longitudinal direction. As described in the previous paper (9), below an impact velocity of 6.0 m/s, the failure origin and chipping-off failure seem to concentrate around the center portion of the free edge of the suction valve. The main crack seems to be always in the longitudinal direction of the suction valve. These evidences coinside with the appearance of flecks obtained from this test. As given in Tables 3 and 4, the magnitude of the stress is about 250 N/mm². This is because the suction valve seems to collide against the valve stopper with a comparatively low velocity of 2.3 m/s.

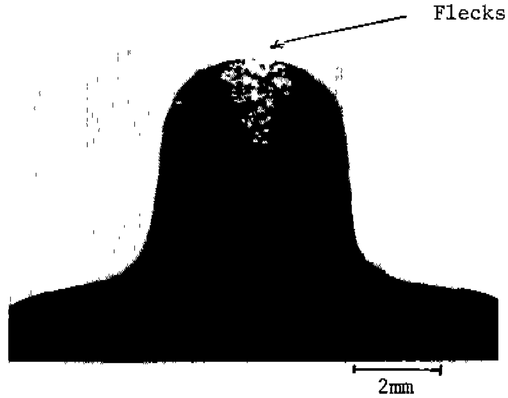


Fig. 10 Flecks at free edge portion in test No. 1

Generation Mechanism of Impact Stress : The shape of individual grain was also examined to obtain some information regarding the cristallographic relationship between grain growth and stress. As a result, it is clarified that the grain orients to the longitudinal direction of the suction valve. This result means that the free edge of suction valve seems to be bent in the transverse direction of the valve length and that fluctuated vibration mode with high frequency will be produced at the free edge of the suction valve as shown with arrows in Fig. 11 immediately after striking. As a result, the repeated bending stress might be applied to the suction valve, followed by the colour change of flecks initiated at the center portion of the suction valve on the seat side.

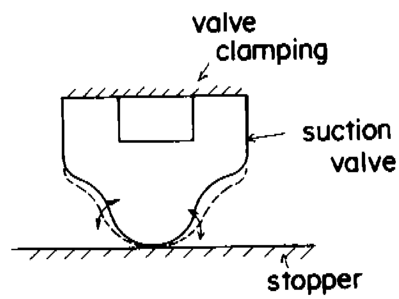


Fig. 11 Vibration mode at free edge portion just after suction valve hits stopper

CONCLUSIONS

The copper electrodeposite technique was applied to the stress measurement of the suction valve. A series of rotating-bending fatigue tests was carried out to determine the relationship between the stress level and the appearance of flecks. The suction valve with copper electrodeposite was operated under compressor operating conditions. Comparing the results of the rotating bending fatigue tests with the appearance of flecks on the valve surface, the magnitude, stress distribution, and generation mechanism are examined. The results obtained from this study are as follows.

(1) The copper electrodeposite technique is successful to determine the magnitude and distribution of the stress produced in the suction vlave. It is considered, however, that further investigation to cope with the limitation to temperature is necessary to widely apply this technique to the stress measurement of the compressor valve against all the operating conditions.

(2) The stress concentration is found at both edges of the clamping portion because the suction valve is bent in the longitudinal direction during suction stroke.

(3) The free edge of the suction valve seems to be bent in the transverse direction of the valve length. This may be produced by fluctuated vibration mode with high frequency immediately after striking.

(4) The appreciable stress concentration is found at both edges of the clamping portion in valve system I, in which the suction valve supported by the root clamping with the same shape as the cylinder inside wall has the stress concentration at the clamping portion. On the contrary, the remarkable reduction in the stress is found in valve systems II and III, in which the root clamping have a straight shape by machining the cylinder block out in bevel or inserting a spacer between the cylinder block and the suction valve.

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