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Deformation and Stress of Refrigeration Compressor Flexible Ring Valve

A. Futakawa

K. Namura

H. Emoto

DEFORMATION AND STRESS OF REFRIGERATION COMPRESSOR FLEXIBLE RING VALVE

Akemi Futakawa, Dr. Eng., Fellow Engineer, Koji Namura, Engineer
Central Research Laboratory, Mitsubishi Electric Corporation
Amagasaki, Hyogo, Japan
and Hironori Emoto, Manager
Air Conditioning and Refrigerating Equipment Engineering Section
Nagasaki Works, Mitsubishi Electric Corporation
Nishisonogi, Nagasaki, Japan

ABSTRACT

The purpose of this study is both theoretically and experimentally to present the deformation and stress of a flexible discharge ring valve, and to get design concept on this type valve and its backer plate. The strain measurements of the valve were carried out on the strain gauges mounted at the root of the spoke and at the transition point in the spoke. The deflection measurement was also performed by electrodes and then the relationships among strain, deflection, and pressure were examined. Moreover, the stress and deformation of the valve were statically calculated by the finite element method. These calculations were performed against various drag forces under three different supporting conditions. Comparing the theoretical results with the experimental results, the relationship between the valve deformation and stress was discussed over the wide range of operating pressures. The design concept of the backer plate was also discussed in conjunction with the valve deformation and stress.

1. INTRODUCTION

The design of a refrigeration compressor is based on two performances in terms of reliability of the machine components and efficiency. Previous researchers(1)∿(5) have extended the state of the art of compressor modeling to the point where it is possible to adapt a compressor simulation and predict the operating performance in terms of efficiency quite successfully. Most of them, however, have been carried out on the reed valve and there are few(6)∿(9) on the flexible ring valve because of three dimensional deformation under complex boundary conditions.

The flexible ring valve is widely employed in large compressors which have enough flow rates. In the design of this type valve, the designer will encounter to inconsistent requirements that the valve stress should be restrained below the fatigue strength of valve materials from the view point of valve reliability, and that the valve deformation should be taken as large as possible from the view point of gas flow or efficiency. In order to cope with these difficult problems, it is important to clarify the relationship between three dimensional deformation and stress distribution of the flexible ring valve in conjunction with restraint conditions for the valve deformation.

In this study, the experimental investigation was performed using the test equipment which had the same construction as that of an actual machine. The strain measurement was carried out on the strain gauges mounted on the valve surface at the root of the spoke and at the transition point in the spoke. The deflection of the valve was also measured by detecting contact between the valve and backer plate by the electrodes which were attached on the surface of the backer plate. Moreover, the deflection and stress of the valve were statically calculated by the finite element method. These calculations were performed against various drag forces for three different cases. The first was the case that the valve deformed without touching the backer plate. The second was the case that the valve deformed until it touched the backer plate at the outer periphery in the middle of the ring after touching at the outer periphery in the direction of the spoke. The third was the case that the valve deformed in the reverse turn. Comparing the theoretical results with the experimental results, the relationship between the valve deformation and stress was discussed in conjunction with the restraint conditions for the valve deformation. The design concept of the backer plate was also discussed.

2. TEST EQUIPMENT AND TEST PROCEDURE

2.1 Test Equipment

The test setup is shown schematically in Fig. 1 and photographically in Fig. 2. In this study, air was used as pressure medium uniformly to deform the valve. The compressed air was supplied by an air compressor and was led to an air container. The valve riveted to the valve plate was installed at the end of an approach-channel, and an electromagnetic controlled valve was connected between the approach-channel and the pipe connecting to the air container.

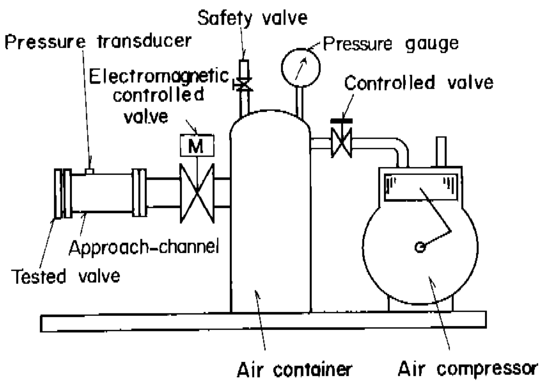


Fig.1 Schematic diagram of test equipment.

Fig.2 External view of test equipment.

2.2 Configurations of Flexible Ring Valve and its Related Parts

Fig.3 shows a cross section of the flexible discharge ring valve and its related individual components used in this test. The valve is sandwiched between the valve plate and backer plate and then is riveted together with them at the center portion. The backer plate has a symmetrical shape to the spoke and has a certain curvature between the spoke and the outer periphery in the middle of the ring, leading to increasing valve lift.

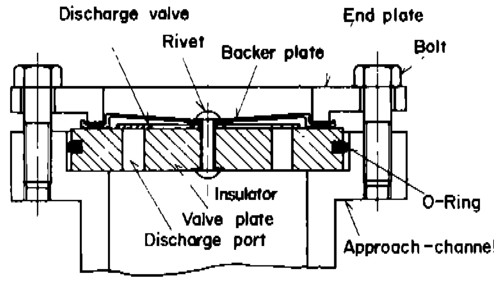


Fig.3 Cross section of valve and its related parts.

2.3 Measurement Methods

(1) Strain Measurements

Fig.4 shows the external view of the flexible discharge ring valve used in this test. Two types of strain gauges were mounted on the valve surface on the piston side at two different locations in accordance with the manufacture's instruction. One of them, one-element gauge, was bonded in the vicinity of the root of the spoke and was oriented in the direction of the spoke. The other, two-element rosette, was bonded at the transition point in the spoke and was oriented so that one-element was in the plane which contained the axis of the spoke, thus providing a convenient reference for reporting the direction of the principal stresses. In this paper, those locations are called points A and B as shown in Fig.4.

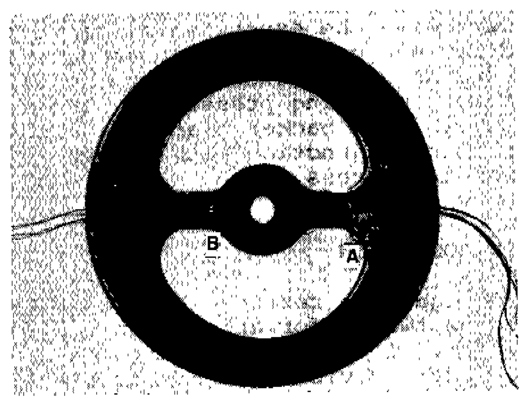


Fig.4 External view of tested valve.

In order to provide for the valve uniformly to contact to the valve seat of the discharge port, it was necessary that the lead wires from the strain gauges were pulled out in such a manner as to apply to the stationary contact pressure distributed uniformly along the valve seat. This was accomplished by machining the slits on the valve plate in which the lead wires were relieved. The output leads of the strain gauges were connected to a dynamic strain indicator and then this output was led to a photographic recorder in order to record the variations in strain.

(2) Displacement Measurements

In order to measure the deflection of the valve, a simple circuit was arranged so that a small voltage could be displayed on the oscilloscope, with valve and electrodes operating as on-off switch. Fig.5 shows the external view of the backer plate and electrodes. The moment when the valve touched the backer plate was detected at four different locations in the vicinity of the outer peripheries of the valve. This was accomplished by the electrodes bonded on the surface of the backer plate. In this paper, the locations of the electrodes are called points C and D as shown in Fig. 5. Points C and D are the locations corresponding to the outer peripheries of the valve in the spoke and its transverse directions, respectively. The electrode was made of aluminum foil bonding insulation film on its back side. As this accomplishment might lead to changing the valve lift, the insulation film with the same thickness as electrodes was inserted in the valve center. And the valve was sandwiched between the valve plate and backer plate, and then they were fastened together with the rivet covered with an insulation tube. A lead wire led from the cathode of a D.C. battery of 1.5V was connected to the rivet. Other lead wires from the electrodes were connected to the anode and then D.C. voltage was applied to each electrode.

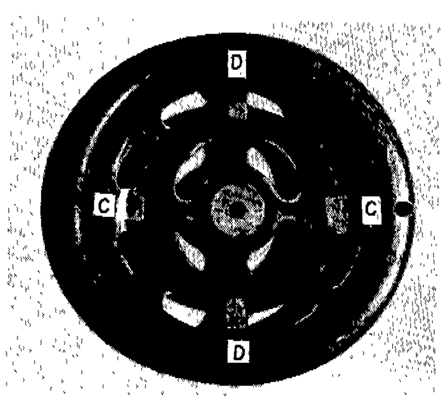


Fig.5 External view of backer plate.

(3) Pressure Measurements

A pressure transducer was installed to the approach-channel at the distance of 80 mm away from the valve. This transducer was the strain gauge type pick-up with the flat frequency of 3 kHz.

2.4 Test Procedure

For making a determination of the strain produced in the valve, the air compressor was started and the compressed air was supplied to the air container until a certain pressure was attained. The electromagnetic controlled valve was opened and then compressed air was led to the valve instantaneously. The pressure was indicated on the inlet side by the pressure transducer. The strain measurements of the valve were made at two locations described above and the outputs were recorded on the same sheet of the oscillograph paper with the pressure simultaneously. In order to check contact between the flexible ring valve and backer plate, the variations in D.C.current passing through each electrode were also recorded as on-off switch. Those allowed a complete set of variations in strain, pressure, and deflection.

3. STRESS ANALYSIS

A finite element computer program was assembled for the analytical solution of the plate. Descriptions of the finite element method are given in references (10)∿(11). Fig.6 shows a finite element idealization for a quadrant of the valve. As shown in Fig.6, in this paper, the direction of the spoke is defined as y direction, and the transverse direction is defined as x direction.

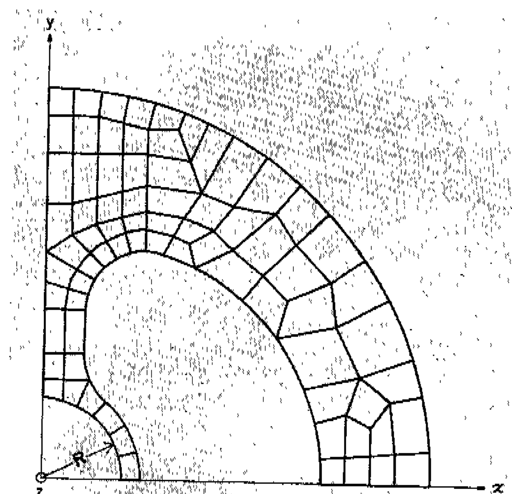


Fig.6 Finite element idealization for quadrant of valve.

The valve was subdivided into a number of quadrilateral elements which were defined by the corner nodal points shown in Fig.6. To improve accuracy, smaller elements were used in zone where rapid variations in stress were anticipated. As the valve was sandwiched between the valve plate and backer plate at its center portion, the valve might contact within radial distance R and separate beyond it in operating condition. This seems to mention that in the exact calculation, the nodal points on the parting line within the radial length of contact R should be common to elements in three plates. And it also mentions that the other elements adjacent to the parting line on each plate beyond radial distance R are separated from their corresponding elements in the mating plate and these elements should have no common nodal points.

In this analysis, however, the assumption was made that the backer plate and valve plate were rigid bodies because their thicknesses were remarkably larger than that of the valve. So the stress analysis was made under the supporting conditions that the flexible ring valve was fixed at radial distance R. The load acting on the valve was assumed to be a purely perpendicular load distributed uniformly over the region of the ring.

The output of the finite element computer program included the deformation and stress of each node in the x and y directions. These outputs were plotted on the sheets by the plotter, that is, the outputs of the deformation were plotted with the overall view of the three dimensional model for a quadrant of the valve and the outputs of the stress were plotted with the contour plots of stress intensity for the plane stress.

In this stress analysis, three different kinds of supporting conditions were investigated. The first one was the case that the valve was freely deformed without touching the backer plate. This was performed to clarify the relationship between three dimensional deflection and the stress distribution of the valve. The second one was the case that the valve was deformed as simply supported at point C. The third one was the case that the valve was deformed as simply supported at point D. Those calculations were made to get fundamental knowledge about the effect of the restraint conditions for the valve deformations on the stress distribution of the valve.

4. TEST RESULTS AND DISCUSSION

4.1 Variations in Strain

Fig.7 shows a typical record obtained from the test arrangement shown in Figs. 1 and 3. In this figure, two traces from the top denote the variations in current detected by the electrodes bonded at points C and D. The variations as on-off switch show the moment when the valve touches the backer plate at each location. The third and forth traces show the variations in strains in the x and y directions measured by the strain gauge bonded at point A, respectively. The strain in the y direction is compression but is recorded with reversed sign from effective use of the sheet. A bottom trace shows the pressure variation.

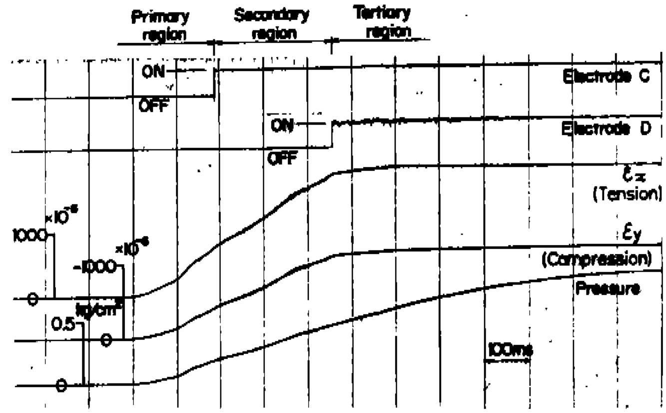


Fig.7 Typical record of strain, pressure, and current.

As can be seen in Fig.7, the variation in strain is divided into three regions. That is, there is a primary region where the strain increases in proportion to the pressure. The primary region is followed by contacting between the valve and backer plate at point C, leading to the secondary region. In the secondary region, the strain still increases in proportion to the pressure, but the increasing rate in strain slightly changes in comparison with that in the primary region. In the tertiary region after touching at point D, the strain gets kept almost constant in spite of pressure increasing. This result illustrates that the deformation of the valve is more restricted by the backer plate.

4.2 Comparison between Analytical and Experimental Results of Strain Variation

Fig.8 shows the relationship between the pressure and the strains determined analytically and experimentally. The analytical results were obtained under the condition that the valve deflected until it sat flat on the backer plate after touching

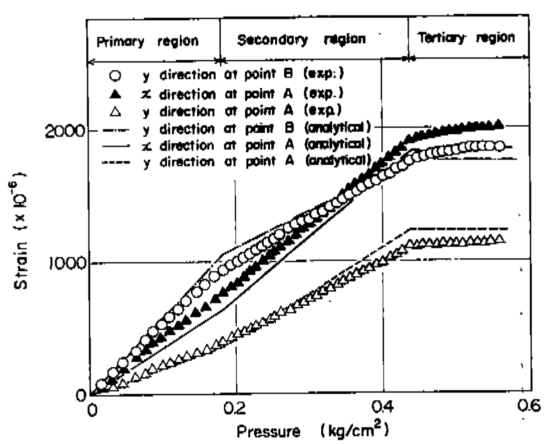


Fig.8 Comparison between analytical results and experimental results.

at points C and D. In this calculation, the effective coefficient of drag 0.75 ∿ 0.80[6] was used. On the basis of the good correlation between the results of the analytical and experimental strain values for the valve, the analytical result seems to have been quite satisfactory from the stand point of having achieved restraint conditions.

4.3 Valve Deflection for Case of No Backer Plate

The output of the deformation plotted with the overall view of three dimensional model for a quadrant of the valve is shown in Fig.9. In this figure, the solid line denotes the result under the uniform lateral load of 0.1 kg/cm^2 and the dotted one denotes that under initial condition. As can be seen in Fig.9, the spoke of the valve deflects as if it seems like a cantilever assumed as fixed at the center and as free at the outer periphery. The deflection of the ring, however, increases with the tangential deviation along the ring from the spoke. The same tendency is also found in the twisting angle of the ring. This means that the ring is deformed with the bending and twisting moments caused by the uniform load perpendicularly applying to the valve.

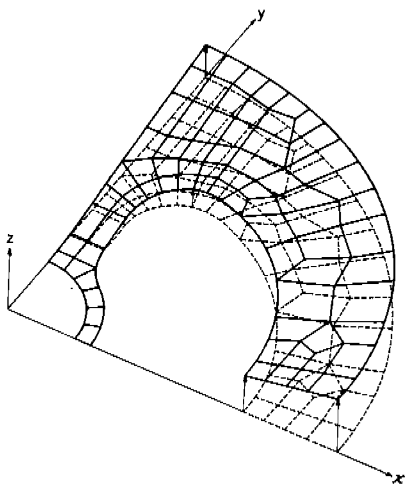


Fig.9 Output of deformation plotted with overall view of three dimensional model for a quadrant of valve under free deformation.

4.4 Stress Distribution of Valve

Since the exact nature of the contact-type boundary constraints was not known, the effects of changing the degree of constraint on the valve stress had to be determined. This was accomplished by comparing the calculated results for three different kinds of constraint conditions. The finite element analysis was conducted at three stages of this investigation.

(1) Stress Distribution under No Restraint

The first stage of the finite element analysis was performed for the case of the valve freely deforming without touching the backer plate.

The contour plots of stress intensity of the valve in the x and y directions are shown in Figs.10 and 11, respectively. These results were obtained by applying the uniform lateral load of 0.1 kg/cm^2 to the ring portion. It is observable in the x direction that the location of the maximum stress intensity is at point A, and that the stress at point B is also comparatively large. It is also clear in the y direction that the stress becomes maximum at point B, and that the stress at point A is compression. Those locations are the perforated region of the valve containing holes with complex shape. This may lead to the problem of inferior evidence of tumbling

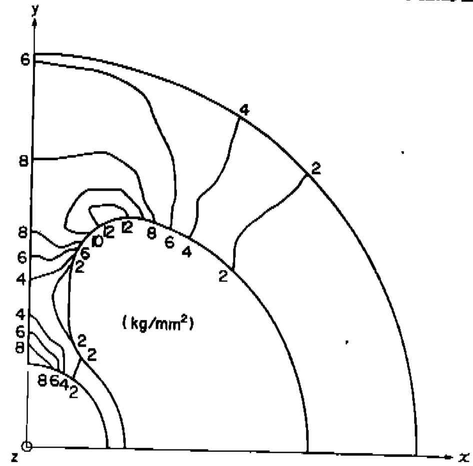


Fig.10 Contour plots of stress intensity of valve in x direction under free deformation.

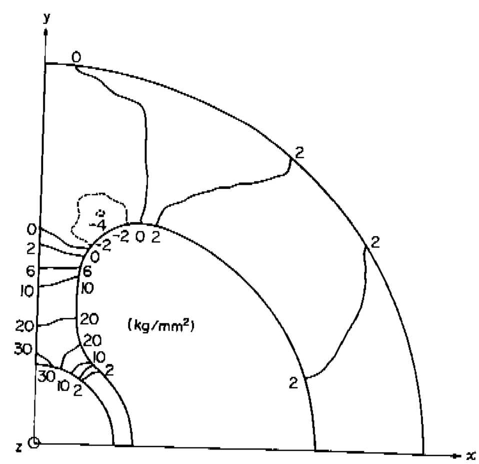


Fig.11 Contour plots of stress intensity of valve in y direction under free deformation.

for the edge of the valve. This suggests that reduction in stresses at those locations is needed to get higher reliability of the valve without any reduction in the gas flow area.

(2) Deformation and Stress Distributions under Restraint Conditions

The second and third stages of the finite element analysis were performed to clarify the effect of the constraint conditions on the valve stress. Figs.12 and 13 show the outputs of deformation plotted with overall view of three dimensional model for a quadrant of valve supported at points C and D, respectively. Fig.14 is the contour plots of the variation of stress in the x direction after the valve touches the backer plate at point C. Fig.15 is ones in the y direction after touching at point D.

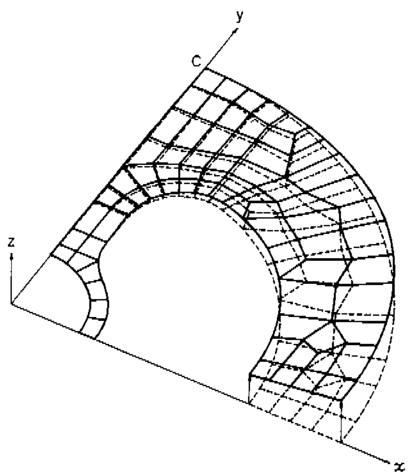


Fig.12 Output of deformation plotted with overall view of three dimensional model for a quadrant of valve supported at point C.

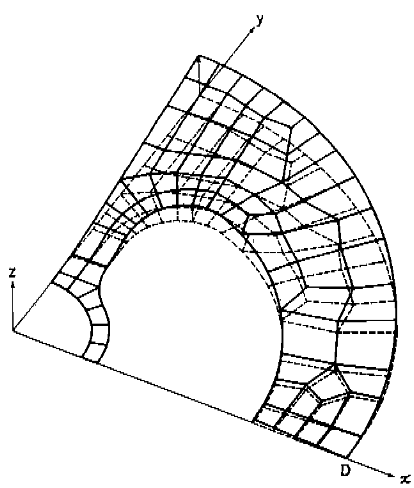


Fig.13 Output of deformation plotted with overall view of three dimensional model for a quadrant of valve supported at point D.

These results were calculated under the uniform lateral load of 0.1 kg/cm^2. As the stresses in the other direction are smaller than that shown in Figs.14 and 15, these results are omitted from the illustration.

When the valve deforms as supported at point C, the stress produced in the valve becomes maximum at point A. Comparing this result with the deformation of the valve shown in Fig.12, it notes that the stress at point A is mainly ruled with the flexural and torsional deformations of the ring. When the valve deforms under restraint of displacement at point D, the stress of the valve becomes maximum at point B. Comparing this result with the deformation of the valve shown in Fig.13, it is clear that the stress at point B is mainly ruled with the flexural deformation of the spoke in the y direction.

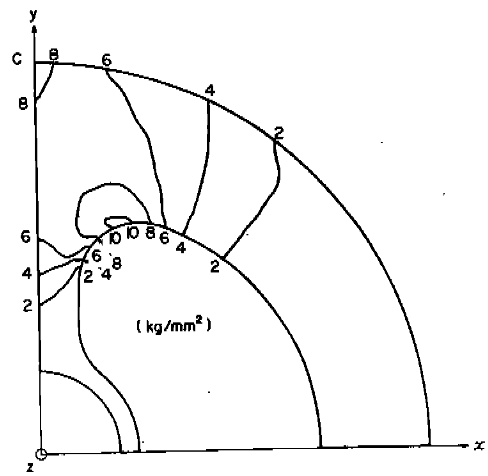


Fig.14 Contour plots of stress intensity of valve in x direction supported at point C.

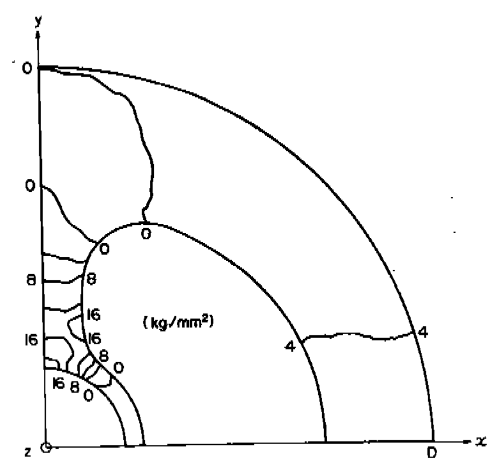
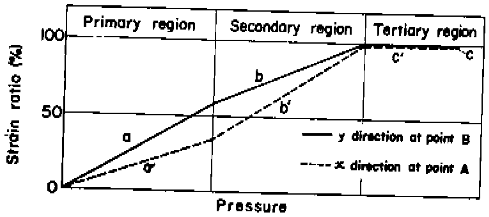


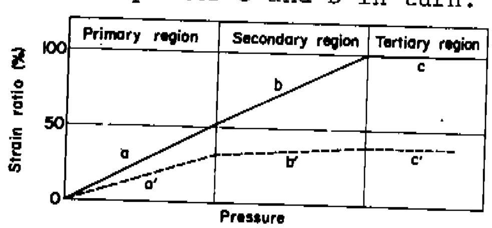
Fig.15 Contour plots of stress intensity of valve in y direction supported at point D.

4.5 Design Concept of Backer Plate

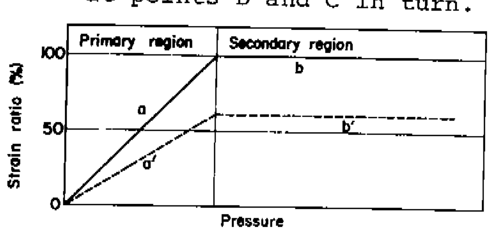
In order to get better understanding of the valve stress, the strain variations produced in the valve at points A and B are schematically shown with the solid and dotted lines in Figs.16 (a) ∿ (c) for three different restraint conditions, respectively. The ordinates of these figures show the strain levels denoted with percentage for the allowable strain. Fig.16 (a) illustrates the strain variations under the condition that the valve touches the backer plate at points C and D one after another. Fig.16 (b) indicates one under the condition in its inverse turn. Fig.16 (c) shows one under the condition simultaneously touching at points C and D. In these figures, the strain variations delineate three distinct regions of constraint conditions. Each region is indicated by the consecutive letters of the alphabet, which designate the successive legs of the strain variations. For example, in the primary region shown in Fig.16 (a), the strain will be produced by the only deformation of the valve without touching the backer plate; in the secondary region, the strain will be produced by the deformation of the valve supporting at point C of the outer periphery; in the tertiary region, the strain



(a) Valve touches backer plate at points C and D in turn.



(b) Valve touches backer plate at points D and C in turn.



(c) Valve touches backer plate at points C and D simultaneously.

Fig.16 Schematic strain variation vs. pressure correlations under three different conditions.

will be restricted by the backer plate.

If the valve touches the backer plate at points D and C one after another, comparatively large strain will be produced at point B as can be seen in Fig.16 (b). If the valve simultaneously touches the backer plate at points C and D, the deflection of the valve might be determined with the deflection at point C from the view point of the valve strength. This will invite the loss of gas flow area. From those results, if the valve deforms so as to touch the backer plate at points C and D one after another, and the backer plate is designed with the shape corresponding to the three dimensional deformation of the valve when touching at point D, successful design of the backer plate will be expected in terms of higher reliability of the valve strength and larger gas flow area.

From the view point of eliminating the impact strain, it is considered to be better if the backer plate is designed so that the valve could wrap about the backer plate by giving slightly lower lift than that given in accordance with the manner described above.

The design concept described above is in accordance with practical experience for the backer plate. The design of the backer plate has been largely a matter of trial and error up to date. However, through this investigation, it is considered to be made possible to determine quantitatively the shape and dimension of the discharge ring valve and backer plate.

CONCLUSION

The results obtained from this investigation are as follows.

(1) When the uniform distributed lateral load is applied to the valve, three dimensional deformation is produced in the valve, in which the deflection in the direction of the spoke is comparatively smaller than that in the transverse direction.

(2) At the root of the spoke, the flexural stress becomes predominant because of the flexural deformation of the spoke.

(3) At the transition point in the spoke, the stress due to the torsional deformation superimposes to the bending stress because of the torsional and flexural deformations of the ring.

(4) When the valve deforms under no restriction, the stress at the root of the spoke has the tendency to become larger than that at the transition

point in the spoke because of the rigidity of the spoke which is required for quick return during compressor operation.

(5) From the view point of the valve strength and gas flow area, successful design will be expected if the backer plate is designed so that the flexible discharge ring valve touches the backer plate at the outer periphery in the direction of the spoke at first and then wraps about the backer plate until it touches the outer periphery at the middle of the ring.

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