

1982

Impact Fatigue Behaviour of Flapper Valve Steel

A. Futakawa

K. Namura

Follow this and additional works at: <https://docs.lib.purdue.edu/icec>

Futakawa, A. and Namura, K., "Impact Fatigue Behaviour of Flapper Valve Steel" (1982). *International Compressor Engineering Conference*. Paper 382.

<https://docs.lib.purdue.edu/icec/382>

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at <https://engineering.purdue.edu/Herrick/Events/orderlit.html>

IMPACT FATIGUE BEHAVIOUR OF FLAPPER VALVE STEEL

Akemi Futakawa, Dr. Eng., Manager and Koji Namura, Engineer
Central Research Laboratory, Mitsubishi Electric Corporation,
Amagasaki, Hyogo, Japan

ABSTRACT

The purpose of this study is to discuss the impact fatigue failure mechanism of a suction valve that involves the fracture with fragments torn off from the edge or surface. The shape and dimensions of the test specimen and stopper were made the same as those of the suction valve and stopper in an actual compressor. The specimen was operated by short-duration compressed air pulses, and struck against the stopper and seat alternately. The impact velocities of the specimen against the stopper and seat were controlled by the pressure of the compressed air.

The short-duration compressed air pulses were generated by air shutters. Impact fatigue tests were performed under several impact velocities of the specimen against the stopper. The cracked surface and fatigue failure surface were observed at each certain number of impact cycles with an optical microscope and a scanning electron microscope. The crack feature, crack propagation, and crack origin were examined. From those results, impact fatigue failure mechanism of the suction valve is clarified.

INTRODUCTION

The problem of the compressor valve is most considerable importance for withstanding high impact shock. Impact fatigue strength of valve materials in alternating impact has been experimentally by Svenzon (1)(2), Dusil (3)(4), and others (5). The effect of oblique impact and seat positioning on impact fatigue strength have been discussed by Svenzon (1) and Dusil (3). However, most of them have been carried out on the impact strength of valve materials with respect to collision of a valve to a valve seat. Impact fatigue failure with respect to collision of a suction valve to a valve stopper is another important problem in actual compressor design. The study in this area is not sufficiently at this moment.

A lot of researchers have reported that

information about the failure mode, stress state, local stress concentration, fabrication problems and service environment can be obtained from a fractographic analysis of these fracture surface features (6) ~ (8). In order to clarify the impact fatigue failure mechanism of a suction valves, these informations seem to be inevitably valuable because of complex nature of impact fatigue failure.

From this point of view, detail observations of fracture process were carried out to clarify the impact fatigue failure mechanism caused by collision between the tip of a suction valve and a valve stopper during suction stroke. An impact fatigue testing machine was developed for this study, in which the test specimen could be operated by short-duration compressed air pulses. Repeated impact loadings were applied to the test specimen and then impact fatigue cracks were induced. The cracked surface and fracture surface of the test specimen were examined and photographed at various magnifications, using optical and scanning electron microscopes. Area of crack region, rapid fracture, final break off, and abrasion from rebound were identified. On the bases of those results, impact fatigue failure mechanism of the suction valve is clarified.

TEST SPECIMEN AND PROCEDURE

Test Specimen

The shape and dimensions of the test specimens are shown in Fig. 1. The specimen has the same shape and dimensions as a suction valve of an actual refrigerating compressor. The chemical composition of the test specimen is given in Table 1. The tensile properties and hardness is given in Table 2. The test specimens were blanked from the strip parallel with the rolling direction as shown in Fig. 1. The edges were not ground and polished to induce the impact fatigue failure easily.

Test Procedure

Test Apparatus: Fig. 2 shows the schematic of an impact fatigue testing machine.

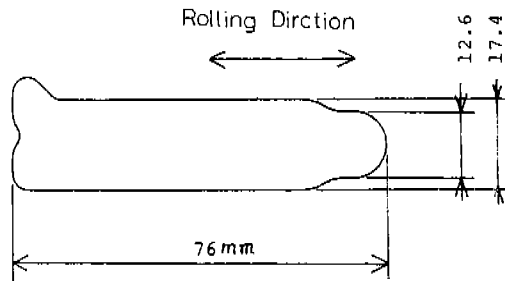


Fig. 1 Shape and dimensions of test specimen

Table 1. Chemical composition of test specimen (wt %)

C	Si	Mn	Cr
1.00	0.20	0.40	0.15

Table 2. Tensile properties and hardness of test specimen

Tensile strength kg/mm ²	Yield strength kg/mm ²	Hardness Hv
197	179	560

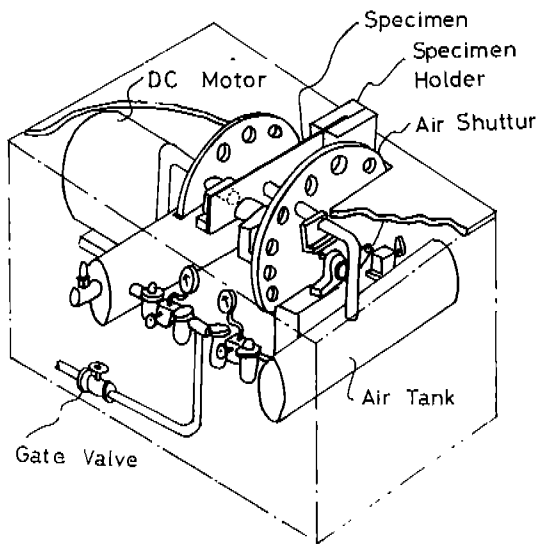


Fig. 2 Schematic of impact fatigue testing machine

Fig. 3 is the schematic diagram illustrating the relationship between the specimen and its related parts. The test specimen was operated by short-duration compressed air pulses. These pulses were generated by air shutters which consisted of two rotating disks, containing a lot of circular transverse perforations in the vicinity of the circumference of the disks.

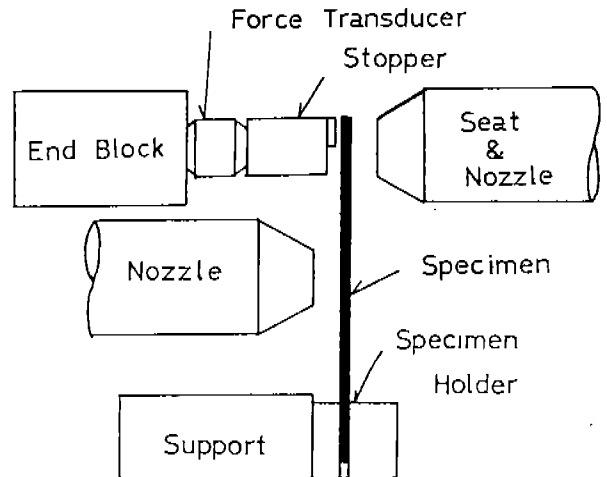


Fig. 3 Schematic diagram illustrating relationship between specimen and its related parts

The disks were driven by a D.C. motor to vary the duration of the compressed air supply. Two nozzles were installed facing to the disks as shown in Fig. 3. The compressed air of which the pressure was controlled with a gate valve was led to an air tank through an air filter and supplied to nozzles. Thus, short-duration air pulses were generated.

Test Procedure: The studies on the cracked surfaces and impact fatigue surfaces have frequently been shown to be of great value in understanding the basic mechanism of impact fatigue. The topographic analysis of post-failure fracture surfaces has also been used to advantage in determinations of failure patterns. Accordingly, this study focuses on the appearance of the cracked surface and impact fatigue surface features and on examination the correlation of this structure with the crack growth pattern.

The impact fatigue tests were carried out under nine impact velocities against the stopper. The operating frequency was 135 Hz. The motions in the tip of the test specimen were recorded by a high speed camera under a wide range of supplied air pressures at the preliminary stage of the impact fatigue test. The relationships between the impact velocity of the test specimen and the supplied air pressure were obtained. In this study, the impact velocity was defined as approach velocity in the tip of the test specimen obtained from these relations. Number of cycles was counted with an electric counter.

The fatigue surfaces were examined with both optical microscopy and scanning electron microscopy. The optical micro-

scopy was used for recognizing the microscopic features of impact fatigue cracks. The test specimen was removed from the impact fatigue testing machine everytime a certain number of cycles was applied the test specimen. Then occurrence and propagation of impact fatigue cracks were identified. This procedure was repeated up to failure. The scanning electron microscopes was used for clarifying the impact fatigue failure surface features. The partially cracked specimens were pulled in a tensile testing machine to expose the crack shape. The failure surface appearance in the impact fatigue and static tensile regions were sufficiently different that there was no difficulty in distinguishing the crack front. Sections which included the impact fatigue failure were cut from the test specimen and mounted for scanning electron microscopy examination. This procedure was also carried out for the test specimens which were broken off.

RESULTS AND DISCUSSION

Macroscopic Observations

Impact Fatigue Damages: Figs. 4(a) and (b) show typical examples of impact fatigue damages produced in this test. Fig. 4(a) was obtained at 1.4×10^5 cycles under an impact velocity of 5.5 m/s. Fig. 4(b) was obtained at 8.7×10^4 cycles under an impact velocity of 7.5 m/s.

As can be seen in Figs. 4(a) and (b), impact fatigue damages are divided into two types of features in accordance with the impact velocity. The first one is the impact damage caused under the impact velocity below 6.0 to 7.0 m/s. Within this region of impact velocity, the failure origin and chipping-off failure seem to concentrate around the center portion of the semicircular edge of the test specimen. The initial propagation of the main crack seems to be always in the radial direction of the semicircular. The second one is that caused under the impact

velocity beyond 7.0 m/s. In this region, the failure origin and chipping-off fractures are scattered along the circumference of the semicircular edge of the test specimen and the propagation of the main crack orients to the longitudinal direction of the test specimen, coinciding with the rolling direction.

To clarify the nature of impact fatigue cracks in more detail, sequences of macrographs were taken along the length of the crack to compare the differences in crack features and crack propagations at different impact velocities. Figs. 5(a) and (b) show typical examples of the macroscopic shapes of the impact fatigue cracks on the seat side and on the stopper side, respectively, which were caused under an impact velocity of 4.8 m/s. Figs. 6(a) and (b) shows that for an impact velocity of 7.5 m/s, which are correspond to the impact fatigue damage shown in Fig. 4(b).

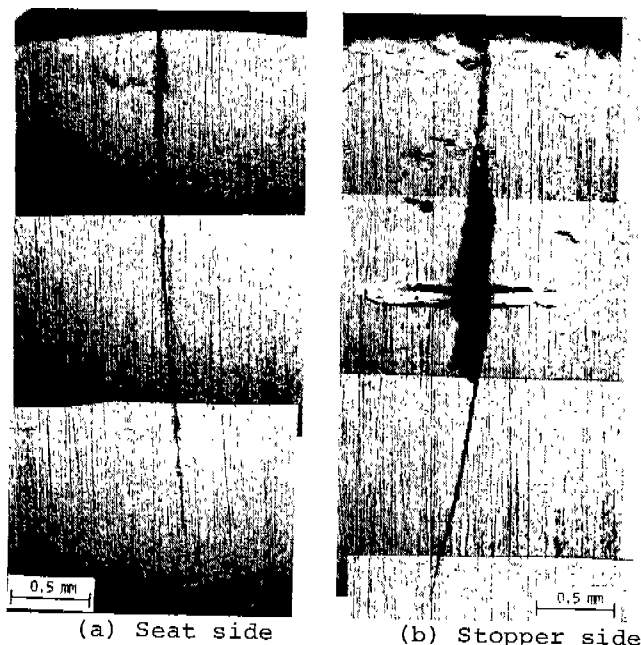


Fig. 5 Typical example of macroscopic shapes of impact fatigue crack ($V = 4.8$ m/s, $N = 5.2 \times 10^5$)

Comparing Fig. 5 with Fig. 6, appreciable difference is found in the nature of fracture initiation. When the test specimen is operated at an impact velocity of 4.8 m/s, the origin of failure is at the center of semicircular edge and then the crack propagates to the radial direction of the semicircular, followed by chipping-off failures. On the contrary, when the test specimen is operated at an impact velocity of 7.5 m/s, a lot of origins of impact failure are found along the circumference of the semicircular edge. Some of

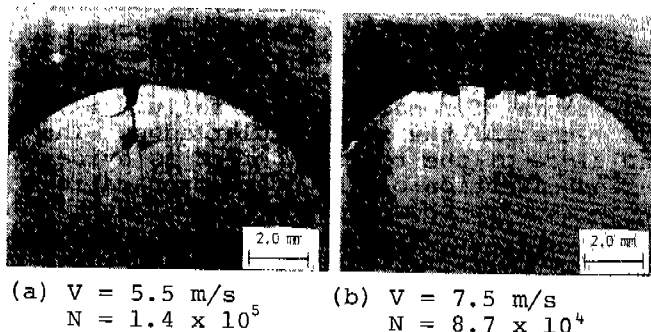
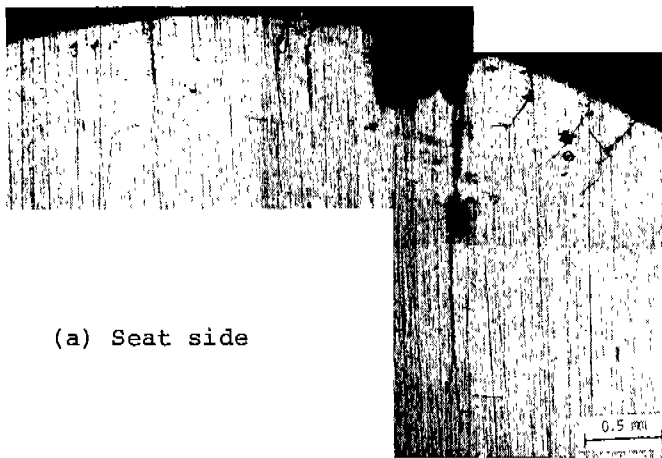
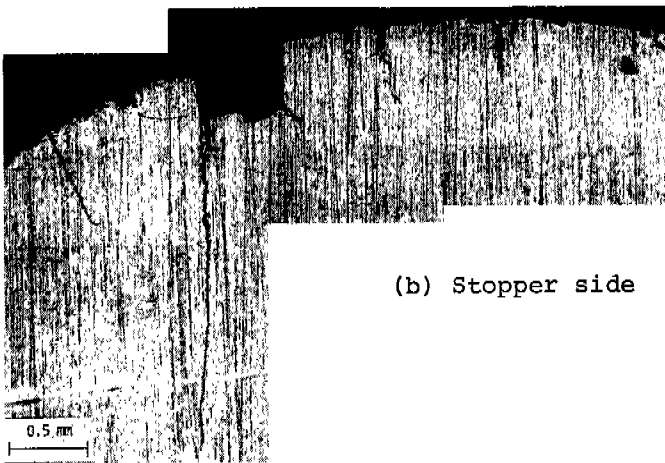


Fig. 4 Typical example of impact fatigue damages on stopper side surface



(a) Seat side



(b) Stopper side

Fig. 6 Typical example of macroscopic shape of impact fatigue crack
($V = 7.5 \text{ m/s}$, $N = 5.1 \times 10^5$)

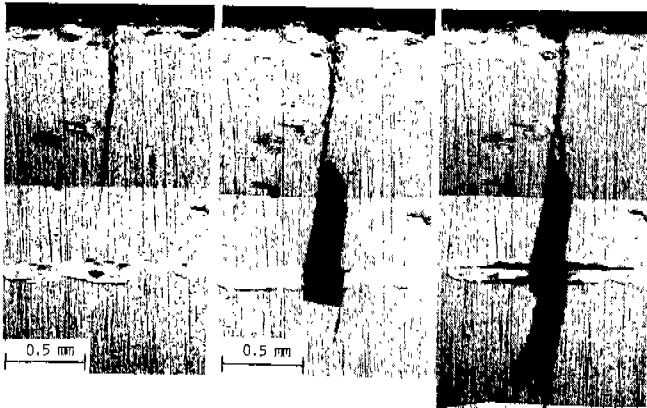
these cracks propagate to the longitudinal direction of the test specimen, coinciding with the rolling direction, and some of them orient to the radial direction of the semicircular.

It is noticed from those results that once impact fatigue has been identified as the mode of failure, the point of origin, or fracture initiation side, and the impact velocity level would be established. This is often the single most important item in the failure analysis in service or in testing, since whatever corrective action is applied must be applied at the failure initiation site to be effective. Although macroscopic examination remains the primary and, in many cases, the only fracture surface analysis tool for most field engineers, this technique is comparatively useful to examine the failure process of the compressor valve because of the simplicity and economy of the necessary equipment.

Impact Fatigue Crack Origin: In order to clarifying the nature of fracture initiation and to get the hypothesis of impact fatigue crack initiation prior to failure, the origin of failure was examined by comparing Fig. 5(a) with Fig. 5(b) and Fig. 6(a) with Fig. 6(b). Particularly noticeable in Figs. 5(a) and (b) is comparatively long crack expanding to the longitudinal direction, accompanying with large chipping-off failures on the surface of the stopper side. From this result, the origin of the primary crack is at the center of the circumferential edge and directional characteristics in the crack growth is attributed to the strip rolling processing, when the test specimen is operated at low impact velocity. On the contrary, when the test specimen is operated at higher impact velocity, a large number of cracks are found around the circumferential edge on the seat and stopper sides as shown in Figs. 6(a) and (b). This observation leads to the hypothesis of impact fatigue crack initiation that the failure origin is at the multi-points of the circumferential edge, when the test specimen is operated at higher impact velocity.

Crack Growth History: A system was developed for classifying surface feature types so that any systematic developments in crack formation could be detected. A series of impact fatigue tests were carried out at nine impact velocities and then the macroscopic features on either side of the surface with cracks were examined in detail with an optical microscopy. Photographs of the crack feature were taken at each stage after a certain number of cycles was applied to the test specimen. The growth history of the impact fatigue crack was determined from the composite pictures of the crack region formed by overlapping identical area in adjacent photographs.

Let's attack the crack growth history of the test specimen at an impact velocity below 6.0 to 7.0 m/s. Figs. 7(a) to (c) show the crack features at 2.9×10^5 , 4.5×10^5 , and 5.8×10^5 cycles, respectively. On the fatigue side of the crack fronts, several distinct types of crack features are found. As described above, the origin of impact fatigue failure is at the center of the semicircular edge. The influence of the rolling defect is evident on the direction of the crack propagation. The fatigue process forms long straight line with a length of about 1.5 mm on the surface approximately parallel with the rolling defect. At 4.5×10^5 cycles in Fig. 7(b), comparatively large chipping-off failure appears at the crack front site on the surface. This photograph gives the impression of spreading into two



(a) $N = 2.9 \times 10^5$ (b) $N = 4.1 \times 10^5$

Fig. 7 Crack features on stopper side at low impact velocity ($V = 4.8$ m/s)



(c) $N = 5.8 \times 10^5$

branches toward the crack front from a distance of about 1.0 mm apart the circumferential edge, leading to the linkage of two branched cracks. Fig. 8 shows the cross sectional view of the chipping-off failure zone. The cross section with vee shape means that a small fragment has torn off from the surface on the stopper side. The almost same crack growth history is observed at 5.8×10^5 cycles in Fig. 7(c). These observations lead to the conclusion that within an impact velocity of 6.0 to 7.0 m/s, a single crack is generated at the center of the circumferential edge and then the main crack which propagates to the radial direction spreads into branches, followed by chipping-off failures due to the linkage of these branched cracks.

On the crack growth history at an impact velocity beyond 7.0 m/s, the multi-crack origins along the circumferential edge are found as distinct type of the impact fatigue failure as shown in Fig. 6. Determining minutely the shape of the fracture crack leading edge from Fig. 6, the front shape of a few cracks is slightly curving to the tangential direction. These observations lead to the hypothesis that the lost of comparatively large

fragments from the circumferential edge as can be seen in Fig. 6 is caused by the linkage of individual cracks in the radial, or longitudinal direction, with the cracks in the tangential direction.

Microscopic Observations

In order to establish the identification and analysis of impact fatigue failures whose macroscopic failures are ambiguous, the failure origin was more precisely examined on the failure surface at higher magnification. This was done for the partially cracked specimens obtained from the tests at an impact velocity of 5.5 m/s. Fig. 9 shows an allover view of the impact fatigue failure surface. A half-moon-shaped line is clearly observed on the fracture surface at the crack front on the seat side. This gives substance to evidence that the crack origin is at the corner of the circumferential edge on the seat side and propagates to the stopper side direction in addition to the radial direction.

Fig. 10 shows the magnified fracture surface at the circumferential edge. Although very severe rub marks are found on the fracture surface, the ridge pattern seems to spread from the corner on the seat side to the stopper side. This result suggests that the crack origin is at the corner of the circumferential edge on the seat side and that the crack propagates to both radial and stopper side directions.

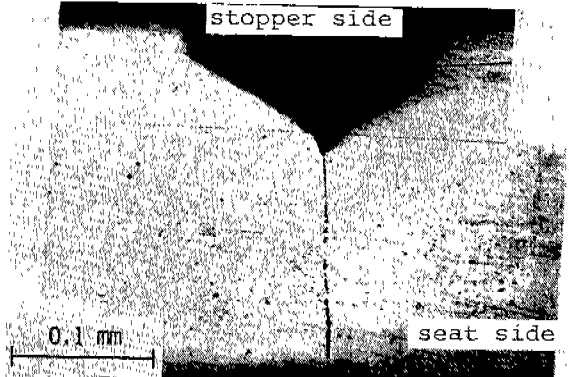


Fig. 8 Cross sectional view of chipping-off failure zone



Fig. 9 Allover view of impact fatigue failure surface

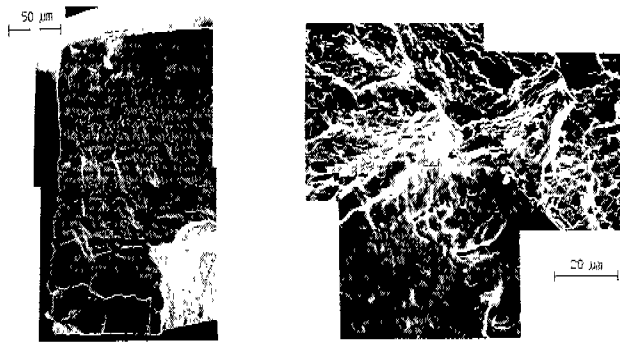
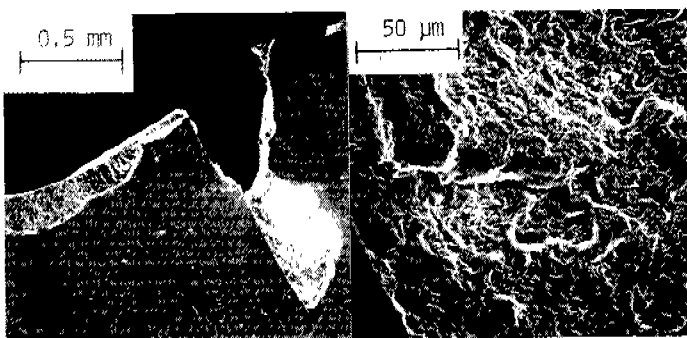


Fig. 10 Magnified fracture surface at circumferential edge

Fig. 11 Magnified photograph of region A in Fig. 9

Fig. 11 shows a magnified photograph of region A shown in Fig. 9. Three different features are observed in this area; left upper side, bottom side, and right side. The fracture surface feature in the left upper side is a typical impact fatigue surface which is similar to that reported by Dusil (3). In the fracture surface feature in the bottom side, there are chevron marks as rapid fracture features. This may be caused by rapid fracture at the final stage induced after the crack propagates as far as a certain distance from the surface on the seat side. The fracture surface in the right side is a typical brittle fracture surface which is caused by pulling in a tensile testing machine to expose the crack shape.

Fig. 12(a) shows a crack in the circumferential direction stretching from the radial crack and Fig. 12(b) shows the magnified aspect at the chipping-off failure portion. This fracture surface is a typical fatigue surface containing a lot of rub marks. From this result, it is clear that the crack in this area is also



(a) Allover view (b) Magnified aspect

Fig. 12 Crack in circumferential direction stretching from radial crack

gradually expanded by applying to cyclic stresses.

Impact Fatigue Failure Mechanism

On the bases of the evidence obtained through the various analysis procedures described above, some considerations are taken on the impact fatigue failure mechanism of a suction valve when it hits repeatedly a valve stopper during suction stroke. Figs. 13 (a) to (c) show illustration of the dynamic deformation when the suction valve hits a valve stopper. Fig. 13 (a) shows the valve deformation just before striking. Fig. 13 (b) and (c) show the valve deformation after striking at low impact velocity and higher impact velocity, respectively.

At the early stage during suction stroke, the tip of the suction valve moves to a valve stopper deforming as shown in Fig. 13 (a). In the case where the impact

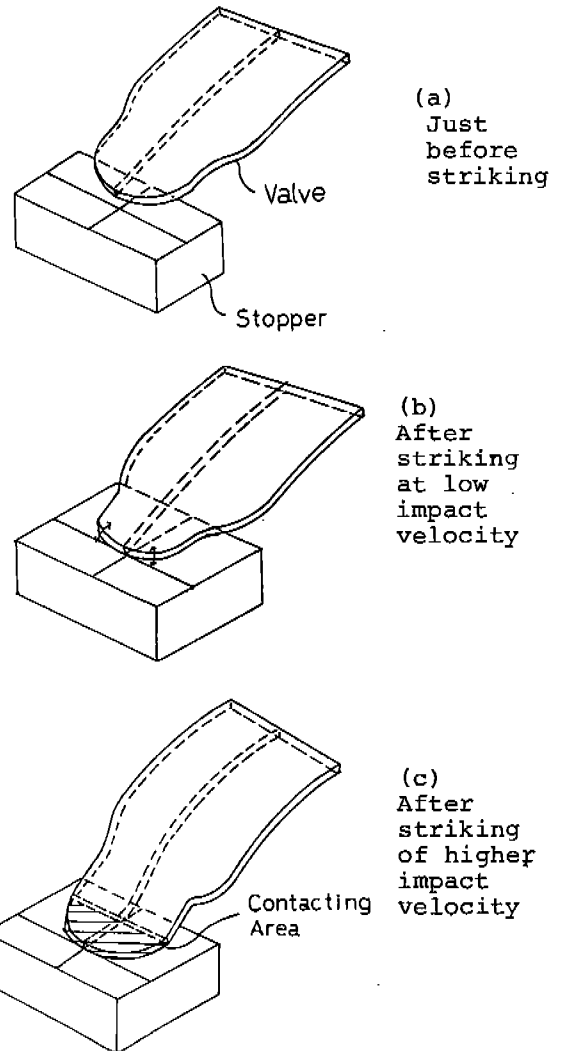


Fig. 13 Illustration of dynamic deformation

velocity is low, fluctuated vibration mode with very high frequency will be produced at the tip portion of the suction valve as shown with arrows in Fig. 13 (b) immediately after striking. As a result, large repeated bending stress might be applied to the suction valve, followed by impact fatigue failure initiated from the corner of the center edge on the seat side. When the impact velocity is much higher, the tip portion of the suction valve might contact to the valve stopper with comparatively large area as shown in Fig. 13 (c), accompanying with high frequency vibration in the circumferential and radial directions. Accordingly, large impact stresses, which are caused by not only bending deformation in the circumferential direction but also that in the longitudinal direction, are produced along the circumferential edge of the suction valve. These stresses might rule the impact fatigue failure with a lot of cracks along the circumferential edge.

Relationship between Impact Velocity and Number of Cycles to Failure

Fig. 14 shows the relationship between the impact velocity and number of cycles to failure. The black marks shown in Fig. 14 denote the moment where a small crack was initiated and the arrows denote the duration from the crack initiation to the lost of fragments from the edge or surface.

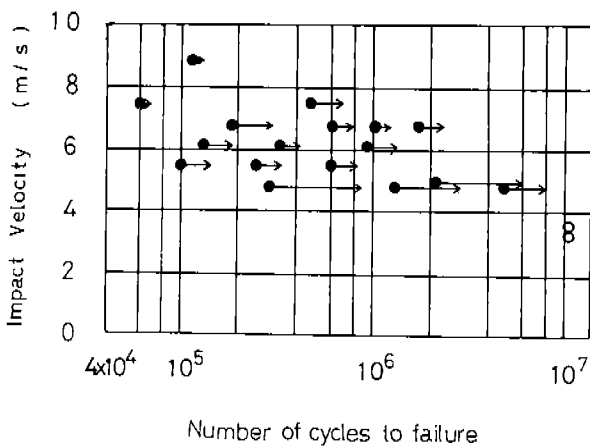


Fig. 14 Relationship between impact velocity and number of cycles to failure

As can be seen in Fig. 14, the impact fatigue mode is divided into three regions with respect to the impact velocity. In the first region above 6.0 to 7.0 m/s, the chipping-off failure, or the lost of fragments from the edge or surface, is produced at a short period after cracks are initiated. This phenomenon is caused by the linkage of the multi-cracks induced along the circumferential edge. In the

secondary region between 6.0 to 7.0 m/s and 4.0 to 4.5 m/s, crack propagates to the radial direction for a little while after the crack is initiated and then the chipping-off failure is induced. This phenomenon is caused by the linkage of cracks spreading into branches from the main cracks on the way to propagation in the radial direction. In the tertiary region below 4.0 m/s, no impact fatigue failure is induced into the test specimen.

From those results, an allowable impact velocity of about 4.0 m/s is recommended in the design of the tested suction valve. In this study, the test specimens of which edges were not ground and polished were used to induce the impact fatigue easily. Higher allowable impact velocity, therefore, seems to be acceptable. However, the value obtained from this study is considered to be an allowable impact velocity in safety design. In order to establish the general concept on the allowable impact velocity, further investigations are needed to conduct with respect to the various surface and edge finishment and the dimensions and shape of the suction valve.

CONCLUSIONS

An impact fatigue testing machine was developed and a series of impact fatigue tests were carried out on suction valves as test specimens. The cracked surface and fractured surface of the test specimen were examined and photographed at various magnifications, using optical and scanning electron microscopes. On the bases of those results, impact fatigue failure mechanism of the suction valve is clarified.

The results obtained are as follows:

- (1) The developed impact fatigue testing machine, which is consisted of two rotating disks with a lot of perforations in the vicinity of the circumferential edge and two nozzles facing to the disks, is successful to conduct impact fatigue tests on suction valves by means of short-duration air pulses.
- (2) When the suction valve is operated at an impact velocity of beyond 6.0 to 7.0 m/s, a lot of cracks are initiated along the circumferential edge of the test specimen. Some of them propagate to the longitudinal direction of the test specimen and some of them to the radial direction of the semi-circular. The chipping-off failure is induced by the linkage of these cracks due to cracks spreading in the circumferential direction.

- (3) When the suction valve is operated at an impact velocity between 4.0 to 4.5 m/s and 6.0 to 7.0 m/s, a crack is initiated at the center of the circumferential edge and then propagates to the radial direction. The chipping-off failure is induced by the linkage of cracks initiated due to spreading into branches from the main crack.
- (4) The origin of the impact fatigue crack is at the corner of the circumferential edge on the seat side. This is produced by fluctuated vibration with high frequency induced immediately after striking.
- (5) The allowable impact velocity of the tested valve is about 4.0 m/s. This value give the allowable impact velocity in safety design. In order to establish the valve design concept on the allowable impact velocity, further investigations are needed to conduct with respect to the edge and surface finishment and the dimensions and shape of the suction valve.
- (8) Dusil, R. and Johansson, B.: "Fatigue Fracture Behaviour of Impact Loaded Compressor Valves", Proceedings of the 1978 Purdue Compressor Technology Conference, pp. 124-128, 1978.

REFERENCES

- (1) Svenzon, M.: "Impact Fatigue of Valve Steel", Proceedings of the 1976 Purdue Compressor Technology Conference, pp. 65-73, 1976.
- (2) Svenzon, M.: "Fractography of impact fatigue", Sandvik AB, Steel Research Center Report, 64-15E, Paper 6, FSI, April, 1976.
- (3) Dusil, R. and Johnsson, B.: "Material Aspects of Impact Fatigue of Valve Steel", Proceedings of the 1978 Purdue Compressor Technology Conference, pp. 116-123, 1978.
- (4) Dusil, R. and Johnsson, B.: "Influence of Seat Positioning and Seat Design of Valve Fatigue Performance", Proceedings of the 1980 Purdue Compressor Technology Conference, pp. 368-373, 1980.
- (5) Smith, Ian, O.: "The Metallography of Impact Fatigue", Proceedings of the 1978 Purdue Compressor Technology Conference, pp. 111-115, 1978.
- (6) "Electron Fractography", ASTM STP 436, 1968
- (7) Beachem, C.D., Fracture, Vol. 1, p. 243, 1968. Academic Press.