1974

Stress Management of High Speed Compressor Valves

Akira Kurabayashi
Hitachi Ltd.

Yutaka Shinji
Hitachi Ltd.

Yoshikatsu Kunii
Hitachi Ltd.

STRESS MEASUREMENT OF HIGH SPEED COMPRESSOR VALVES

A. Kurabayashi, Research Manager,
Mechanical Engineering Research Laboratory, Hitachi Ltd.
Adachi-ku, Tokyo, Japan

Y. Shinji, Mechanical Engineer,
Mechanical Engineering Research Laboratory, Hitachi Ltd.
Adachi-ku, Tokyo, Japan

Y. Kunii, Mechanical Engineer,
Mechanical Engineering Research Laboratory, Hitachi Ltd.
Shimizu-shi, Shizuoka-ken, Japan

INTRODUCTION

Compressors for air conditioners and refrigerating machines have recently been made smaller, speed-up and subjected to severer operation. A precision grasp of stress distribution applied to suction valves and derivery valves in compressors during actual operation has been an important question in relation to the performance of valves and the strength of valve plates.
A few reports have been made on the strength of valve plates but they are fragmentary and not systematic. The establishment of the technique of stress measurement applied to valve plates and a series of studies including the analysis of stress on valve plates have been greatly required. With a view to grasping stress on valve plates accurately, application and questions concerning the three methods of measuring stress applied to thin plates like valve plates, i.e. the brittle coating method, the strain gauge method and the copper plating method, have been studied and these measuring techniques have been established. Stress level and stress distribution in each section of various valves have been measured through the application of these methods to actual operating compressors.

STRESS MEASUREMENT OF VALVE PLATES

Valve plates as the object of this report varied in shape according to the type of mechines and use. They were fairly thin as about 0.3 - 0.5 mm and it may safely be said that methods applicable to the stress measurement of usual machine parts or structures could not be always directly used. The technique of measuring stress applied to thin plates having complex shape is considerably restricted and will be subject to a severer restriction if stress has to be measured during machine's actual operation with refrigerant. With due regard to these conditions, the three methods of measurement were employed. Establishing these techniques and using them properly according to purpose or use will prove effective in the measurement and analysis of stress on valve plates which are both subject to a considerably severe restriction.
Table I shows a comparison of features among the three methods emploed, i.e. the brittle coating method, the strain gauge method and the copper plating method. The brittle coating method can be used in forming a qualitative judgment on the direction of principal stress and stress concentration on valve plates having complex shape only by applying coating material to the surface to be measured and quantification is possible through the strain gauge method. The copper plating method makes possible measurement during machine's actual operation with refrigerant, since this method is not corroded by refrigerant and lead wire is not needed.

TEST COMPRESSOR AND VALVE

A 2.2kW, 2-pole hermetic compressor for air conditioners was used as a test compressor and a suction ring valve used in the compressor was selected as a test valve. The construction of the sample valve is shown in Fig.I. The valve plate of the ring valve was supported by the cross-shaped SV cage between the cylinder head and the cage. Valve lift was limited by the depth of the notches provided at the ends of the SV cage. Notches on opposite ends of the cross were equal in depth and different from those in the right-angled direction, so that the valve itself might have spring action.

BRITTLE COATING METHOD

Brittle coating material is cracked at a right angle to the direction of principal tensile stress. The observation of the cracks, therefore, makes it possible to grasp the direction of principal stress and stress concentration and also to make quantification throgh a comparison with the standard sample. Since strain sensitivity when brittle coating material begins to

crack depends upon the thickness of coated film, temperature and humidity, quantitative measurement is difficult and the method is more useful in qualitative measurement of the direction of principal stress and stress concentration.
The stress coat made by Magnaflux in U.S.A was used as brittle coating material. Since the coating material itself was very brittle, it was impossible to put the test valve into the machine. The valve plate coated with the material and dried was put in as shown Fig.I and the assembly was fixed in a horizontal wind pipe. Air was send pressurized from the front to put load on the valve plate and thus cracks on the valve plate were observed. Fig.2 shows experimental results. Since the crack pattern was symmetrical, both that on the piston side and that on the counter piston side are given in the same figure. On the counter piston side, stress concentration was recognized at contacts between small valve lift and the SV cage. Principal stress at the contacts were almost in the circumferential direction, which means that bending stress was applied from small valve lift to large valve lift.

STRAIN GAUGE METHOD

A good number of reports have been made on the strain gauge. Wire rod has shown a significant improvement and the appearance of a measuring instrument for control which uses it has made it possible to quantify stress with considerable accuracy.
In respect of applying the strain gauge to the valve plate for the compressor, the following discussion covers the effect of strain gauge base thickness and adhesive layer thickness upon accuracy in measuring bending stress applied to a thin plate and also covers the results of stress measurement during machine's actual operation with refrigerant.

(I) Measurement of Bending Strain on Thin Plate

Discussed in the following is an error which, when the strain gauge is used in measuring bending stress on thin plate, is caused if strain (indicated strain) appeared on gauge wire is regarded as strain (true strain) on the surface of the parent material measured. Fig.3 shows the simplified construction with the gauge glued in place. The gauge wire is regarded as a flat plate with thickness corresponding to the wire diameter. Concerning neutral axis position y_1, from Fig.3 we have

$$y_1 + y_2 = 2t_1 \qquad (I)$$

$$y_4 = y_2 + t_2 \qquad (2)$$

$$y_3 = y_2 + t_3 \qquad (3)$$

From the equilibrium of force, we obtain

$$\frac{M}{2} = \int_{-y_1}^{0} E_1 \varepsilon b_1 y\,dy$$

$$= \int_0^{y_2} E_1 \varepsilon b_1 y\,dy + \int_{y_2}^{y_2} E_2 \varepsilon b_2 y\,dy + \int_{y_3}^{y_4} E_2 \varepsilon b_2 y\,dy + E_3 \varepsilon b_2 t_4 y_3 \qquad (4)$$

where E_1 : Modulus of longitudinal elasticity of parent material
E_2 : Modulus of longitudinal elasticity of adhesives layer, gauge base
E_3 : Modulus of longitudinal elasticity of gauge wire
b_1 : Width of parent material
b_2 : Width of gauge base, wire and adhesives layer
t_4 : Thickness of wire
y : Distance from neutral axis
ε : Strain
M : Bending moment
$= a\,y \qquad (5)$
a : Constant showing the relation between strain and distance from neutral axis

Calculating a from the equations (4) and (5), we obtain indicated strain ε_i as follows:

$$\varepsilon_i = a\,y_3 = \frac{3}{2} \cdot \frac{My}{b_1 E_1 y_1^3} \qquad (6)$$

True bending strain ε_r on the surface of the parent material when the strain gauge is not glued can be obtained in the same way as stated above.

$$\frac{M}{2} = \int_0^{t_1} E \varepsilon b_1 y\,dy \qquad (7)$$

$$\varepsilon_r = a t_1 = \frac{3}{2} \cdot \frac{M}{b_1 E_1 t_1^2} \qquad (8)$$

where ε_r: True bending strain on the surface of sample
2t: Thickness of sample plate

The error to obtain, i.e. error δ resulting from gauge base thickness and adhesive layer thickness, can be calculated from the equations (6) and (8) as follows :

$$\delta = \frac{\varepsilon_i - \varepsilon_r}{\varepsilon_r} \times 100 = \frac{y_3}{y_1^3} \times t_1^2 - I \quad (\%) \qquad (9)$$

From the equations (I) - (4), the following cubic equation is obtained and the neutral axis position y_1 is calculated.
From equation (9) the error can be calculated.

$$2b_1 E_1 y_1^3 - \{6t_1(b_1E_1 - b_2E_2) + 3b_2E_2(2t_1 + t_2) + 3b_2E_3t_4\}y_1^2 + \{12t_1^2(b_1E_1 - b_2E_2) + 3b_2E_2(2t_1+t_2)^2 + 6b_2E_3t_4(2t_1+t_3)\}y_1 - \{8t_1^3(b_1E_1 - b_2E_2) + b_2E_2(2t_1+t_2)^3 + 3b_2E_3t_4(2t_1+t_3)^2\} = 0 \qquad (10)$$

With a view to confirming the analyzed results, a testing device which could put arbitrary weight on the end with a cantilever was contructed. In view of application to the valve plate for the compressor, a bakelite gauge (base thickness of about

0.05 mm) which is said to have long-time stability and excellent heat resistance and a foil strain gauge with an epoxy base (base thickness of about 0.015 mm) which is put on the market with the base gauge recently made thinner as its feature were selected as testing strain gauges.
Phenolic adhesives (measuring about 0.01 mm in adhesives layer thickness) and cyano-acrylic adhesives (measuring about 0.02 mm in adhesives layer thickness) were used as adhesives. Tests were conducted using the combinations of them.
Fig.4 and 5 shows the results of measurement with sample plate thickness on the abscissa and errors on the ordinate. Values calculated from the equation (9) are shown as solid lines in the figures. Fairly close agreement between measured and calculated valved was obtained, but the figures suggest a problem in the use of the strain gauge for the purpose of measuring bending stress applied to a thin plate like the valve plate and show that the correction is actually needed.

(2) Stress Measurement during Machine's Actual Operation With Refigerant

When the valve plate glued together with the strain gauge was put in the compressor, stress applied to the valve plate during actual operation with refrigerant was measured, by way of example, as shown in Fig.6. This is the wave form of stress measured at 1.2 mm from the inside end near the contact between the small valve lift and the SV cage where the valve plate seemed to receive the largest stress judging from the results of measurement by the brittle coating method. It was observed that stress became the largest when the valve opened and then the valve closed with vibration. The bakelite gauge was used as the strain gauge from the view-point of heat resistance and refrigerant resistance and phenolic adhesives was used for adhesion. The stress value given in the figure has underwent the correction of the error shown in the preceding section. Since stress measurement by the strain gauge needs some gluing area, measurement at stress concentration is impossible, but this is the most effective method in the quantification of stress and the observation of the wave form.

COPPER PLATING METHOD

The copper plating method needs no lead wire and provides easy measurement of revolving bodies and small spaces. The method is considered to be best suited for the measurement of stress applied to the valve plate for small high-speed compressors during actual operation with refrigerant and particulary for the quantification of stress concentration. The method, however, did not necessarily provide satisfactory accuracy of measurement in the quantification of stress and gave stress value 10 - 30% larger than that measured with the strain gauge at some tests made by the authors.
A good number of reports have been published on the copper plating method by Prof. Okubo and so on. The valve plate for the compressor has a special problem that it has high ambient temperature and receives fluctuating load. It seems that these reports do not clearly show their effect. The following discussion covers points which seem to come into question in the quantificatin of stress on compressors.

(1) Effect of Temperature under Repeated Load

The ambient temperature of the valve plate during machine's actual operation is about 60°C. Quantification was generally conducted on the basis of the results obtained from correction specimens at room temperature without due consideration for the effect of the ambient temperature under repeated load. It seems that the production of spots depends upon the ambient temperature. The relation between the ambient temperature and critical bending strain (the smallest strain which produces spots) was studied by changing the ambient temperature under repeated load. Repeated one-side bending tests were conducted in oil with a cantilever fatigue tester and oil temperature was controlled by an immersion heater put in the oil.
Experimental results are given in Fig.7. The figure shows that the critical bending stress becomes smaller as the ambient temperature is higher and the production of spots largely depends upon the temperature. If the number of repetitions is 1.0×10^{6}, for example, the critical bending strain at 18°C is 1,600$\mu\varepsilon$ and at 60°C 1,300$\mu\varepsilon$, or about 25% smaller. Quantification depends upon the density of spots, and if spots at 60°C are quantified on the basis of correction specimens at 18°C, the quantification will be 25% too large. This seems to have been a major cause of the fact that the value measured by the copper plating method was 10 -30% larger than that measured with the strain gauge.

(2) Relation between Number of Repetitions and Stress Value

Spots appear more densely as the number of repetitions is increased. The relation at room temperature between the number of repetitions and the critical bending strain has already been reported. The following discussion covers the relation at different ambient temperature. Experimental results at 18°C, 60°C and 80°C under repeated load are given in Fig.8. The figure shows that at each temperature spots appear more densely and the critical bending strain becomes smaller as the number of repetitions is increased. The relation is as follows:

$$\varepsilon^{m}\times N=K \qquad (11)$$

where ε : Critical bending strain

m : Constant
N : Number of repetitions
K : Invaluable

The constant m varies according to temperature under repeated load. At 18°C m=4.8, at 60°C m=6.7 and at 80°C m=8.

(3) Effect of Stress Wave Form

As compared with repeated load of single vibration frequency placed on correction specimens, considerably complex fluctuating load acts upon the valve plate during machine's actual operation with refrigerant as shown in Fig.6. With a view to grasping the effect of stress wave form, sine, triangular wave and square wave were employed The result are shown in Fig.9. The effect of stress wave form does not see, and is the same as fatigue on metal. The result of repeated speed 40 Hz corresponds with the result of 7.1 Hz.

(4) Effect of fluctuating load

The preceding section shows that the production of spots is in the same relation as fatigue. It is therfore considered that the cumulative fatigue damage law is applicable to the effect of fluctuating load.
Suppose strains ε_1, ε_2 ···ε_n occur n_1, n_2 ····n_n times respectively in a cycle (see Fig.10), the equivalent number of repetitions n_{eq} of strain ε_1, is calculated as follows:

$$n_{eq} = n_1 + n_2 \cdot \frac{N_1}{N_2} + n_3 \cdot \frac{N_1}{N_3} + \cdots\cdots + n_n \cdot \frac{N_1}{N_n}$$
$$= n_1 + n_2\left(\frac{\varepsilon_2}{\varepsilon_1}\right)^{\beta m} + n_3\left(\frac{\varepsilon_3}{\varepsilon_1}\right)^{\beta m} + \cdots\cdots + n_n\left(\frac{\varepsilon_n}{\varepsilon_1}\right)^{\beta m} \qquad (12)$$

where n_{eq} : Equivalent number of repetitions
ε_1 :SStrain of first load
$\varepsilon_{2,3\ldots}$: Strain of second, third,·····load
n_1 :RRepeatition number of first load
$n_{2,3\ldots}$: Repeatition number of second, third, ······load
β : Coefficient of correct =0.5

This equation shows that the number of repetitions is influenced by terms from the second on of the right side through the action of fluctuating load and becomes larger than number of repetitions n . It is necessary to take account of the number of repetitions corresponding to the terms from the second on of the right side. Fig.11 shows the result of various fluctuating loads. It makes possible to quantify in complex fluctuating loads.

(5) Stress Measurement during Machine's Actual Operation with Refrigerant

Valve plates plated with copper were put in the compressor and stress applied to the valve plates during actual operation with refrigerant was measured on the basis of the results mentioned above.

Table 2 shows a comparison between the strain method and the copper plating method in the measurement of two valve plates of different shape which seemed to differ also in the wave form of stress. It is clear that fairly close agreement between the results of measurement by the two methods can be obtained by taking account of the ambient temperature and the equivalent number of repetitions n_{eq} based upon the difference in the wave form of stress. The quantification in the copper plating method was conducted through the spot production limit method.
Fig.12 shows the results of the measurement of the sample ring valve during machine's actual operation with refrigerant through the use of the copper plating method. Very close agreement was obtained between the results of measurement by the stress coating material method (Fig.2) and those by the strain gauge method (Fig.6). Stress concentration was recognized at contacts between the small valve lift and the SV cage. The copper plating method makes it possible to quantify stress concentration which is not easily measured by the strain gauge and also to measure stress distribution.

CONCLUSION

With a view to measuring effective stress applied to valves used in compressors for small high-speed air conditioners and refrigerating machines, application and questions concerning the three methods of measurement, i.e. the stress coating material method, the strain gauge method and the copper plating method have been studied. The results are summarized as follows:
(1) The three methods have their own features. Stress on the valve plate can be very effectively measured if they are properly used according to use, conditions and so on. It is proper to use the brittle coating method in determing the direction of principal stress, the strain gaug method in observing the wave form of stress during machine's actual operation with refrigerant (this is effective in examining the performance of valves including the delay of valve closing) and quantifying stress, and the copper plating method in quantifying stress distribution and stress concentration.
(2) When the strain gauge is used in measuring stress on thin plate of less than 1 mm in thickness, the error shown in the equation (9) must be examined and corrected according to plate thickness, the gauge, adhesives used and so on.
(3) When copper plating is used in measuring valve plates for compressors, it has been confirmed that fairly close agreement between the results of measurement by the copper plating method and the strain gauge method can be obtained by taking account of the ambient temperature and the equivalent number of repetitions based upon the difference in the wave form of stress.

REFERENCES

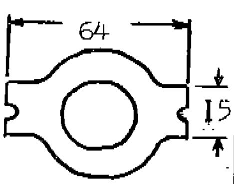
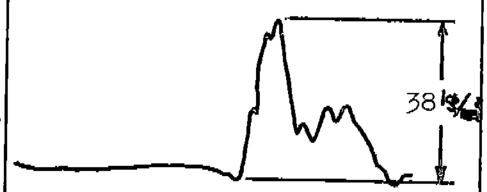
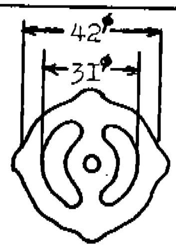
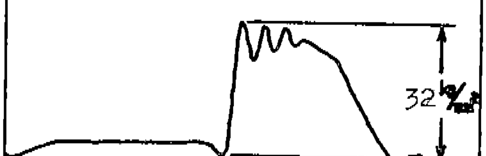
(I) Okubo: Copper Plating Stress Measuring Method, 1966-IO (Asakura Shoten)

(2) A.Kurabayashi, Y.Shinji, Y.Kunii: The Hitachi Hyoron, Vol.53, No.II (I97I-II)

Table I Three Methods of Measurement

		Brittle coating method	Strain gauge method	Copper plating method
Features	Merits	*Useful in observing stress distribution *Judgment on the direction of principal stress is possible	*Measurement of dynamical strain is easy *Quantification *High precision	*Best suited for measurement during machine's actual operation with refrigerant *Measurement of small part is easy
	Demerits	*Quantification is not possible *Measurement of fluctuating stress is not possible	*Lead wire is needed	*Skill is needed in plating
Application	Stress distribution Stress concentration	◎	×	○
	Quantification	×	◎	○
	Operation with refrigerant	×	○	◎

Table 2 Comparison between Strain Gauge Method and Copper Plating Method

Shape of valve plate	Strain gauge method	Copper plating method
		39 kg/mm²
		34 kg/mm²

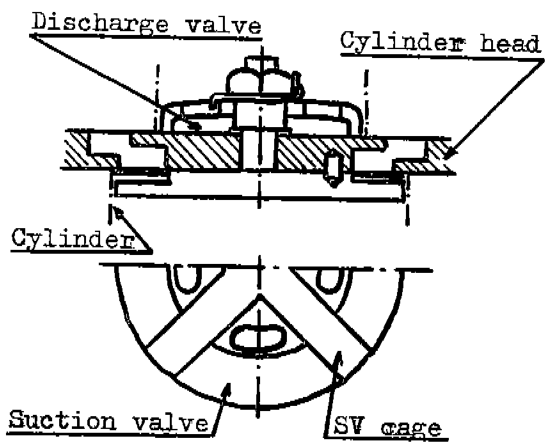


Fig.I Construction of Sample Valve

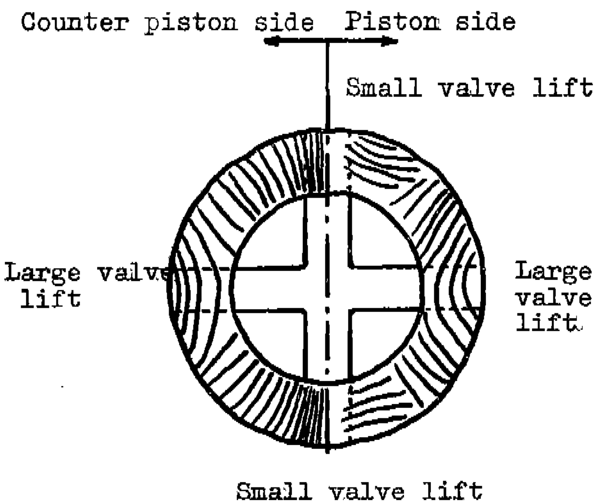


Fig.2 Results of Stress Measurement (Brittle Coating Method)

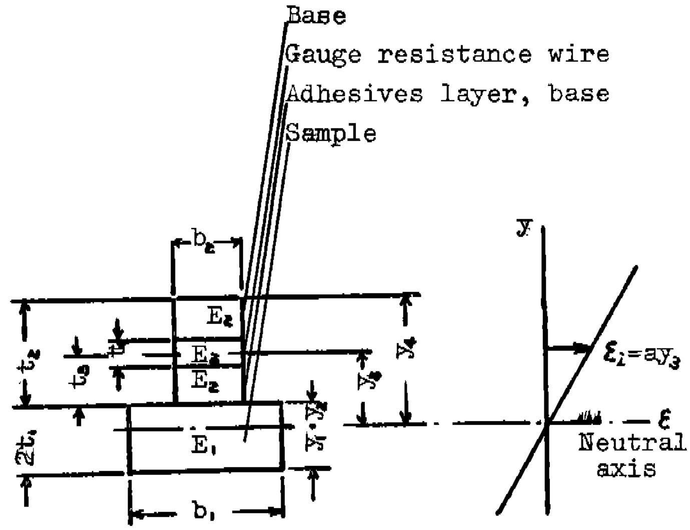


Fig.3 Simplified Figure of Strain Gauge

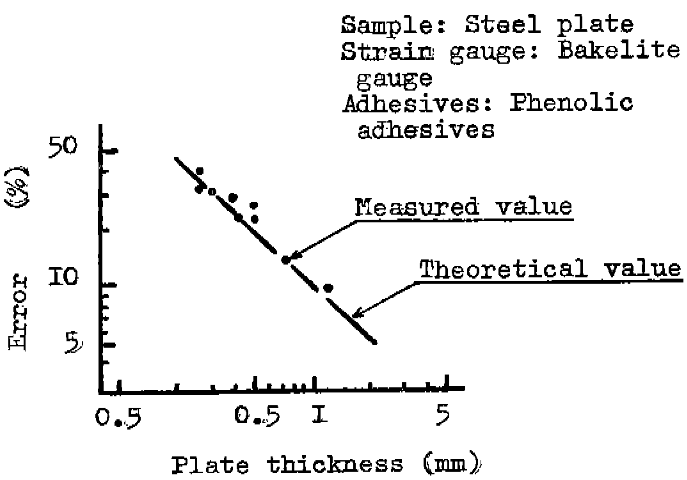


Fig.4 Accuracy of Measurement of Bending Strain on Thin Plate (I)

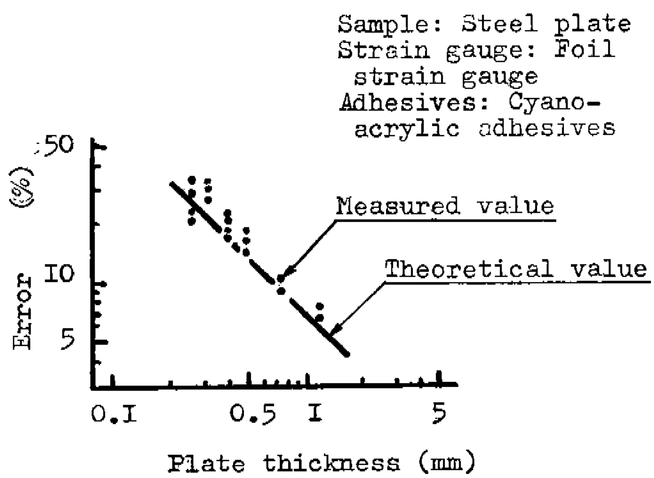


Fig.5 Accuracy of Measurement of Bending Strain on Thin Plate (2)

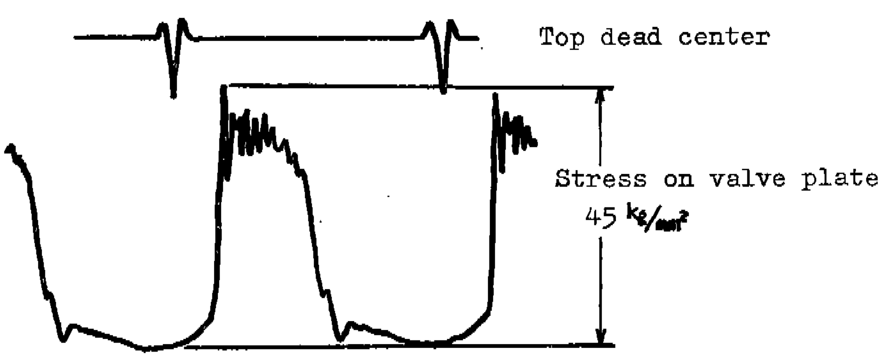


Fig.6 Wave Form of Stress on Valve during Machine's Actual Operation (Strain Gauge Method)

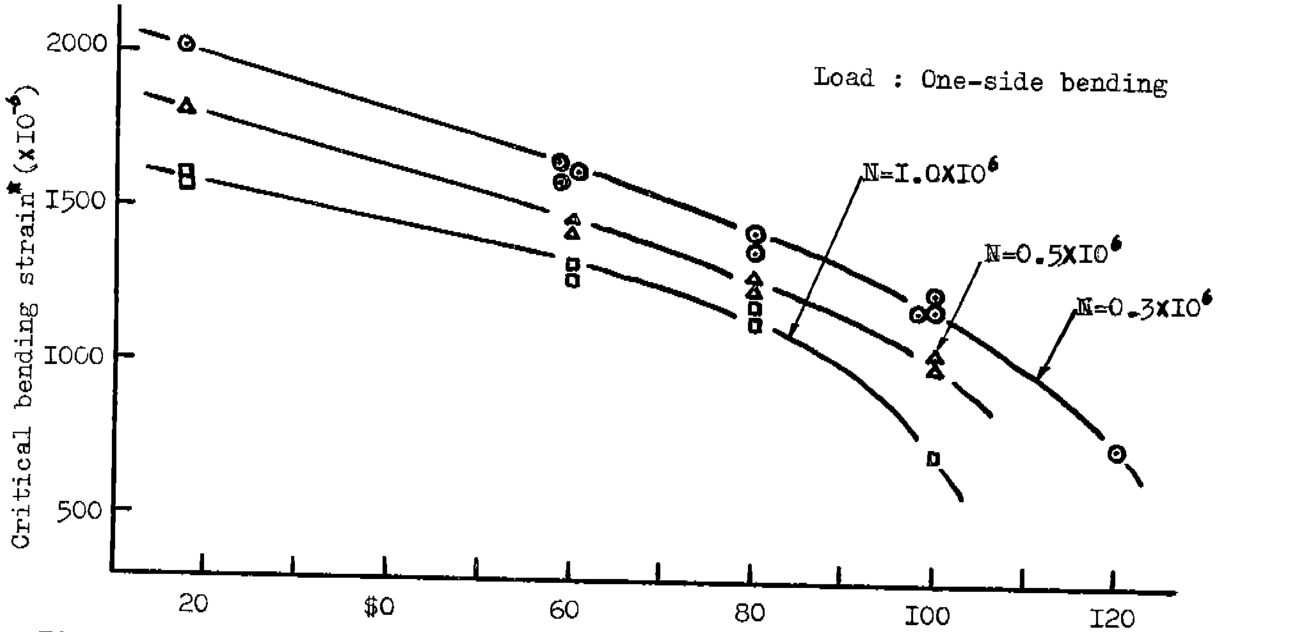


Fig.7 Effect of Temperature under Repeated Load

*Strain of the smallest spots to be produced when repeated load is placed.

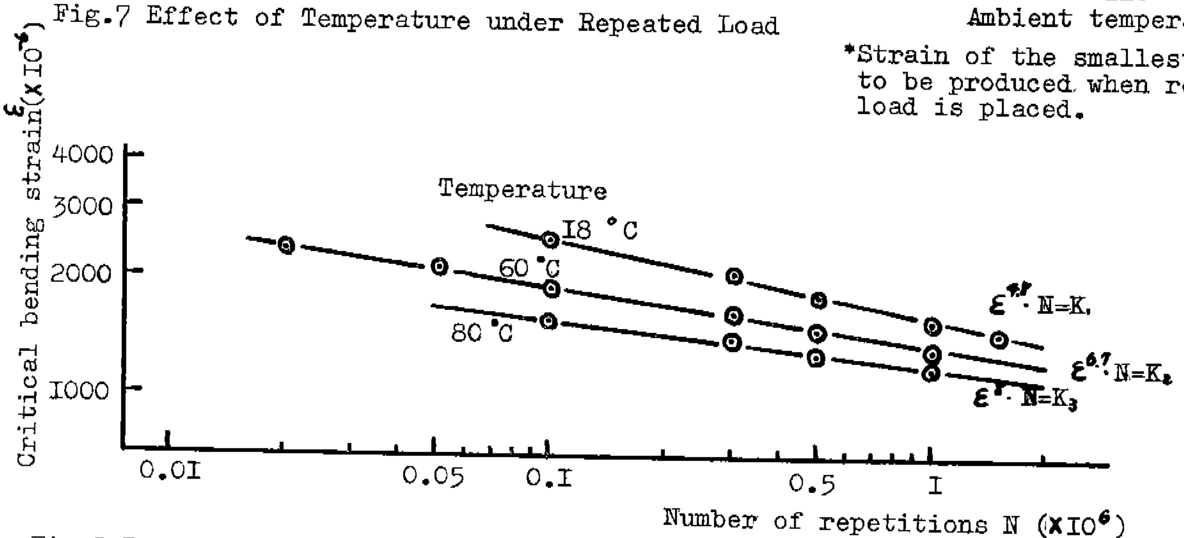


Fig.8 Relation between Temperature and Critical Bending Strain

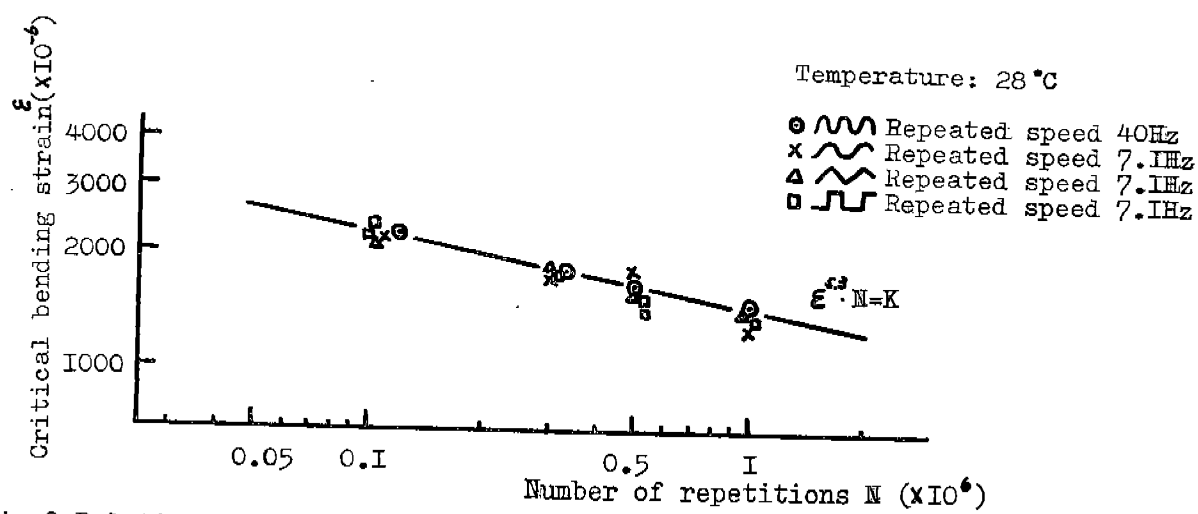


Fig.9 Relation between Stress Wave Form and Critical Bending Strain

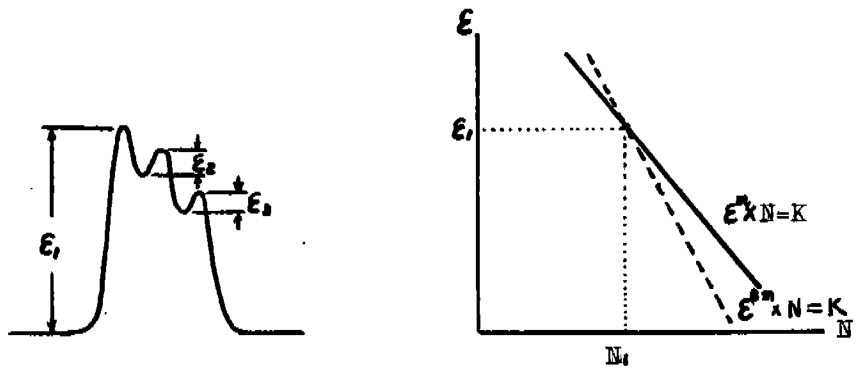


Fig.10 Equivalent Number of Repetitions

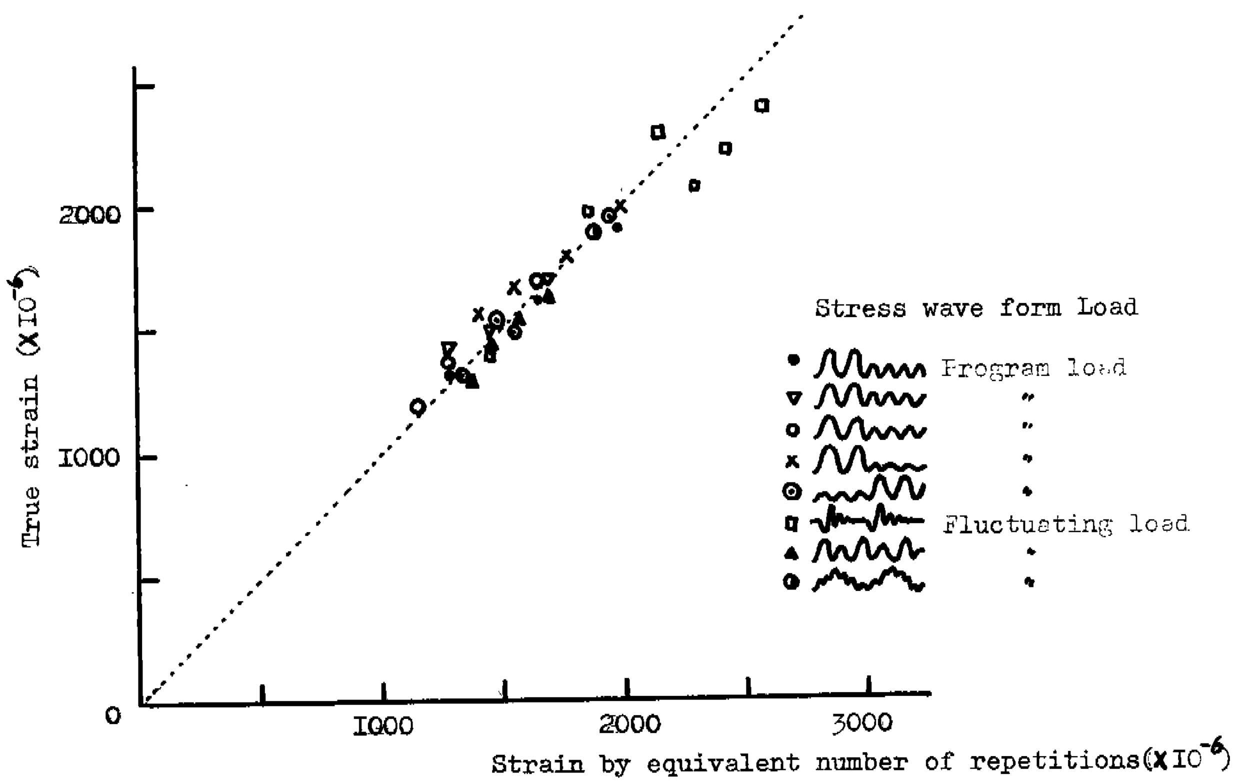


Fig.II Effect of Fluctuating Load

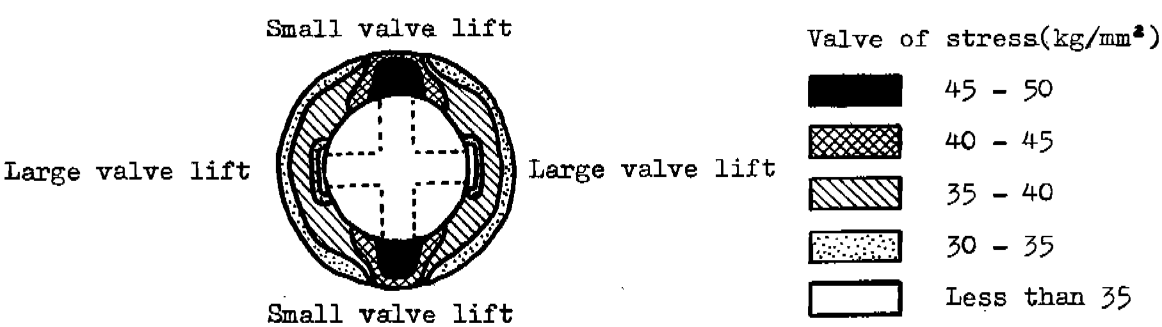


Fig.12 Results of Measurement of Stress Distribution (Copper Plating Method)