Proceedings of The Institute of Acoustics

Acoustic Emission in Plasticity

T.Kishi, Y.Sakakibara and R.Horiuchi
Institute of Space and Aeronautical Science
University of Tokyo, Japan.

I. INTRODUCTION

There is a general agreement that acoustic emission during plastic deformation is related to dislocation motion (1). However no clear relationship until now has been obtained between acoustic emission and metallurgical matters. The authors have studied A.E. behaviour due to the Bauschinger effect and have reported the existence of an acoustic emission peak accompanying this effect (2)(3)(4)(5). In the present paper by analysing this peak, a new method is proposed for obtaining a back-stress component in flow stresses which control strain hardening and fatigue hardening. In the light of this work the Kaiser effect and fatigue strength are discussed.

II. EXPERIMENT

Fig.1 is a block diagram showing a typical experimental system for data acquisition. The output of a piezoelectric transducer, resonant at 140 kHz, was amplified and filtered by a 20-200 kHz bandpass filter before time recording of emission rate counts and/or D.C. output mean voltage. The overall system gain was 70 dB. The data were recorded on magnetic tape and the amplitude distribution of signals obtained by playback, the threshold voltage being changed in the process. Tension and compression tests were performed in an Instron type machine at room temperature at a crosshead-speed between 0.1mm/min and 5mm/min. Acoustic emission data were measured from the top-end of the specimen under a controlled condition of strain. The specimens used in this paper were polycrystalline Al, Cu, α-Brass, SUS 304 and Al-Si alloys. Pure Al single crystals were also studied to ascertain the effect of grain boundary. The final heat treatment condition, grain size of polycrystals and chemical composition of the materials are given in Table 1.

III. EXPERIMENTAL RESULTS OF BAUSCHINGER AE PEAK

Experiments were performed under the cyclic strain amplitudes of 1%, 3%, 5% and 8%. Fig 3 shows the result under the condition of 5% strain amplitude in Al polycrystals. As seen in the figure, an acoustic emission peak (point C) was found during the compression followed by tension. The same peak (point C') was observed during tension followed by compression, too. During unloading fewer acoustic emission signals (point A) were observed, as was already pointed out by Sanker (3). However, the signals of this peak are bigger, and there was a good correspondence between the onset of the acoustic emission peak (point B) and that of macroscopic strain in stress reversal. Acoustic emission assumes a minimum (point D) in the stress plateau region and increases again with increasing stress.

Similar peaks were observed in all other specimens used as shown in Fig 4, but the apparent feature of each peak was different in each material. For example in the case of α-Brass and SUS 304, these peaks appear during unloading, and take a maximum at the stress immediately following zero stress.

The relation between the maximum of the peaks (point C and C' in Fig.3) and the number of the cycle is given in Fig.5. The magnitude of the peaks decrease with the cyclic numbers and becomes constant to correspond with the saturation stress of the cyclic stress-strain curve.

As shown in Fig.6(a), the height of this peak increases with an increase of crosshead speed. Fig.6(b) shows the relation between AE output and plastic strain rate both at the maximum and steady-state (point C and E in Fig.3). In the measured range of strain rate, the output voltage (V) is proportional to (strain-rate)$^{1/2}$, i.e. $(\dot{\epsilon}_p)^{1/2}$, which is a well-known relation in the plastic deformation under the uniaxial condition. Consequently, it can be concluded from this result that the Bauschinger AE peak is the emission due to normal plastic deformation.

The strain amplitude dependence of these peaks is shown in Fig.7. At any strain amplitude there exists the Bauschinger AE peak, of which maximum height and reverse strain ϵ_p(max) increase with an increasing strain amplitude.

This result, that AE energy release increases with pre-strain, has a good correspondence both with the result of hardness change and with that of specific heat change in this deformation region. ( ) ( )

The amplitude distribution of AE signals in this Bauschinger AE peak profile is shown in Fig.8. The data were obtained at two points in the peak profile and at one point in steady-state region in Al, as shown in Fig.8(a) To make the physical meaning of this peak profile clear, relative number of events versus emission amplitude have been plotted in Fig.8

It is clear from this figure that the relative number of events has the same distribution in each stage of the peak profile, in spite of the variation of emission energy in the profile. This result has a significant and interesting meaning as indicating that in the increase of emission energy in the Bauschinger AE peak profile, it is only the event number of AE which increases. This means that each emission energy level in the peak profile corresponds to the number of emission events.

Since it can be assumed that the backward yielding occurs in this Bauschinger AE peak profile inhomogeneously in the unit of some sites (sites means the cell or sub-boundary), then it may be concluded that each level of emission energy in the peak profile is proportional to the number of site, which yields in this stress as shown in Fig.9.

IV. BACK STRESS DISTRIBUTION AND ITS MEAN VALUE

As shown in previous chapter, the yielding in backward direction occurs inhomogeneously in the region of the Bauschinger AE profile, and the emission energy is proportional to the yielding event number for the backward direction. In this 'chapter', from this point of view of inhomogeneous deformation, a new method is presented to get back stress component in flow stresses, which controls work hardening and fatigue hardening.

Recently, as suggested by Hirsch et al (8), it is recognized that the flow stress consists of THREE components. In simple tensile deformation, in general, the flow stress is given by

$$\sigma_F = \sigma_o + \sigma_{for} + \sigma_b \qquad \text{------(1)}$$

where σ_o represents friction stress, σ_{for} the forest contribution, and σ_b the long range back-stress. In the case of dispersion hardened materials, σ_o is defined as Orowan stress which is equal to yield stress, as shown by Moan (9) and Mori (10)

In any case, σ_o and σ_{for} components do not depend on load direction, while the back stress component σ_b will become a driving force for backward yielding. From this assumption, the backward flow stress is given by

$$\sigma_R = \sigma_o + \sigma_{for} - \sigma_b \qquad \text{------ (2)}$$

Therefore, if σ_R is defined, the mean back stress can be obtained easily from Eqs. (1) and (2) as follows

$$\sigma_b = \frac{1}{2}\left(\sigma_F - \sigma_R\right) \qquad \text{------ (3)}$$

However, this is the case where back stress and forest components are homogeneous in the specimen at forward deformation.

However, on account of existence of inhomogeneties, such as grain boundaries, cell boundaries, inclusions and precipitates, it is more reasonable to assume that there exists inhomogeneous distribution of these stress components in the materials.

Then, assuming that the flow stress components of the i-th site in the specimen are σ_{fori} and σ_{bi}, the forward and backward flow stress components of the i-th site are given respectively by

$$\sigma_F = \sigma_{oi} + \sigma_{fori} + \sigma_{bi} \qquad \text{------- (4)}$$

$$\sigma_{Ri} = \sigma_{oi} + \sigma_{fori} - \sigma_{bi} \qquad \text{------- (5)}$$

Consequently, when σ_{Ri} is given, the back stress of i-th site can be obtained as follows

Acoustic Emission in Plasticity

$$\sigma_{bi} = \frac{1}{2}(\sigma_F - \sigma_{Ri}) \quad \text{------ (6)}$$

From this result, the mean back stress $\bar{\sigma}_b$ is simply given by

$$\bar{\sigma}_b = \frac{1}{N}\sum_i \sigma_{bi} \cdot N_i \quad \text{------ (7)}$$

where N_i is the number of sites which have the back stress σ_{bi} and N is the total number of sites in the specimen. Therefore if the value of σ_{bi} and N_i or (N_i/N) are given experimentally, the mean value of σ_F (Eq.(1)) can be obtained.

As mentioned in the previous paragraph, the Bauschinger AE peak shows the inhomogeneous reverse yielding and the energy level in the peak profile corresponds to the number of sites which yield at this stress level. Therefore in Fig.9, the total area of the peak profile is proportional to the total number of sites N, and the shaded area S_i to the number N_i, which is the number of yielding sites in the reverse stress range between σ_{Ri} and $\sigma_{Ri} + d\sigma_{Ri}$, σ_{bi} can be derived from $_F$ using Eq.(6), and so the mean back stress can be given from Eq. (7)

In the following paragraph, the effect of stacking fault energy, precipitates, strain amplitude, strain rate and recovery on the mean back-stress are summarized.

V. BACK STRESS COMPONENT IN FLOW STRESS

The Bauschinger AE peaks normalized by the maximum value of each peak versus stress normalized by forward applied stress are shown in Fig.10. In any material there exists a Bauschinger AE peak. However, in the case of α-Brass and SUS 304, the peaks appear during unloading and take the maxima just after zero stress. The contribution of back stress can be easily calculated from the dotted line.

The mean back stresses calculated by Eq.(7) are summarized in Table 2. In pure Al and Cu, the back stress component is about 15-20% of the flow stress, on the contrary, it reaches 25-40% in α-Brass and SUS 304. This is the increasing inclination of mean back stress with a decreasing stacking fault energy. This result corresponds well with the well-known behaviour of the Bauschinger effect (11).

The influence of ageing after solution treatment in Al-Si alloys on the mean backstress is shown in Fig. 10. This alloy is a typical dispersion hardening material and Si particles are believed to be a strong inclusion in a plastically deformed matrix. The mean back stress and its ratio to applied flow stress vary according to the ageing condition, the mean back stress amounts to 35% of the flow-stress.

In the next place, pre-strain dependence of mean back stress in pure Al is shown in Fig.12. Though mean back stress increases with pre-strain and saturation at about 5-10% pre-strain, the ratio of mean back stress to flow stress is almost constant in this experimental strain range.

The effect of strain rate on back stress is indicated in Table 3. In the range of the crosshead speed, mean back stress keeps constant.

It is well-known that the Bauschinger effect disappears promptly in the process of low temperature annealing (12). Fig.13 clarifies the effect of low temperature annealing on mean back stress. It is clearly recognized that back stress disappears at the recovery treatment of 200°C x 30 min, which clearly explained the above mentioned recovery of the Bauschinger effect. From this result, it can be concluded that the mean back stress obtained from AE signals can be explained by the result of the Bauschinger effect, and has a physical meaning as a component of flow stress.

Up to this point, only the results of polycrystals were summarized. To clarify the meaning of yielding sites the behaviour of single crystals will be described here.

The Bauschinger AE peaks exist also in Al single crystals in two different orientations, in spite of the low level emission voltage as compared with that of polycrystals, as shown in Fig. 14. The mean back-stress obtained from these peaks are 15-19 of flow stress, which corresponds well with the result of polycrystals.

This result, that the grain boundary has no direct effect on mean back-stress, explains that the yielding site we proposed has no direct relation with the grain boundary. From this result it may be concluded that the work-hardened structure itself controls the back stress and so in the advanced region of pre-strain cell or the aggregation of cells correspond to the site, which is the original unit of emission signals.

VI. KAISER EFFECT

It is recognized that the Kaiser effect cannot be observed in some materials. In the case of the high back-stress materials, Bauschinger AE peak appears in the unloading state and this signifies the existence of a structure change during the unloading process. As shown in Fig.15, in the case of SUS 304 of which the mean back-stress is high, considerable amounts of emission are observed during unloading and so clearly Kaiser effect does not occur. In the case of Al and Cu, fewer emissions are observed before reloading up to original applied stress. However, in this case it is recognized that the Kaiser effect is observed. From this figure, it can be concluded that the amount of back-stress will become a measure of certification of the Kaiser effect. If the ratio of back-stress to flow-stress is below 20 , the Kaiser effect should be observed.

VII. FATIGUE

Acoustic Emission in Plasticity

Finally, following the application of back-stress, the fatigue strength of Al-Si alloys will be discussed here. As shown in Fig.10, the ratio of back-stress to flow-stress changes with the ageing condition. The solid lines in Fig.16 indicate the relationship between nominal stress and the number of cycles to failure, while the dotted lines indicate the relationship between forest stress component and the number of cycles.

There exists the considerable difference between the fatigue limit of two materials, however, if it is shown against forest stress component, the difference of fatigue limit becomes negligible. Thus it is suggested that fatigue limit is controlled only by forest stress, which is obtained by subtracting the back-stress component from flow-stress, because the frictional term in Eq.(1) is negligible in f. c. c. metals.

It is reasonable to consider that the back-stress component is controlled only by a flip-flop motion of dislocation and so it causes no structural damage inside the material. On the contrary, the forest term is sometimes governed by non-conservative motion of dislocation, which will become the origin of some structural damage, and controls the fatigue strength.

VIII. CONCLUSION

An acoustic emission peak accompanied by stress reversal was newly found in f. c. c. poly- and single crystals. A new method to obtain mean back-stress component in flow-stresses, which controls the fatigue hardening, was proposed by analyzing this AE peak, and this derived back-stress clearly explained the phenomena of the Bauschinger effect, the Kaiser effect and fatigue limit strength.

REFERENCES

1. J.R.Frederick and D.K.Felbeck: 'Acoustic Emission' ASTM SPT 505, (1972), 129.

2. T.Kishi et al: Preprints of The 78th Spring Meeting of Japan Inst. of Metals, Tokyo, Japan, (1976), 189.

3. N.G.Sanker, J.R.Frederick and D.K.Felbeck: Met.Trans.1 (1970), 2979.

4. T.Kishi et al: Scripta Met.9(1975), 1023-1026.

5. T.Kishi et al: J.Jap.Inst.Met.,40(1976), 492.

6. I.Gokyu and T.Kishi: Journal of Jap.Soc. for Tech. of Plast., 10(1969),863.

7. L.M.Clarebrough: Recovery & Recrystallization, p.79.

8. P.B.Hirsch:'Physics of Metals, 2. Defects' p.189-246. Ed. by P.B.Hirsch. Cambridge University Press.

9. G.Moan, C.M.Sargent and J.D.Embury: 'Proc. 3rd.Int.Conf. on Strength of Metals & Alloys', 1 (1973), 36.

10 T.Mori and K.Narita: Acta Met., 23 (1975), 85.

11. I.Gokyu and T.Kishi: 'Proc.13th Japan Congress on Materials Research' (1970), 125

12. T.Kishi and R.Horiuchi: J.Japan Inst. Met., 39 (1975), 92.

	Chemical composition	Grain size
Al	purity 99.5(%)	70μ
Cu	OFHC Copper	30μ
α-Brass	Cu-30%Zn	70μ
SUS 304	18%Cr-8%Ni	
Al-Si	Al-1.2wt%Si	

Table.1 Chemical composition and grain size of each material .

	σ_b/σ_F	$\epsilon_\beta(3/4)$
Al	16(%)	0.15(%)
Cu	15	0.25
α-Brass	22	0.62
SUS 304	37	0.83

Table.2 The mean back stress calculated by the Bauschinger AE peak, and Bauschinger effect.

Al Strain Amplitude 2.5 1 Cycle Comp.

C.H.S.(mm/min)	0.5	1	2	5
σ_b/σ_F	0.17	0.18	0.16	0.14

Table.3 The strain rate dependence of the mean back stress.

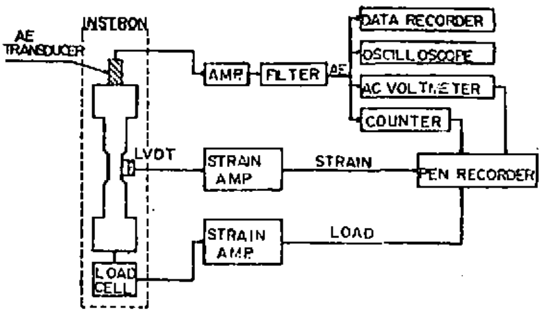

Fig.1 Block diagram of instrumentation set-up for acoustic emission measurement.

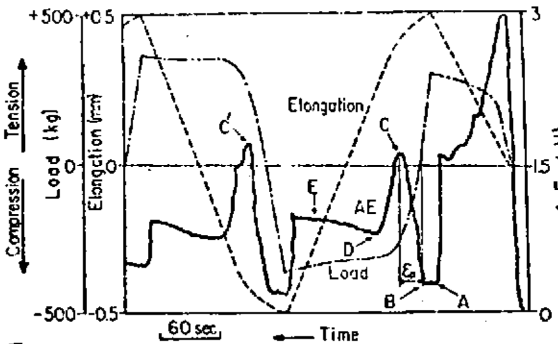

Fig.3 Acoustic emission peak due to the Bauschinger effect under the controlled condition of 5% strain amplitude.

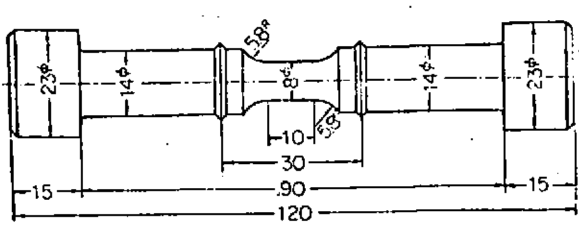

Fig.2 Specimen for cyclic deformation.

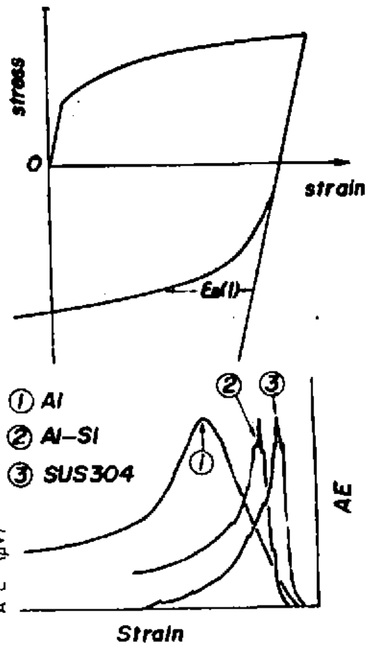

Fig.4 The apparent feature of the Bauschinger AE peak of various materials.

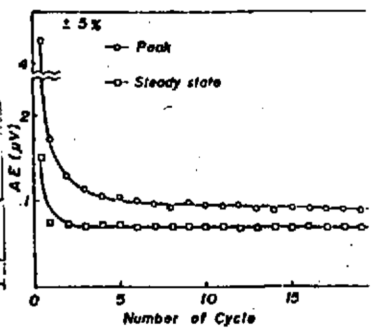

Fig.5 Changes in acoustic emission as a function of stress cycles.

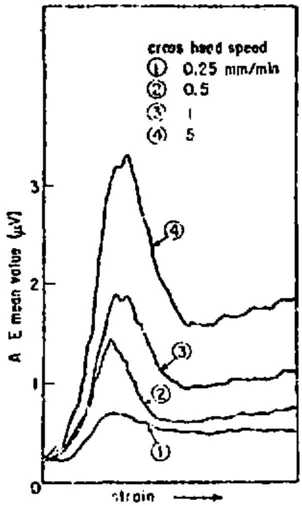

Fig.6(a)

Cross-head speed dependence of the peak maximum in the Bauschinger peak.

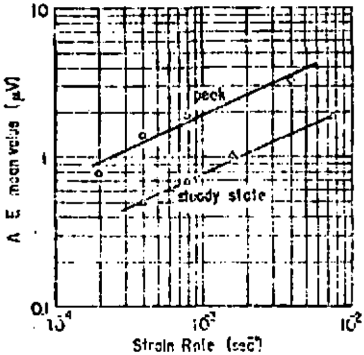

Fig.6(b) Elastic strain rate dependence of the maximum calculated from Fig.5(a)

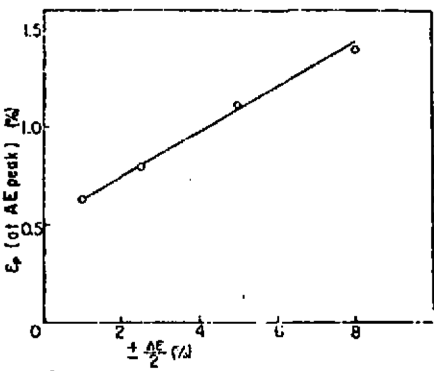

Fig 7.
The relationship between strain amplitude and the amount of reverse plastic strain at the peak maximum.

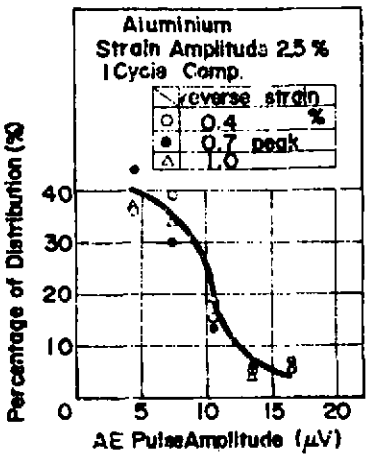

Fig.8 The relative number of events versus amplitude in Bauschinger AE peak.

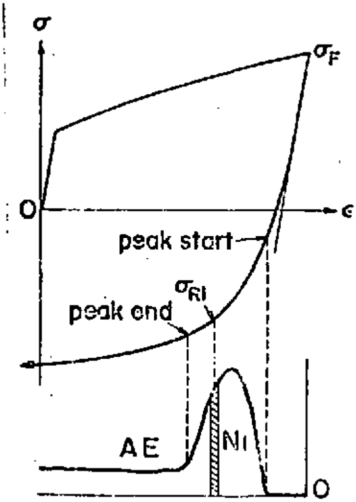

Fig. 9

The distribution of yielding sites N_i at backward yield stress σ_{Ri}, obtained by analysing AE peak profile.

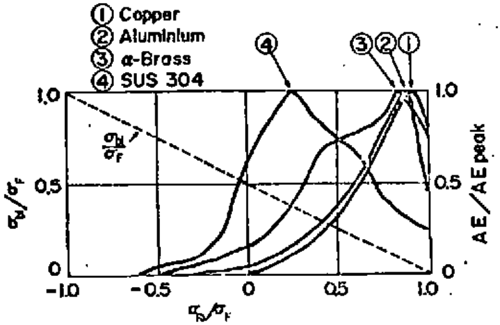

Fig.10

Bauschinger AE peak normalized by the maximum value of each peak versus the reverse stress normalized by forward applied stress.

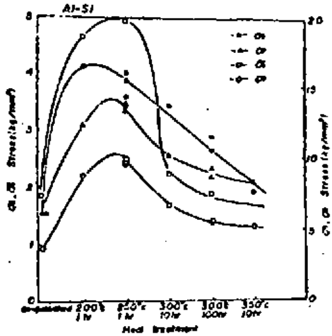

Fig.11

The influence of aging after solution treatment in Al-Si alloys on the mean back stress.

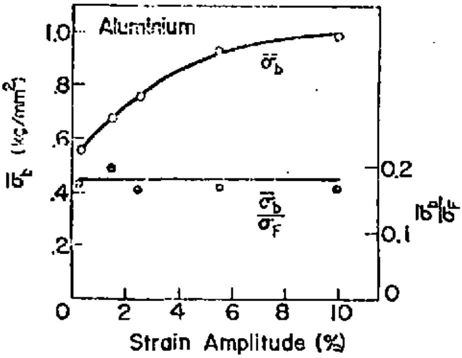

Fig.12 The pre-strain dependence of mean back stress.

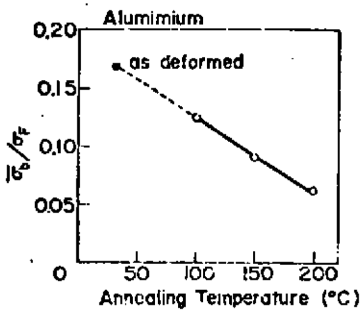

Fig.13

The effect of low temperature annealing on mean back stress.

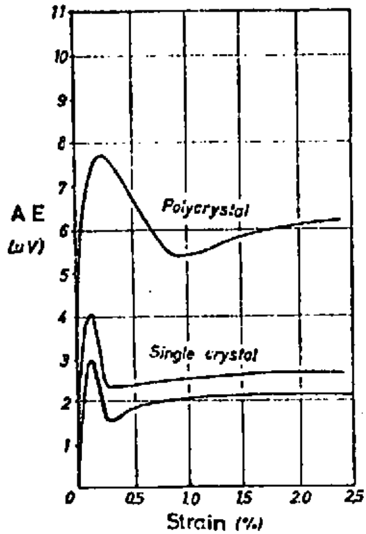

Fig.14

The Bauschinger AE peaks of Al single crystals and polycrystal.

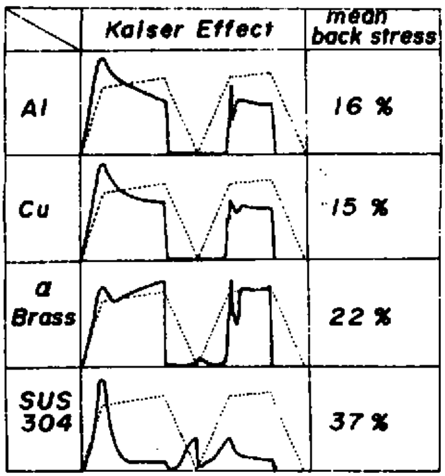

Fig.15

The typical Kaiser effect and the value of mean back stress of various materials.

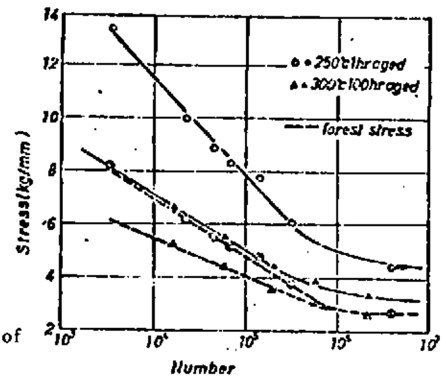

Fig.16

The relation between the cyclic number to fatigue failure and apllied stress (solid line) or forest stress (dotted line).