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Fretting fatigue of automotive leaf spring

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SYNOPSIS Fretting fatigue tests on leaf springs and small axial-loading specimens were carried out under constant loading and random loading simulating field load spectra. The results for leaf springs were compared with literature data on similar springs. The behavior of fretting fatigue crack initiation and propagation in the leaf springs was found to be almost the same as in the small laboratory specimen. No significant differences between their fretted surfaces and also between their fatigue fracture surfaces were observed. Ramdom loading reduced the fretting fatigue lives by a factor of 1.5. The effect of shot peening on fretting fatigue was also investigated. Shot peening improved the fretting fatigue strengths in both specimens by a factor of two. The residual compressive stresses induced by the shot peening process were responsible for the improvement. It is suggested that the fretting fatigue life of leaf springs can be estimated from that of laboratory specimens, provided the clamping pressures and the relative slip ampplitudes of both are of the same magnitude.

1 INTRODUCTION

The fatigue strength of leaf springs is well known to be reduced by fretting. Fretting fatigue cracks initiates at a very early stage due to the relative slip in the contact area between leaves, and is accelerated by the concentrated local stress induced by the contact of leaves. Although several published reports on fatigue of leaf springs are available (1-4), in which interest has been focused mainly on the scatter of fatigue life, few investigations have been made from the view point of fretting fatigue (5). The authors have carried out fretting fatigue tests using small axial-loading specimens of a spring steel (JIS SUP9 steel), and have discussed the fretting fatigue processes (6) and the effect of contact material on fatigue strength (7). They have also carried out fracture mechanics predictions of fretting fatigue lives using measured data on frictional forces between the fretting pads and specimens (8).

In the present study, fatigue tests of leaf spring specimens were carried out under constant loading and random loading simulating field load spectra. Fretting fatigue processes in the leaf spring specimens were observed in detail. The effect of shot peening on fretting fatigue was also investigated. The method of estimating the fretting fatigue life of leaf springs from that of laboratory axial-loading specimens is discussed.

2 EXPERIMENTAL PROCEDURES

The materials used were two spring steels specified in the same standard (JIS SUP9). The chemical compositions and mechanical properties are given in Table 1 and 2 respectively. Small axial-loading specimens and leaf spring specimens were machined from material-A and -B, respectively. Two kinds of leaf spring specimen, the dimensions of which are 50mm in width, 500mm in length and 5mm in thickness, were prepared: One was as- heat treated and the other was shot peened (0.42mm arc-height) subsequent to heat treatment. A schematic illustration of the leaf spring specimen and loading apparatus is shown in Fig.1. Loading is through rollers which are free to rotate and move apart slightly. In the present paper, the upper leaf spring is named No.1 leaf spring and the lower one No.2 leaf spring, as shown in Fig.1. The material used for clamping plates was low carbon steel (JIS SS41), the dimensions of which are 70mm in length, 100mm in width and 10mm in thickness.

A servohydraulic testing machine with a capacity of 294kN was used for the fatigue tests. Since leaf springs in practice are under a mean load due to the weight of the automotive vehicle, constant loading and random loading tests were carried out with a mean load of 2.2kN. Two kinds of random load simulating field load spectra (9), as shown in Fig.2(a), were used: One (named Random-A) corresponds to a good road and the other (Random-B) to a potholed road condition. Samples of the random loads are shown in Fig.2(b). The clamping torque was 34.3N-m giving a clamping pressure of 60MPa, which corresponds to that for previous fretting fatigue tests on small axial-loading specimens (6-8).

Fretting fatigue tests on shot peened axial-loading specimens were also carried out. The shape and dimensions of specimens and testing procedures were given in detail in previous papers (6-8).

3 EXPERIMENTAL RESULTS

3.1 Leaf spring specimen

The relationship between load amplitude and number of cycles to failure of leaf spring specimens is shown in Fig.3. The root-meansquare value of load amplitude is used for random loading tests. The fatigue life was defined by the number of cycles at failure of the specimen. As can be seen from the figure, the fatigue life in the case of Random-A loading was almost equal to that in the case of constant loading. The fatigue life in the case of Random-B loading, which had a larger standard deviation and higher maximum load, was shorter than that for constant amplitude loading. Shot peening significantly improved the fatigue strength. For example, the fatigue strengths at $3*10^5$ cycles, which is the design fatigue life of leaf springs, were 1.10kN for the as-heat treated specimen and 2.25kN for the shot peened specimen; therefore shot peening improved the fatigue strength by a factor of two.

Fracture of leaf spring specimens always occurred on the tension side of No.2 leaf spring. The histogram of the position of crack initiation is shown in Fig.4. The fatigue crack nucleated near the clamping region, and the average position of crack initiation was at 1.14mm from the edge of the clamping plate. The macroscopic appearance of the fretted areas near the fractured region is shown in Fig.5. The lengths of the fretted regions in the longitudinal direction of the leaf spring specimen are shown in Fig.6. The lengths and positions of fretted areas seemed to be largely independent of the test condition. On average the center of the fretted region was at 1.2 mm from the edge of the clamping plate, and corresponded to the average position of crack initiation.

Fretted surfaces and fracture surfaces were examined in detail under a scanning electron microscope. The results of observations were very similar to those on small axially loaded specimen reported previously (6): Accumulations of debris, wavy marks and numerous tiny surface pits were observed on the fretted surface. A flat and featureless fracture surface was observed near the region of crack initiation whereas a normal fatigue fracture surface was found away from the region of crack initiation. Figure 7 shows typical fretting fatigue cracks in as-heat treated and shot peened leaf spring specimens. In both specimens, the initial directions of the cracks were at a fairly steep angle to the surface, but when the cracks were beyond the direct influence of the fretting action they changed direction to become perpendicular to the surface. The characteristics of crack growth were very similar to those of small axial-loading specimens reported previously(6-8).

3.2 Shot peened small axial-loading specimen

The S-N diagram for shot peened small axial-loading specimens is shown in Fig.8. For reference, the results for fretting fatigue tests on unpeened specimens (dotted curve) and for plain fatigue tests on unpeened specimens (solid curve) are also shown in the figure. The fatigue strength at the endurance limit of the shot peened specimen (two-dotted curve) was significantly improved; a factor of 1.7.

4 DISCUSSION

4.1 Comparison with the results on leaf springs in service

The results on fatigue tests of leaf springs in service have been reported (10). The S-N diagrams of leaf springs for passenger cars and for trucks described in Ref.10 are shown in Fig.9. The stress amplitude of leaf springs was estimated based on the transformed section method for combined cantilever beams. In the present study, the stress amplitude was also estimated based on the assumption of combined cantilever beams, the rigid end of which is the center of clamping bolt, as shown in Fig.10. The stress amplitude σ_a is given by

$$\sigma_a = 1.2P_a\,(0.1675 - x) \qquad (1)$$

where Pa is the load amplitude (N), and x the distance from the edge of the clamping plate (m). The relationship between load and deflection at loading point derived from the model agreed with the experimental results within 10%. The present results are plotted in Fig.9. As can be seen from the figure, the present results were within the scatter band for leaf springs in service. The results for shot peened leaf springs reported by Ogawa and Iwamoto (2) and the present results for shot peened leaf spring specimens are also shown in Fig.9. It can be seen that the present results are close to those reported by Ogawa and Iwamoto irrespective of the material and the test condition. The mean stress in the case of Ref.2 is higher than that in the case of the present study by a factor of 1.44. Better agreement is obtained when the mean stresses coincide.

From the foregoing comparisons, it appears that the present leaf spring specimen satisfactly simulates leaf springs in service.

4.2 Prediction of fatigue life from the laboratory specimen

The S-N diagrams in plain fatigue for small axial-loading specimens (solid curve) and in fretting fatigue for unpeened specimens (dotted curve) taken from previous papers (6-8) are shown in Fig.11. The S-N diagram for fretting fatigue of shot peened specimens (two-dotted curve) is also shown in the figure. The present data on leaf spring specimens are plotted in the figure to discuss the prediction of fatigue life of leaf springs from that of laboratory specimens. In the figure, since the mean stress for leaf spring specimens was 443MPa whereas that for laboratory specimens was zero, the stress amplitudes for leaf spring specimens were normalised to those for zero mean stress using the following modified Goodman equation (11).

$$\sigma_{ao} = \sigma_a \,/\, (1 - \sigma_m / \sigma_u) \qquad (2)$$

where σ_{ao} is the stress amplitude for the zero mean stress, σ_m the mean stress and σ_u the tensile strength. As can be seen from the figure, although the S-N curves for leaf spring specimens tended to be rather steep, they agree well with those for laboratory axial-loading specimens irrespective of the shot peening treatment and the wave form.

In fretting fatigue, the coefficient of friction, the contact pressure and the relative slip amplitude are well known to be the relevant factors. In the present study, the clamping torque of bolts was controlled to obtain the same contact pressure as that for fretting fatigue tests on laboratory specimens. The relative slip amplitude and the friction coefficient are difficult to measure in leaf spring specimens so the experimental data could not be obtained. However, the relative slip amplitude can be estimated by using the model showed in Fig.10. From the results, the relationship between stress amplitude σ_a and relative slip amplitude S (=θt) at the mean position of fracture (x=1.14mm) is shown in Fig.12. The relative slip amplitude at the mean position of fracture agreed well with that of small axial-loading specimen (dotted line).

Since the contact pressures and the relative slip amplitudes in both specimens agree, the coefficients of friction in both specimens probably coincide.

From the foregoing discussion, it is suggested that the fretting fatigue life of leaf springs can be estimated from that of laboratory specimens, provided the clamping pressures and the relative slip amplitudes of both are of the same magnitude.

4.3 Effect of shot peening

Shot peening causes work hardening of the surface, the generation of a residual compressive stress, and general roughening of the surface. G. Leadbeater et al (12) have shown that the improvement in fretting fatigue properties is largely due to the residual compressive stress, and that surface roughening has also a small beneficial effect but work hardening of the surface does not influence the fretting properties. In the present study, the effect of residual compressive stress has been further examined.

Results of fretting fatigue tests on laboratory specimens annealed at 623K for 3hr subsequent to shot peening are shown in Fig.8. From the measurements of X ray diffraction, the values of residual compressive stress were 576MPa for the shot peened specimens, and 240MPa for the shot peened and annealed specimens. Annealing at 623K for 3hr did not affect the hardness of the specimen surface. As can be seen from the figure, fatigue life varied with the level of residual compressive stress. Assuming that the effect of residual stress is almost equivalent to that of mean stress, fretting fatigue tests were carried out on laboratory specimens under mean stresses of -500MPa and -240MPa. The results are shown in Fig.8, using symbols △ and ▲ , respectively. The fatigue lives of specimens tested under compressive mean stress equivalent to residual stress almost coincide with those of shot peened specimens. Therefore, when predicting the fatigue life of shot peened leaf springs from that of laboratory specimens, it is sufficient to carry out fatigue tests on laboratory specimens under the equivalent mean stress; tests on shot peened specimens are unnecessary.

5 CONCLUSIONS

(1) The leaf spring specimen used in the present study simulated well leaf springs in service.
(2) Fretting fatigue processes in leaf spring specimens were quite similar to those in small axial-loading specimens.
(3) Random loading simulating a rough road reduced the fatigue life of leaf spring specimens whereas that simulating a good road did not do so.
(4) Shot peening improved the fatigue strength of leaf spring specimens by a factor of two. The improvement in fatigue strengths is largely due to the compressive residual stress.
(5) It is suggested that the fretting fatigue life of leaf springs can be estimated from that of laboratory specimens, provided the clamping pressures and the relative slip amplitudes of both are of the same magnitude.

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Table 1 Chemical compositions (wt per cent)

	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Al
SUP9-A	0.55	0.26	0.73	0.021	0.008	0.04	0.74	0.03	0.11	0.021
SUP9-B	0.58	0.24	0.81	0.026	0.022	0.09	0.84	0.03	0.25	0.030

Table 2 Mechanical properties

Material	Heat treatment	Yield strength σ_y(MPa)	Tensile strength σ_B(MPa)	Elongation ψ(%)	Vickers hardness Hv
SUP9-A	850°Cx0.5hr.O.Q. 400°Cx1.5hr.A.C.	1538	1677	13.3	498
SUP9-B		1421	1549	12.4	431

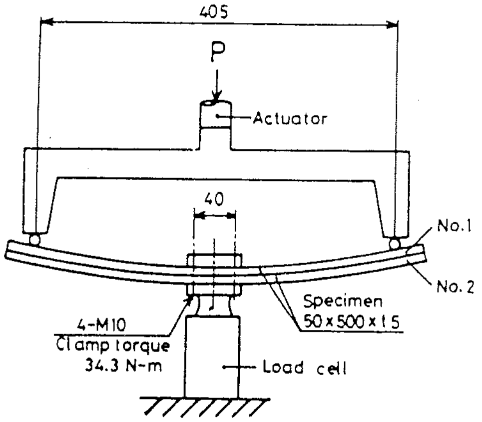


Fig 1 Leaf spring specimen and testing apparatus

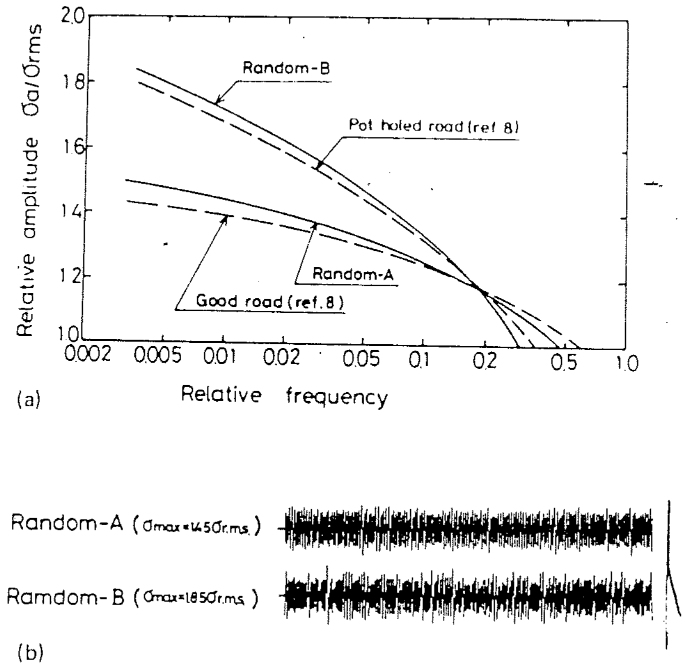


Fig 2 Random load
(a) Cumulative distributions
(b) Wave forms

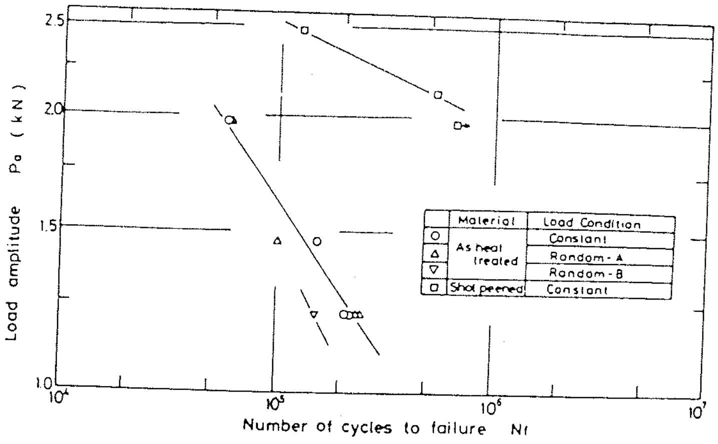


Fig 3 Relationship between load amplitude and number of cycles to failure

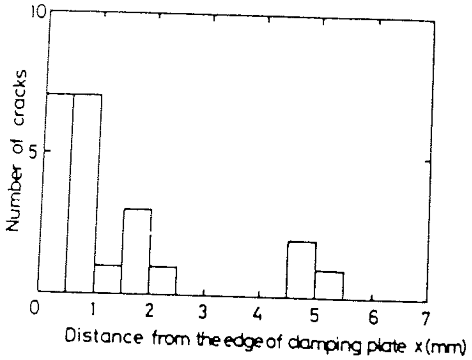


Fig 4 Histogram of the position of crack initiation

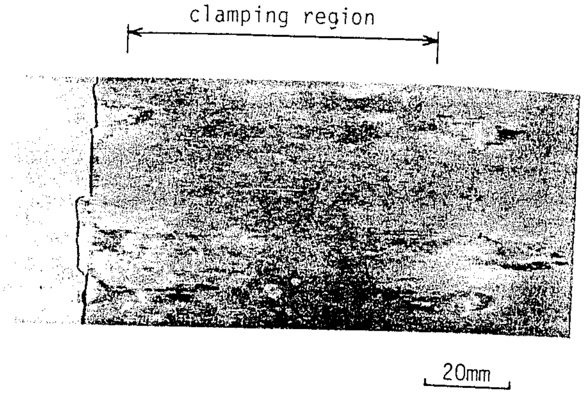


Fig 5 Macroscopic view of the tension side of number two leaf spring (as-heat treated, constant amplitude loading, Pa = 1.96kN)

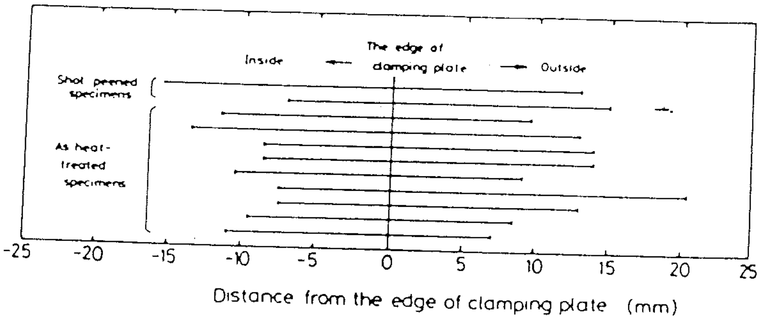
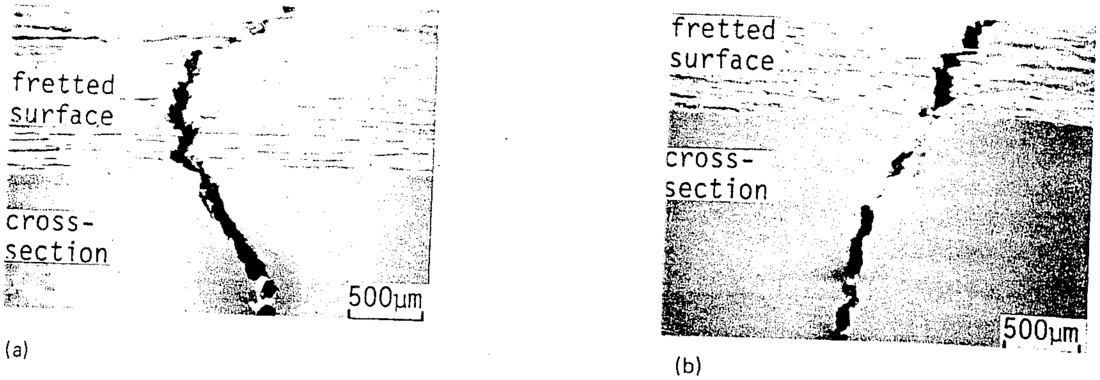


Fig 6 Lengths and positions of fretted regions



(a)

(b)

Fig 7 Longitudinal sections through fretting regions
(a) as-heat treated, constant loading, Pa = 1.2kN
(b) shot-peened, constant loading, Pa = 2.3kN

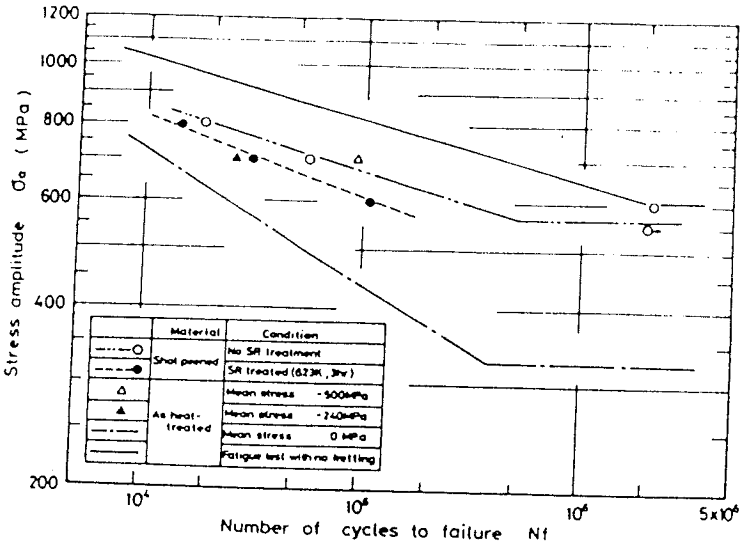


Fig 8 S–N diagram for shot-peened axial-loading specimens

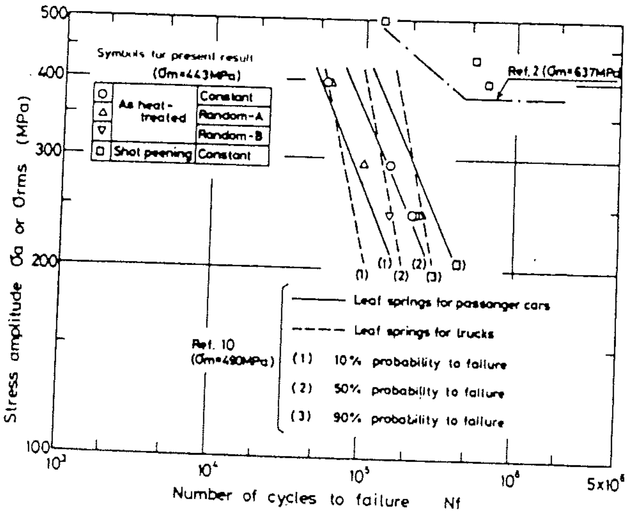


Fig 9 S–N diagrams for leaf springs in service

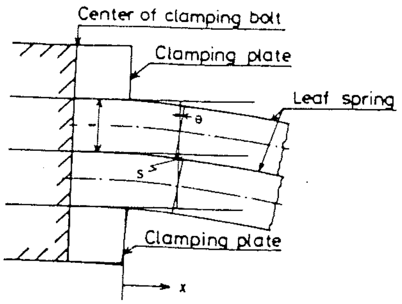


Fig 10 Schematic model for estimating the stress amplitude and the relative slip amplitude

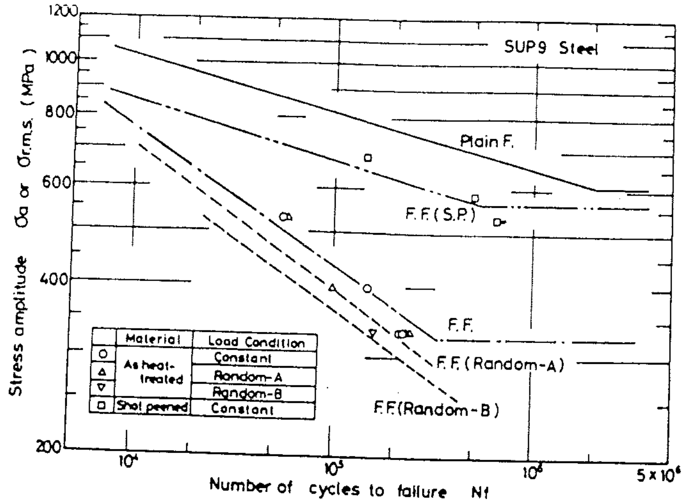


Fig 11 S–N diagram for small axial-loading specimens and leaf spring specimens

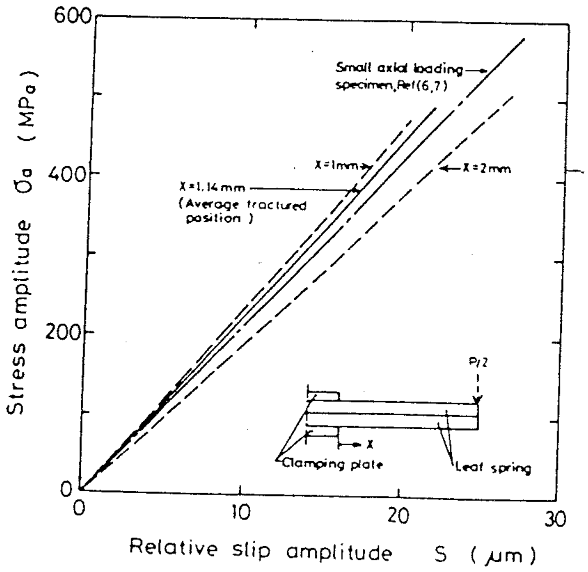


Fig 12 Relationship between relative slip amplitude and stress amplitude