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IMPROVEMENT IN FATIGUE BEHAVIOR BY OVERLOADING

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INTRODUCTION

Designers are continually plagued by the fatigue behavior of materials when designing components subjected to time varying loading conditions. A great deal of study has provided insight into the mechanism of fatigue, but the basic mechanism of fatigue is still not clearly understood. Experimental studies have provided not only insight into the mechanism of fatigue, but also empirical information to aid in designing against fatigue.

It is well known that many factors influence the fatigue behavior. Service conditions usually differ significantly from laboratory conditions and in general, this results in a reduced fatigue limit in service. It is imperative that the designer account for the service conditions to insure adequate component reliability. One of the more important factors influencing fatigue is the stress concentration. In fact, it has often been said that this is the single most important factor in fatigue. Most fatigue failures are initiated at a stress concentration.

Imporvement in fatigue behavior can be achieved through careful design and special processing, such as shot peening, grinding, etc. Many of the processes specifically used to improve fatigue behavior result in the formation of residual compressive stresses. It is well known that residual compressive stresses can provide significant increases in the fatigue limit, but, because of difficulties in determining the residual stress distribution, quantitative data of its affect is limited. Rowland (1) concluded that the effect of residual stresses and applied mean stresses are the same, and that the general effect of compressive mean or residual stresses is equivalent to an extension of the Goodman line as a straight line into the negative mean stress region.

One method of generating residual stresses which can be particularly beneficial to certain types of components is overstressing. Not only will this significantly affect the fatigue limit, but overstressing can also cause considerable delay in fatigue crack growth or even complete crack arrest. Overstressing can be particularly beneficial in parts containing stress concentrations, since it can result in the desired residual compressive stresses at the root of the notch where fatigue failure is most likely to occur.

The influence of overstressing on the fatigue behavior, both fatigue limit and crack growth delay, are discussed below. An example of typical stresses and stress-time histories in compressor valves is also presented which show that overloading may provide a significant improvement in fatigue performance of compressor valves.

RESIDUAL STRESSES FORMATION BY OVERLOADING

Residual stresses will be created by overloading whenever localized yielding occurs. If a stress gradient exists and the load is sufficiently high, then localized yielding will occur. In the case of a beam in bending, the localized yielding occurs at the surface and the resulting residual stress distribution for idealized stress-strain behavior will be similar to that shown in Figure 1. Stress concentrations resulting from geometric variations provide the necessary stress gradients to cause localized yielding at the root of the notch. Figure 2 shows a typical residual stress distribution due to tensile overloading of a notched plate. To be beneficial in fatigue the resulting surface residual stress must be compressive, since fatigue cracks initiate at a free surface. In general, overloading in the same direction as the applied service loading will result in the desired compressive residual stresses.

Residual tensile stresses created during straightening operations have been known to cause premature fatigue failures in rotating members such as crankshafts. This example points out the importance of knowing the residual stress pattern, regardless of its origin.

INFLUENCE OF OVERLOADING ON THE FATIGUE LIMIT

Preloading has been used to generate desired residual stresses in components such as leaf springs and gun tubes. Several investigators have observed increases in the fatigue limit of 50 to 300 percent by preloading notched bars (2-4). These studies indicate that the increase in the fatigue limit is

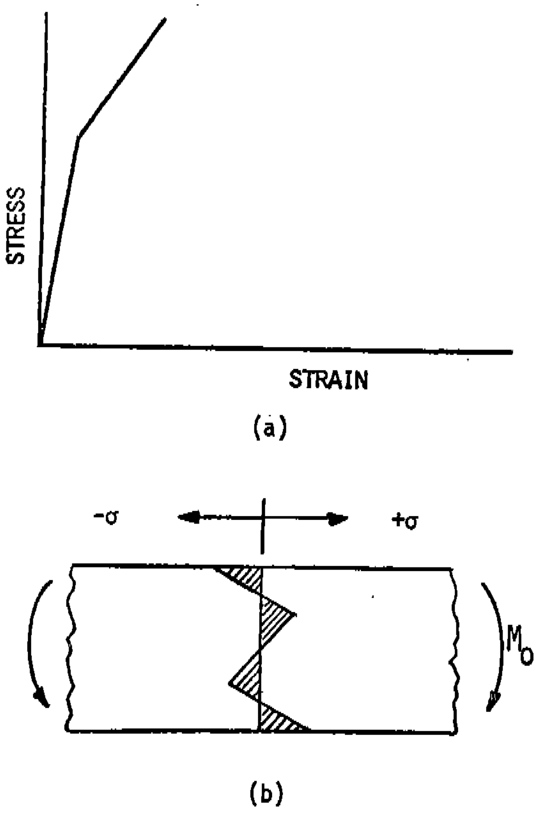

Figure 1(a) Idealized stress-strain behavior
(b) Residual stress distribution for a beam which has been overloaded in the direction shown by M_0.

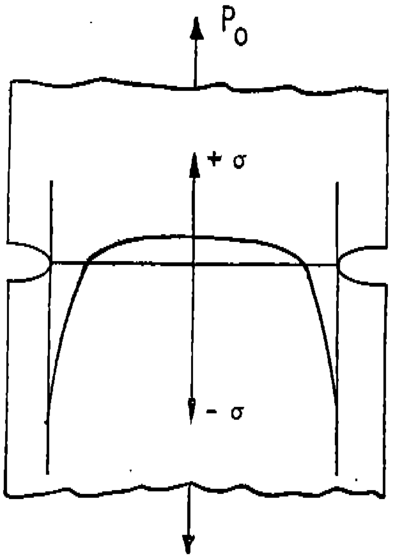

Figure 2. Typical residual stress distribution in a notched plate due to a tensile overload, P_0.

greater for heat treated materials than for annealed materials. Furthermore, the higher the strength of the material the greater the increase in the fatigue limit. In annealed materials the increase in fatigue limit appears to be due primarily to the increased hardness from cold working of the material whereas in high strength materials the effect is primarily due to the residual compressive stresses. It has also been observed that preloading has a greater influence on the fatigue limit than on the fatigue life at higher stress levels. This is apparently due to less fatigue softening of redistribution of stresses at the lower fatigue stress levels.

The work of Gerber and Fuchs (4) illustrates the general effect of prestressing and will be discussed in more detail. In this study, notched and unnotched specimens of AISI 4340 steel, heat treated to two different hardness levels, were tested in rotating bending. The two different heat treatments used gave the following properties:

HR_c	Yield Strength	Ultimate Strength
24	121 ksi	170 ksi
49	225 ksi	265 ksi

Five different specimen types were used in the study. Stress concentrations for the different specimens are given in Table 1.

The specimens were preloaded in axial tension prior to fatigue testing. The effect of preload obtained by Gerber and Fuchs is shown in Figure 3 for the soft condition (24 HR_c) and in Figure 4 for the hard condition (49 HR_c). In these figures the fatigue limit is plotted versus the ratio of the nominal preload stress to yield strength, where the nominal preload stress is the axial stress concentration factor times the net stress. The difference in the fatigue limit with no preload between specimen 100 and 200 and between specimens 101 and 202 is primarily due to the size effect.

It is interesting to note that in this study a greater percentage increase in the fatigue limit was obtained for the higher strength material. Also the higher stress concentration showed a greater percentage increase in fatigue limit (Specimen 201-H Figure 4). Furthermore, the detrimental effect of the stress concentration was nearly completely eliminated by preloading the specimens.

Another interesting observation made by Gerber and Fuchs was that the specimens given the larger preloads developed circumferential fatigue cracks that became nonpropagating. (Some specimens cycled 16 million cycles showed complete crack arrest (4,5)).

EFFECT OF OVERLOADING ON FATIGUE CRACK GROWTH

The effect of changing stress amplitudes on fatigue life has been studied for many years and has resulted in many proposed cumulative damage theories. Crack growth which can take up a significant portion of the fatigue life is influenced by the load sequence. Recent studies involving single peak overloads and multiple peak overloads both

Table 1

Stress Concentration Factors for Specimens Used by Gerber and Fuchs (4).

Specimen Type	Axial Stress Concentration	Bending Stress Concentration	Diameter, in. (at notch root)
100 (smooth)	-----	-----	.200
101	2.65	2.15	.200
200 (smooth)	-----	-----	.500
201	3.95	3.20	.500
202	2.65	2.15	.500

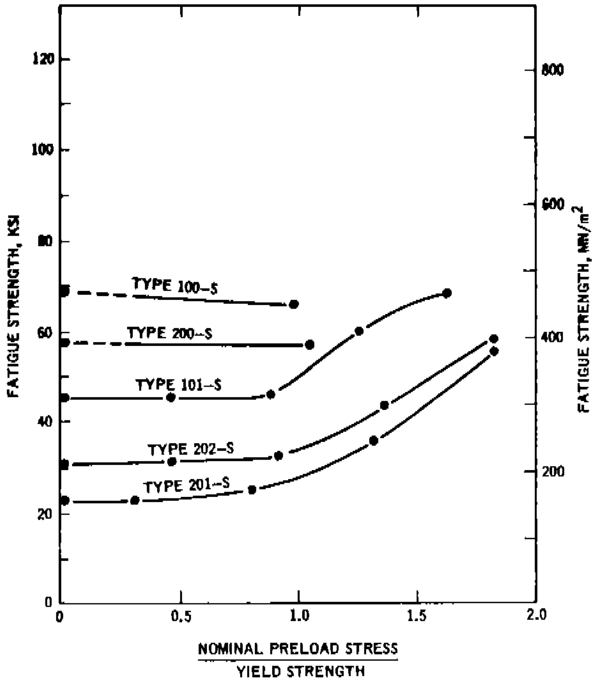

Figure 3. The effect of preload on the fatigue limit of soft (24 HR_C) specimens (4).

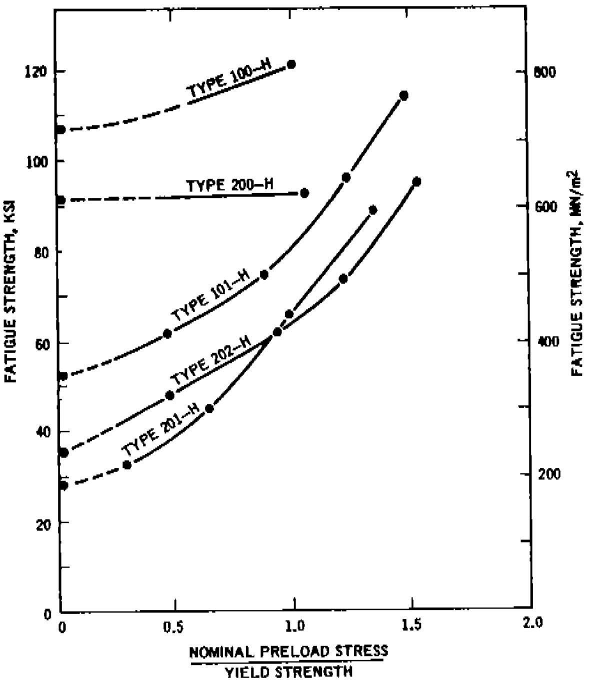

Figure 4. The effect of preload on the fatigue limit of hard (49 HR_C) specimens (4).

consecutive and periodic, have shown that significant delays in crack growth can occur (6-11). Typical behavior due to an applied tensile overload is illustrated in Figure 5, which is a plot of crack length versus number of cycles. Immediately following the overload, the crack growth rate increases, then decreases considerably, followed by a gradual increase back up to the growth rate prior to the overload. In Figure 5, r'_o corresponds to the crack length extension which is influenced by the overload. von Euw (8) and Probst (11) showed that this affected region corresponded to the size of the plastic zone at the tip of the crack created by the overload.

Probst (11) applied single peak overloads to center cracked 2024-T3 aluminum alloy sheet specimens. Figure 6 shows the typical overload and fatigue

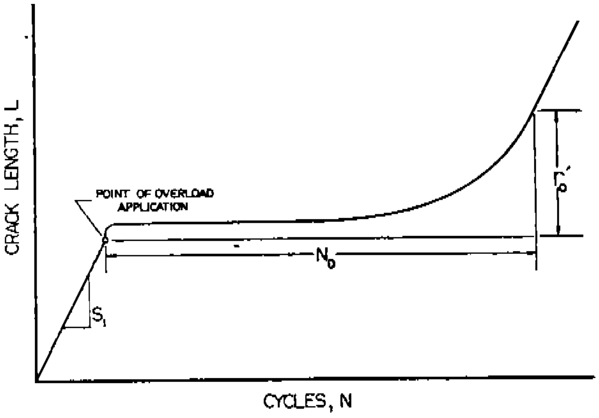

Figure 5. Typical ℓ vs. N curve showing effect of tensile overload (11).

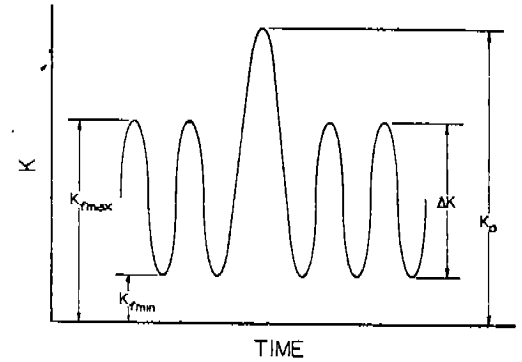

Figure 6. Typical overload and fatigue cycling used by Probst (11).

cycling sequence. He used the stress intensity factor[1], K, as the controlled test variable and to correlate the data. In this study, Probst found that if the applied overload, K_o, was large enough, complete crack arrest resulted. (no observable crack growth in 1 million cycles) This general behavior is illustrated in Figure 7, which shows the overload required to obtain complete crack arrest for a given fatigue loading. Using the concepts of the crack closure model proposed by Elber (14), Probst showed that the line separating the two regions in Figure 7 corresponded to a residual stress or clamping action on the crack which must be overcome by the applied loading in order for the crack to open and further crack growth to occur. Using this model, he developed an expression for the number of delay cycles resulting from the applied overload.

Paris (12) showed that fatigue crack growth rate could be readily correlated with the applied ΔK, since it is directly related to the magnitude of the stress at the crack tip.

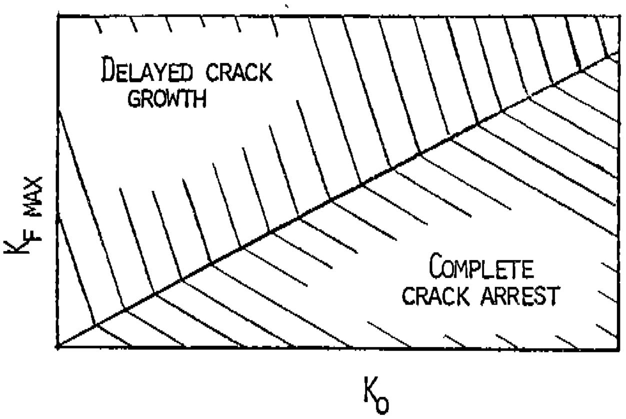

Figure 7. Applied overload, K_o, necessary to produce crack arrest (11).

The investigations mentioned previously show that significant delays in crack growth or complete crack arrest can result from tensile overloading. Several consecutive overloads have been shown to increase the delay cycles more than a single overload (7). Periodic overloading of notched tensile specimens showed that there is an optimum ratio of overloads to fatigue cycles to obtain the greatest increase in fatigue life (10). Since the plastic behavior at the tip of a sharp crack is not entirely understood, the primary causes of crack delay have not been established, however, the observed behavior can be explained by means of residual stresses.

GENERAL APPLICATION TO COMPRESSOR VALVES

The stress distribution in a flexible compressor valve is a complicated function of the position on the valve and the instant of time during the valve operation. One of the most difficult tasks of the valve designer is to predict the magnitude and location of the maximum tensile stress in the valve to determine the possibility of fatigue failure during compressor operation. The constraints on valve space, lift, impact, and valve life are frequently critical and competing. The technique for improving fatigue behavior discussed in this paper could provide a method for materially improving compressor valve life in a critical situation by applying a preload on the valve in the direction of normal loading.

Many valves exhibit possible locations of high tensile stress level with sharp stress gradients immediately surrounding the location as shown in Figure 8. Other valves can have this necessary condition due to the combination of frequency dependent stress modes during the dynamic operation of the valve. This situation which is normally detrimental to the continued operation of the valve is

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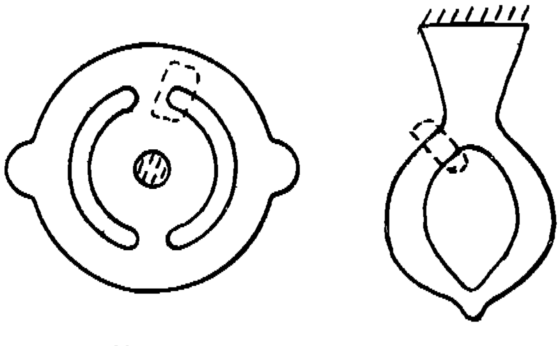
[1] The stress intensity factor, K, is a measure of the intensity of the stress at the tip of a sharp crack. Linear elastic fracture mechanics has shown that the elastic stress distribution at the tip of any sharp crack is the same and that the magnitude of the stresses in the vicinity of the crack tip is determined by the stress intensity factor. The stress intensity factor depends on the applied stress, crack length and the specimen or component geometry. The general form of the stress intensity factor is

$$K = \sigma\sqrt{\pi\alpha a}$$

where σ = applied nominal stress
a = crack length
α = geometry factor

For an infinite plate with a through the thickness crack subjected to a biaxial tensile stress, the geometry factor, α, is unity. See reference 13.



VALVE A VALVE B

Figure 8. Valve geometries showing possible high stress rates.

just the necessary condition to permit localized yielding during the overload and localized residual compressive stresses after release of the overload. The stress gradient through the thickness of a cantilever reed valve can be utilized to provide residual surface compressive stresses. The residual compressive stress will then reduce the tensile stress level due to the service loading of the valve and allow higher loads before encountering the fatigue limit. In the case of surface flaws of cracks it can retard or suppress the initiation or growth of fatigue cracks.

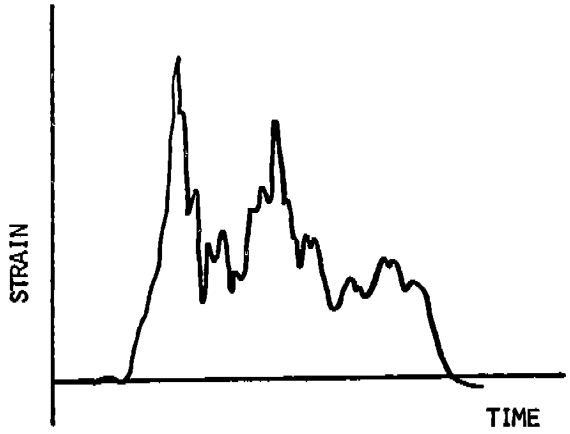
The introduction of surface residual compressive stresses in the compressor valve due to bending loading in one direction is accompanied by a residual tensile stress in the opposite surface. If the operational loading on the compressor valve was reversed bending such as to cause tensile stresses in the surface with the residual tensile stresses the introduction of surface residual stresses would be detrimental to the fatigue behavior of the member. Compressor valves are primarily one directional bending members to control the one directional flow of gas through a port. Typical strain-time histories are shown in Figure 9 for a cantilever and a flexible ring valve. There is the probability of some reversed bending in valve locations close to the stop contact point due to impact against the stop. However, unless the impact is particularly sharp, this effect should be smaller than the general bending effect.

The distribution of the static overload over the valve should be selected such as to develop valve surface strains in the same direction as the service loading imparts and of such a level as to cause only localized yielding at the high stress points in the valve. This loading might be accomplished by pressing the valve against some preshaped form during the forming operation. The level and distribution of the deformation would need to be determined for each valve. Indications are that the correct stress distribution could be obtained by increasing the actual service deformation pattern.

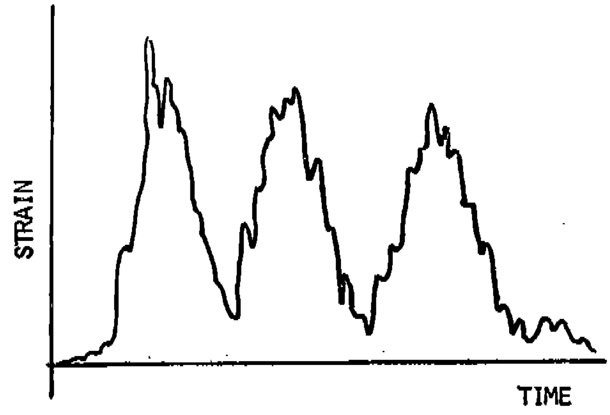
SUMMARY

The application of an overload can significantly improve fatigue behavior by increasing the fatigue limit or reducing the growth rate of an existing fatigue crack. Compressor valves exhibit the general characteristics which have been shown to result in improved fatigue behavior after overloading. These characteristics are:

1. Compressor valves are made of high strength steels.
2. Compressor valves are subjected primarily to one directional bending.
3. Compressor valves are frequently of such geometrical shape as to induce stress concentrations.
4. Fatigue is a primary cause of compressor valve failure due to the repeated bending.



CANTILEVER - FIXED END



FLEXIBLE RING VALVE

Figure 9. Typical valve strain time histories.

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