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Title of Study: FATIGUE OF ENGINEERING MATERIALS

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Major Field: Civil Engineering

Scope of Study: Investigation of the fatigue properties of engineering materials has formed the basis of much study in the past one hundred years. Although the approach to many of the studies were very similar, the results contain a large degree of variance. In order to reduce the variation in test results and to obtain data which is useful, a study of previous work in this area has been made. Particular emphasis has been placed on planning of fatigue test programs, variables which must be considered, and methods of handling fatigue test data. Materials used were chiefly papers presented to national organizations, such as the American Society of Mechanical Engineers, Institution of Mechanical Engineers, and The International Union of Theoretical and Applied Mechanics.

Findings and Conclusions: The variation in fatigue test data is primarily due to three factors: (1) the large number of variables involved, (2) the difference in test procedures, and (3) improper planning of fatigue test programs. In order to obtain useful data, it is essential that these three factors be evaluated to the greatest possible degree. The prediction of the service life of any member subjected to fatigue loads cannot be accurately done by use of static properties.

The extreme cost of fatigue test programs has retarded the advancement of investigation into fatigue properties of engineering materials to a great degree. Therefore, at the present time, little if any information is available on materials other than steels and certain aluminum alloys. This is due to the fact that these are the only materials which industry has subjected to fatigue loads.

ADVISER'S APPROVAL ______________________________

FATIGUE OF ENGINEERING MATERIALS

By

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Bachelor of Science

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the Oklahoma State University
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FATIGUE OF ENGINEERING MATERIALS

Report Approved:

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Dean of the Graduate School

PREFACE

This study has been done as an aid to future researchers in the area of fatigue testing. It is my hope that this report may be used in the preliminary planning of future fatigue test programs.

I wish to express indebtness and appreciation to the following:

Professors Rodger L. Flanders and Jan J. Tuma for their assistance and guidance in the preparation of this report and throughout my graduate study.

Professor and Mrs. Gordon G. Smith for their valuable assistance and encouragement.

The Faculty of the School of Civil Engineering for their many contributions to my education in both my undergraduate and graduate programs.

Miss Velda D. Davis for her excellent typing of this manuscript.

Donald L. Woods

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CHAPTER I

INTRODUCTION

The problem of fatigue is one of the most complex problems with which the engineer must deal. Although fatigue failures were known to exist, few tests were conducted until nearly 100 years ago. Wöhler conducted a series of rotary beam repeated-load tests. Since that time, many investigations of fatigue properties have been conducted. Today, even with a century of research, we still cannot accurately predict the service life of a member subjected to repeated loading.

In our modern high-speed society, fatigue problems are the rule rather than the exception. It is therefore understandable that great emphasis is now being placed on research in this area. Cottell (1)*, has estimated that 80% of all engineering failures are fatigue failures. Although this figure seems high it does indicate the need for a complete understanding of the factors involved.

The basic fatigue failure mechanism has been the basis of much study and is reasonably well understood. The forma-

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*Superior numbers in parentheses refer to numbers in the Bibliography.

tion of fatigue cracks begins as slip-bands within, or at the boundary of, the individual crystals. Under repeated loading these slip-bands are enlarged until they become micro-cracks. As the loading is continued, the micro-cracks merge, eventually leading to failure. Although the basic failure mechanism has been generally accepted, there is some disagreement as to why failure occurs according to this procedure. The reason for this disagreement will become apparent later, as the many variables involved are discussed.

Since the fatigue problem is very complex, it is necessary to review the work that has been done by others in order to formulate a reasonable approach to a fatigue research program. The purpose of this report is a general discussion of the variables involved and recommendations as to the apparent direction of future research.

CHAPTER II

STATEMENT OF THE PROBLEM

The primary function of any engineering structure is to carry the loads that may be applied to it. There are three major areas which must be considered when any design is started. These are: the intended function of the part, the required service life, and the production cost.

The first and third of these can be accurately determined during the design stages. The second can only be approximated. In order to determine the service life of a part under given loading conditions and given geometric shape, it is necessary to perform repeated-load tests on the finished product. Even with a large number of tests, the service life can only be predicted on the probability of failure owing to the large number of variables and the chance effects of combining two or more of these variables in a position that could cause failure.

The fact that very few structures have constant load functions further complicates the prediction of service life. In controlled laboratory tests, the load is usually maintained within very close limits and the variation usually follows a sinusoidal relationship as shown in Figure 1. However, in service, the actual load spectrum may be as shown in Figure 2.

Study of these two figures shows the difficulty in correlating test data and actual service life.

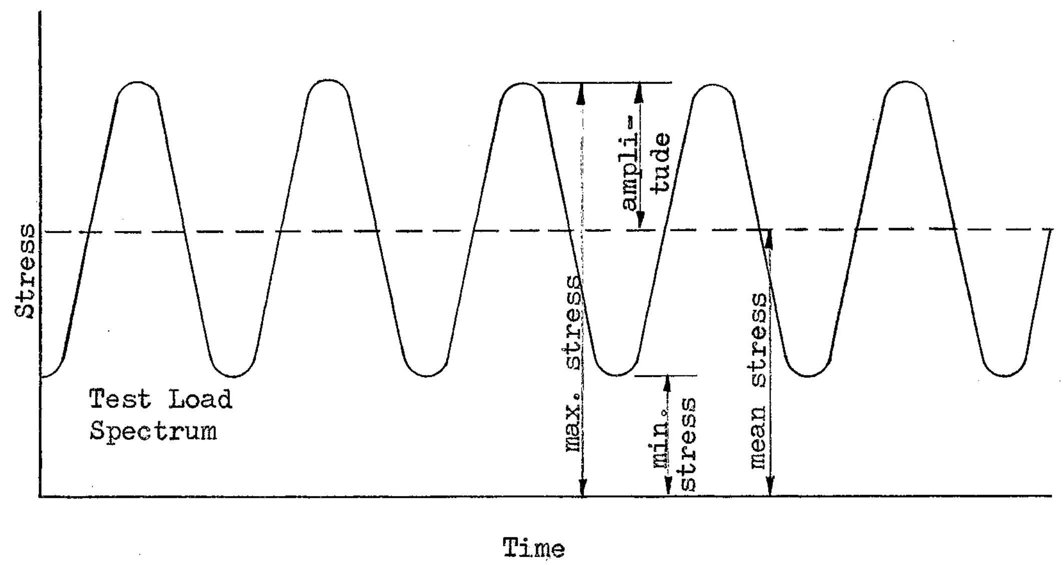

Figure 1.

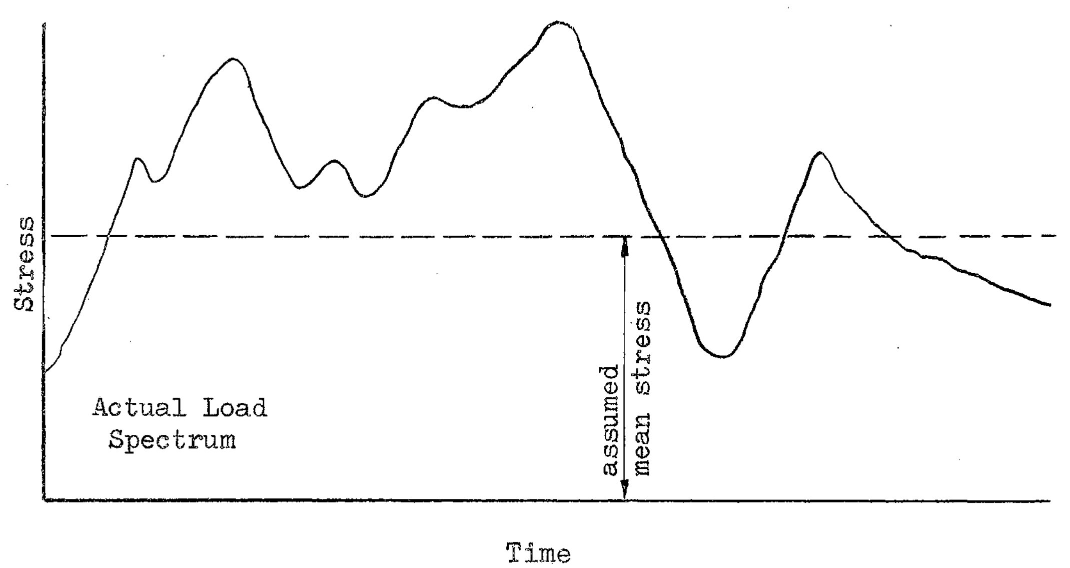

Figure 2.

Attempts have been made to write cumulative damage equations relating the number of cycles at a given stress to the total number of cycles at several different stress levels required to produce failure by fatigue. From Figure 2, it can be seen that no two peaks occur at the same stress level. This means that even if the cumulative damage equations mentioned above are exact, the evaluation of any equation with this type of relationships would be extremely difficult if not impossible. Another factor that must be considered is that the load spectrum for a particular member cannot be determined until the member is actually in service. (2)(3)

Therefore, the design of a member to resist repeated loads is still done by trial and error methods. The member is designed according to the judgement of the designer and mounted in the structure. After a few tests, the load spectrum can be determined and critical points along the member can be found. This information will indicate any design changes that may be necessary.

The problem of predicting service life would be somewhat simpler if all the variables could be studied separately and the effect of each understood. However, fatigue failure is generally due to a combination of two or more factors. Some work has been done which involved the study of individual crystals under repeated loads. This is usually done using the electron microscope or x-ray diffraction methods.

Although this type of study is necessary to understand the basic failure mechanism, it does not enable the engineer to better predict the service life of a given member.

The ultimate goal of fatigue testing is the prediction of the behavior of members of structures under the action of repeated loads. The tests are carried out on component parts, the complete structure, or a small laboratory specimen. The type of test to be used is dependent on the results desired. If it is desired to determine the fatigue properties of a material, the laboratory specimen will be used in order to reduce the number of variables. Generally, it is not possible to predict the behavior of a structural component from a test of this type.

If it is desired to predict the fatigue life of a structural component, the component type tests will be used in order to include all the variables that will actually exist on the component. In general, it is not possible to determine fatigue properties of the material from a test of this type.

Regardless of the type of test there is always a large amount of variation in the test data. This apparent difference in results can be disturbing to someone unfamiliar with fatigue problems. This variation of results cannot be handled by the simple rules that are generally applied in the static testing of engineering materials.

There are many methods of handling fatigue test data. In general, any statistical method that allows for the computation of average or mean values is acceptable. The method to be used in any particular case is determined by the accuracy required.

CHAPTER III

VARIABLES THAT MUST BE CONSIDERED

The problem of fatigue, as has been stated, is very complex. There are many variables which must be considered in determining the causes of any particular fatigue failure. These variables can be broken into three groups according to their origin.

I. The Specimen

   A. Composition
   B. Micro-Structure
   C. Residual Stresses
   D. Inclusions
   E. Heat Treatment (if metal)
   F. Isotrophy
   G. Homogeneity
   H. Surface Condition (machined, polished, plated, etc.)
   I. Specimen Geometry (size and shape)
   J. Delamination (if plastic)

II. Applied Stresses

   A. Intensity of Stress Amplitude
   B. Intensity of Mean Stress
   C. State of Stress
   D. Stress Gradient
   E. Frequency of Stress Cycle
   F. Shape of Stress Cycle

III. Environment

   A. Temperature
   B. Relative Humidity (plastics and wood)
   C. Sunlight and Other Radiation (for plastic)
   D. Corroding Agents (water, acid, alkalies, etc.)

IV. The Machine

A. Type of Machine
B. Mechanical Condition
C. Operation

The Specimen

I-A Composition

The effect of composition on the fatigue strength of a material may be very great. Since the effects of composition have been studied in great detail under static loading conditions, it is reasonable that attempts have been made to correlate the change of fatigue strength with changes in static properties. A general rule has been formulated that will give an idea of the change of fatigue properties with change of composition. Sines and Waisman (2) have stated, "As the static ultimate strength is increased, the fatigue strength will be increased provided the change of other properties (hardness, ductility, etc.) is not too great." This rule has been formulated basically for metals, but may also be applicable to plastics and concrete. This must be confirmed by a series of tests.

It must not be assumed, from the statement above, that the fatigue life of any material can be predicted by its static ultimate strength. Only a rough estimate of the fatigue life can be obtained, and in some cases the change of other properties will be such as to reduce the fatigue strength.

I-B The Micro-Structure

Micro-Structure plays an important role on the fatigue properties of metal. Cazaud (4) has shown that, for mild steel, as the grain size increases the endurance limit goes down. This has also been shown to be true for other materials.

The relative position of components making up a solid mass will have a definite effect on fatigue strength. The slip-bands will form along planes of least resistance and any change in the micro-structure which allows a layer of soft material to form will greatly effect the fatigue strength.

I-C Residual Stresses

In general, residual stresses increase the endurance limit. However, it is interesting to note that most of the residual stresses in critical areas are compressive and the endurance limit is much greater in compression than tension. Although the compressive endurance limit is reduced, it is usually neglected due to the fact that tension is usually the limiting stress.

Residual stresses can obtain a magnitude of 100,000 psi, but will not usually exceed 60,000 psi. Sigwart (7) states that these stresses can be developed by one of the following means:

1. Unequal Loading (Peening, Brinell tests, etc.)
2. Machining (formed as tools chip away material)
3. Unequal Stress Distribution (notch, hole, or large inclusion)
4. Unequal Heating (hardening, nitriding, carburizing, etc.)

Kudryavtser (6), after a study of the effects of residual stresses, concludes that the development of residual stresses for parts without large stress concentrations are comparatively insignificant and in many cases have no material part in fatigue breakdown of material.

Residual stresses, if properly used, could reduce the size of many members now in service. Moore et al., (5), in tests of steel using different heat treatments, definitely has shown that the endurance limit, of a small test specimen under repeated bending, is increased. The use of information of this type will allow more economical design with the same required degree of safety.

I-D Inclusions

Epremian and Mehl (8), have shown that the most important single factor in determining the extent of the variation in fatigue life is probably the number and location of the inclusions. Their work on small laboratory specimens indicates that as inclusion ratings go up the variation in results also increases.

Stulen, Cummings, and Schulte (9), in their investigation of high strength steels, bring out the fact that the effect of inclusions on fatigue life is largely dependent on the size and location of inclusions, and the range of loading. In the low stress range, a single large inclusion will be the cause of failure. As the mean stress is increased the smaller inclusions will contribute to failure, until at very high stresses the large inclusions are of very little importance.

The effect of inclusions should not be overestimated. Hartmann (10), states that inclusions that can be shown to have a pronounced effect on the fatigue strength of smooth metallurgical-type specimens does not necessarily mean that they will lower the fatigue strength of a structural member. The effect of holes, welds, and abrupt changes of section is much greater, and inclusions are important only when they are located in such a position as to create a weak plane by combination with one of the other high stress concentration factors.

I-E Heat Treatment (for metal)

Heat treatments can be used either to increase or decrease the fatigue limit of a given metal. This is usually done by intentionally producing residual stresses (nitriting, carburizing, case hardening, etc.) or by relieving residual stresses by annealing. The grain size is dependent on heat treatment and as shown by Cazaud (4), as grain size increases the endurance limit decreases.

I-F Isotrophy

It has been known for many years that forging and rolling have the effect of imparting to metal a fibrous texture. This means that in the direction of rolling, the metal will have its greatest tensile strength. This also holds true for fatigue strength, as shown by Cazaud (11). Therefore, in the selection of samples, from which test specimens are to be made, it is necessary to select the sample in the longitudinal direction. Often, the fatigue strength perpendicular to the direction of rolling or forging will be less than for the cast metal, which possesses no marked orientation.

I-G Homogeneity

In all basic Strength of Materials, it is assumed that the materials are homogeneous. However, it is well known that this is not true, particularly for concrete, wood, and forged or rolled sections of metal. Although the homogeneity of the material is of little importance under static loading conditions, it becomes very important under dynamic loading conditions. The boundaries between the phases of material within the mass are planes on which micro-cracks may develop.

I-H Surface Condition

The condition of the surface of the specimen subjected to dynamic loads can be the factor that leads to failure. The surface condition effects can be divided in two groups:

A. Intentional Stress Concentrations
B. Unintentional Stress Concentrations

Included in group "A" are such factors as notches, holes, surface hardening, peening, etc. Group "B" includes effects from machining, polishing, plating, scratches, tears, cracks, gouges, and surface discontinuities.

A notch or hole in a test specimen will cause severe stress concentrations, and in almost every case will be the cause of fatigue failure. The effect of notches or holes is usually evaluated in terms of stress concentration factors. The factor K_T is the stress concentration factor under static loading and K_F is the stress concentration factor under dynamic loading. Sines and Waisman (2) conclude that generally K_F will be smaller than K_T due to the localized plastic strains which occur in areas of high stress concentration under cyclic loading. In all cases, holes or notches will reduce the fatigue life of a given specimen. This same conclusion has been reached by Forrest (12). Surface hardening and peening produce a reversed effect on the fatigue life. That is, the fatigue life is generally increased by such processes. The American Society of Metals (13), in tests of carburized steel, have shown that the increase in fatigue life may be as large as 200% over untreated specimens of the same material and same surface finish before carburizing. This report also shows that by removal of a thin surface layer after carburizing, the fatigue life is increased even more.

Coombs, Sherratt, and Pope (14), in their investigation of shot-peening effects on fatigue strength of spring steel, concluded that the effect of shot-peening is to increase the fatigue strength. The shot-peening process, in effect, is a surface hardening process. As is true of certain heat treatments, (carburizing, nitriting, case hardening, etc.) the production of residual stresses within the specimen is the manner in which the fatigue strength is effected. Shot-peening will increase the fatigue strength by 20% to 40% - depending on the size of shot used, velocity of shot, temperature at peening, and type of material. A large increase in fatigue life can be expected for steels by peening and removing surface layers.

The items listed in group "B" (machining marks, polishing, plating, scratches, tears, surface cracks, gouges, and surface discontinuities) will in general reduce the fatigue life of a given specimen, provided that there is no high stress concentration in the critical section. Hartmann (10) states:

> The fact that a material has unintentional stress raisers that can be shown to have a pronounced effect on the fatigue strength of smooth metallurgical-type specimen, does not mean necessarily that they will lower the fatigue strength of a structural member. Such things as rivet holes, bolt holes, re-entrant corners and abrupt changes of section have a much greater effect and unintentional stress raisers will only effect the fatigue strength if they occur at the edge of holes or other stress concentrations.

I-I Specimen Geometry

The size and shape of the specimen have a direct bearing on the fatigue life. The shape of the specimen will, to certain degree, determine the state of stress which will exist. Very little work has been done dealing only with shape effect. However, what investigation has been done, indicates that the shape effects are about the same as the notch effects. That is, a point of high stress concentration is created which will reduce the fatigue life of the member.

The size effects have been studied to a greater degree, but little in the way of conclusive information is available. Horger and Neifert (15), and Uzhik (16), state that there is a growing belief that size has little effect on fatigue strength, if the state of stress remains the same. This condition is very hard to obtain. As the size of the member is increased, the possibility of large inclusions is also increased and therefore, the state of stress may be changed.

Kuhn (17) and Keyser (18), have shown that, in general, as the size of the specimen is increased the fatigue strength is decreased and in all cases, the stress concentration factors for fatigue were less than the values computed by the theory of elasticity. Sines and Waisman (2), in viewing the conclusion reached by Kuhn and Keyser, for reversed bending, felt that the difference in fatigue strength is due to the difference of stress gradient. However, for axial stresses, no stress gradient will exist and therefore, it seems reasonable that internal defects (inclusions) are also responsible to a certain degree.

There is little doubt that any single factor is entirely responsible for the reduction in fatigue strength with an increase in member size, even in members with geometric similarity. The current trend to component testing will, to a certain degree, help to determine the exact effects of size.

I-J Delamination (plastics)

Although no work has been done dealing with the fatigue properties of plastics, it is generally assumed that delamination of the fibers of plastic will act exactly the same as an inclusion in metal. The delamination will create a point of high stress concentration, thus reducing the fatigue strength of the specimen.

Applied Stress

2-A Intensity of Stress Amplitude

The intensity of stress amplitude for a given material is dependent on the value of the mean stress. As the mean stress is increased, the amplitude must decrease. Peterson (21), has suggested the use of a modified Goodman diagram to show the comparison of stress, amplitude, and mean stress. Figure 3 is a diagram of this type.

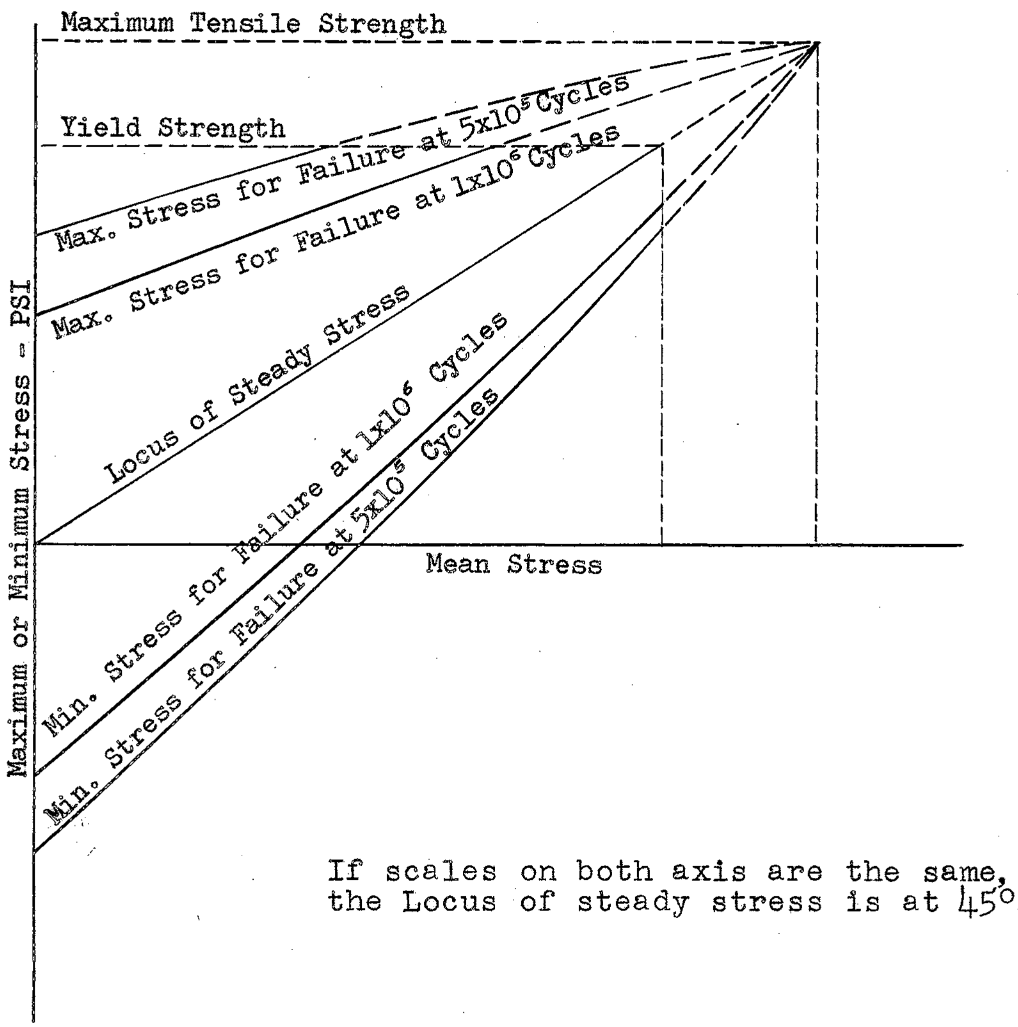

Figure 3. Modified Goodman Diagram

2-B Intensity of Mean Stress

The mean stress has a direct bearing on the fatigue life of the specimen, as can be seen from Figure 3. As the mean stress is increased (in either tension or compression) the amplitude of the stress cycle that will produce failure, at a given number of cycles, is decreased. The value of the amplitude for a given mean stress can be taken directly from a diagram similar to the one shown in Figure 3, which has been drawn for the material of which the specimen is made.

O'Connor and Morrison (19), and Woodward, Gunn, and Forrest (20), in their investigations on the effect of mean stress, point out the fact that the drawing of the diagram mentioned above is very difficult, due to the variation in test results. O'Connor and Morrison also found that with the maximum stress just above the yield point of the material, the variation is so large that comparison of test results is almost impossible.

2-C State of Stress

The state of stress that exists on a test specimen controls to a large degree the fatigue life of the specimen. It is well known that the fatigue limit in torsion is higher than the fatigue limit in tension. This fact lends support to the idea that slipping in a considerable number of grains at peak stress may be a necessary condition for fatigue failure in ductile materials.

The state of stress on the specimen is generally determined by the type of loading and the shape of the specimen.

The orientation of the cyrstals, the type of loading, and the shape of the specimen will determine the state of stress that exists on the crystal. Since the formation of micro-cracks within the crystals is directly dependent on the state of stress, to which the crystal is subjected, it will to a limited degree effect the fatigue life of the specimen.

<u>2-D Stress Gradient</u>

Little, if any, work has been done in the way of investigation into the effect of stress gradient on the fatigue properties of materials. It is known that the fatigue strength is greater for bending loads than for axial loads. The accepted reason for this effect is that the inner fibers, because they are at a lower stress, inhibit the slip in the outer fibers. As stated in Section 2-C, this inhibition of slip by a stress gradient is not present in a specimen under direct axial loading. It is reasonable to believe that fatigue life is greater in bending than in axial loading because of the influence of the stress gradient.

<u>2-E Frequency of Stress Cycle</u>

As the frequency of the stress cycle is increased, the fatigue life is also increased. McClintock (22), suggests that the increase in fatigue life is due to the reduction in the amount of slip that takes place during the stress cycle. Moore (23), has shown that for frequencies up to 10,000 cycles per minute, the error will be less that 5%, and the results will fall within the normal scatter bands developed under lower frequency loading conditions. Sines and Waisman (2), in tests of metal samples at room temperature, show that there is no change in results up to 5,000 cycles per minute, and at frequencies as high as 120,000 cycles per minute, the effect is less than 20%.

Wade and Grootenhuis (23), have shown that the results obtained from very high speed fatigue tests are accurate for materials subjected to a cycle frequency of the same value. They have also shown that the increase in fatigue life is normal and should be expected at frequencies greater than 10,000 cpm.

2-F Shape of The Stress Cycle

Although the effects of the shape of the stress cycle have been studied, very little has been done along this line except as secondary investigations. Since the shape of the stress cycle is governed by the amplitude of the stress and the frequency of the cycle, the effect of the shape of the stress cycle will be the same as mentioned in Sections 2-A and 2-E. This, however, is only under controlled laboratory conditions where the load cycle is sinusoidal (see Figure 3).

Under service conditions, the stress spectrum does not generally follow a uniform pattern and therefore will have a much greater effect on the fatigue life. This effect may be beneficial or detrimental.

Environment

3-A Temperature

There is a considerable change in the fatigue properties of metal as the temperature is increased or decreased. As the temperature is increased, the fatigue strength is reduced. This is generally attributed to the reduction in the bond strength between grains. The problem is further complicated by the fact that at high temperatures, creep also becomes significant.

Little has been done at temperatures below room temperature. However, it is generally assumed that the fatigue strength will be greater as the temperature is decreased.

Information is not available on temperature effects on plastics, concrete, or wood. It is believed that plastics will behave in a manner similar to metal and that concrete and wood will not be affected until the temperature reaches the critical level (spalding of concrete, burning of wood).

3-B Relative Humidity (plastics and wood)

It is assumed that a change in humidity will affect the fatigue life of plastics and wood, but, as yet, no work has been done in this area and therefore, nothing is known about how the fatigue strength will be affected.

3-C Corroding Agents

Corroding agents will, in general, reduce the fatigue life of a member. Such things as water, acid and alkalies attack the surface of the material causing stress concentration points to be developed. As stated in Section I-H, as surface stress concentrations are developed, the fatigue strength of any member may be considerably reduced.

The Machine

4-A Type of Machine

Fatigue testing machines are divided into two types: (1) constant load type, and (2) constant displacement type.

Yorgiadis (25) has stated that, in using a machine of the first type, the load remains the same and therefore, as the failure crack develops, the stress on the critical section of the specimen is increased and the rate of growth of the crack is greatly increased. The fatigue life after the formation of the crack is relatively short.

Using a machine of the second type, the deformation remains constant and as the failure crack develops, the load on the specimen is reduced due to the plastic deformation that occurs. This reduction in load will reduce the rate of growth of the crack and thereby increase the fatigue life of the specimen.

4-B Mechanical Condition

The mechanical condition of the testing machine on which fatigue tests are being performed may have a direct bearing on the results obtained. It is well known that for machines operating at high speeds, it is necessary to make frequent adjustments. The primary reason is generally the change of adjustment due to vibration. Wear is not usually an important factor until the machine has been in service for an extended period of time.

The American Society For Testing Materials (24), in a discussion of the accuracy of fatigue testing machines, states that the error in accuracy of the machine will usually not exceed 3% and lower values may be attained. This error is largely dependent on calibration and maintenance of the load on the specimen throughout the test.

4-C Operation

The effect of operating conditions are usually not evaluated alone. This effect is normally included in the machine error mentioned in Section 4-B.

The most important problem in machine operation is the load control device. If the load control device cannot be adjusted so as to give a minimum variation in maximum and minimum values throughout the test, the value of the test data is greatly impaired.

CHAPTER IV

PLANNING AND INTERPRETING FATIGUE TESTS

Planning Fatigue Tests

The large number of variables discussed in Chapter III show the complexity of the fatigue problem. In order to properly use the test data obtained from any given test, much planning prior to the beginning of the test is essential.

In planning a fatigue test program, it is necessary to determine what variables are to be studied. The choice of variables to be studied will usually be dependent on the anticipated use of the data. This may consist of only one variable or a large number of variables. When only one variable, such as composition, surface treatment, temperature and etc., is to be studied, a metallurgial-type test is likely to be used. When several variables, which may be affected by a change in the manufacturing process, are to be studied, it is common to use a component-type test.

Having decided on the variable or variables to be studied, it is then necessary to consider the number of discrete values of each variable to be studied, the number of specimens to be tested for each change of parameter, and the range of values of the variables to be covered. One of the factors which will determine these choices is the use for which the data is intended. When the required result is to determine, as completely as possible, the effect of the variable, the number of discrete values of the variable being studied should be large. When the desired result is to obtain an indication of the variables effect, the number of discrete values to be considered will be vastly reduced. (24)

It is common to show the affect of variables on fatigue life in terms of an S-N diagram. In order to establish the S-N diagram accurately, at least ten specimens should be tested for each condition of loading for which a point on the S-N diagram is desired. The number of loading conditions to be used is selected according to the range over which the results are desired. This range may begin as low as 500 cycles to failure and extend as high as 500,000,000 cycles to failure. The choice of loading conditions will be determined by the method chosen for the plotting of the data. The loading conditions should be chosen in such a manner as to give a uniform distribution of points throughout the entire range of investigation. (24)

Selection of a Testing Machine

The selection of a fatigue testing machine may be done after the planning of the test has been completed, or the test may be planned to best use the machines available. In either case, there are certain items that must be considered. The type of loading desired, the required accuracy of the data, the ease with which the machine may be operated, adjusted, and maintained, the time required to collect data, and the cost of the specimens.

The common types of loads in general use today are; bending, axial-load, and torsion. The type of load to be used in a given test is usually determined by the type of test (metallurgical or component) and the variables to be studied. As an example, suppose a machine part is subjected to both axial-loads and bending throughout its service life. The testing machine must be capable of producing both axial-loads and bending loads in order to obtain data that can be accurately used in predicting the service life of additional parts.

In order to obtain a given degree of accuracy, the load on the specimen must be maintained within very narrow limits at all times. Any wide variation of load will seriously affect the results. Therefore, much attention is given to the load control devices. If the testing machine is designed so as to give maximum service with minimum maintenance, the most common source of machine error will come from the load control devices.

The ease of operation is another important factor to be considered in the selection of a testing machine to be used, or in the planning of the test to use a machine that is available. If it is necessary to have an operator with the machine most of the time it is in operation, the cost of the tests will probably be prohibitive. Usually, this is only necessary when the load control device is not dependable, and can be eliminated by modification of the load control device, or the choice of a different testing machine.

The time required to collect data and the cost of the specimens can be considered together, since both are usually economical considerations. The time required to collect the necessary data, combined with the cost of preparing the specimen, may be so large as to make the cost of the test program prohibitive. This may be overcome by a revision of the test program. The revision may take the form of a relaxation of the required accuracy, or a reduction of the number of specimens to be tested, or both.

Selection and Preparation of the Specimen

The selection of the sample, from which specimens are to be prepared for a fatigue test, is one of the very important steps in obtaining good data. The importance of proper sampling and preparation of the test specimens cannot be over emphasized.

It is necessary to know the purpose of the test before the sample is taken. If the purpose of the test is to determine the variability of a material, the samples should be taken from several different selected locations, on many different bars, plates, moldings, castings, or other forms of which the variability is to be studied. The plates, bars, etc., should be taken from different samples of the unfinish-material (billets, castings, etc.) at random.

If the purpose of the test is to determine the effect of only one parameter, such as mean stress, amplitude, etc., the samples should all be selected from one piece of the unfinished material. This is done in order to exclude, as nearly as is possible, the variation of the material. The selection should be done very carefully in order to obtain uniform specimens without defects.

The machining and polishing of the specimen should be done in such a manner so as to avoid over-heating the specimen during machining, cold-working the material at the surface of the specimen, and repeatedly stressing the specimen by excessive vibration. The order of machining operations may be of importance. The test section of the specimen should be machined last.

Throughout the machining process, care should be taken to insure that all specimens are as nearly symmetrical as possible.

The measurement of the specimen must be done in accordance with the over-all required degree of accuracy. If for an axial tension test, the calculation of the stress must be within $\pm 1\frac{1}{2}\%$ of the actual values, the area must be measured with an over-all error of not more than $\pm 1\frac{1}{2}\%$, if σ and P are considered to be exact values. For axial loading, the nominal stress is computed by the equation:

$$\sigma = \frac{P}{A} \quad \text{or} \quad P = A\sigma$$

and the area is computed by the equation:

$$A = \frac{\pi d^2}{4} = K d^2$$

Therefore:

$$P = K d^2 \sigma$$

Since "d" is the only variable in the relationship, and since the relative error in multiplication is approximately equal to the sum of the relative errors of the numbers for small errors (24), the error in measuring "d" cannot be greater than the total amount of error allowed, divided by the number of times "d" appears in the load computation relationship. For this example, the relative error in the measurement of "d" cannot exceed:

$$\frac{\text{Total allowable error}}{\text{No. of times "d" appears in equation}} = \frac{1.5\%}{2} = 0.75\%$$

A similar value for bending and torsion can be obtained in this same manner.

The allowable eccentricity, "e", in a round specimen prepared for axial tests can be computed by comparing the bending stress, due to the eccentricity, with the uniformly distributed stress, due to axial load:

$$\sigma_B = \frac{Mc}{I} = \frac{Pe\,\frac{d}{2}}{\frac{\pi d^4}{64}}$$

$$\sigma_A = \frac{P}{A} = \frac{P}{\frac{\pi d^2}{4}}$$

Since σ_B is the variation in stress:

$$\frac{\Delta\sigma}{100} = \frac{32Pe}{\pi d^3} \times \frac{\pi d^2}{4P}$$

$$\frac{\Delta\sigma}{100} = \frac{8e}{d}$$

$$e = \frac{d}{800}\,\Delta\sigma$$

Where

e = allowable eccentricity
d = diameter of specimen
$\Delta\sigma$ = allowable error in stress expressed in per cent
σ_B = stress due to bending on extreme fiber
σ_A = uniform stress due to axial load

General Test Procedure

1. Determine the dimensions of the specimen by direct measurement.

2. Determine any features of the testing machine necessary for computation of stresses. (Bending moment arm on repeated bending machines)

3. Determine the amplitude of stress "Sa" to be used. It is usually best practice to start with a relatively high stress and reduce the amplitude of stress by small increments in succeeding specimens. It should be remembered that tests at stresses below the fatigue strength of the material do not contribute anything to the determination of the fatigue properties, so that time consumed in the test is wasted time. If nothing is known about the fatigue properties of the material, it is usually safe to start at about 2/3 of the ultimate strength of the material.

4. From the dimensions and the desired stresses, compute the load to be applied to the specimen.

5. Mount the test specimen in the testing machine, being careful not to damage the test section of the specimen.

6. Check alignment of the specimen.

7. Adjust loads to produce desired stresses.

8. Record the initial reading of the counter or set counter to zero.

9. Start testing machine.

10. Set the automatic cut-off control, so that the machine will stop when the specimen fails. The definition of failure may be excessive deformation, formation of a fatigue crack, or a fracture. The definition of failure will determine the type of controls that are necessary.

11. When the specimen has failed, record the counter reading and compute the number of cycles sustained. It is wise to check to see if all information about the test has been recorded at this time.

12. Test another specimen at the same, or a different stress level, and repeat the above procedure until enough information is collected to plot the S-N Diagram.

13. Plot the S-N Diagram and check to see if the curve is well defined. If it is not, additional tests should be run at stress levels where additional points are required.

Statistical Methods and the Interpretation of Fatigue Data

The previous discussion has shown that the results of fatigue tests are statistical in nature. In order to effectively use fatigue test data, it is necessary to plan the tests so as to render the data useful for statistical analysis. In this section, a discussion of the more important procedures of tests will be made.

The procedure for conducting fatigue tests can be broken into three general groups:

I. The Standard Tests (constant amplitude)

   A. Single Test Specimen at Each Stress Level
   B. A Group of Test Specimens at Each Stress Level

II. Response Tests (constant amplitude)

   A. "Probit" Method
   B. Staircase Method
   C. Modified Staircase Method

III. Increasing Amplitude Tests

   A. The Step Method
   B. The Prot Method

The Standard Tests
(Constant Amplitude)

I-A Single Test Specimen at Each Stress Level

In the standard test of this type, each fatigue specimen is cycled at different constant stress amplitude until fracture occurs. The stress levels are chosen to cover the entire range, from high stresses, which cause failure to occur in a limited number of cycles, to low stresses, at which failure will not occur (runouts), or at which failure will occur only after a very large number of cycles. The first stress level should be chosen above the fatigue limit of the material and reduced with each succeeding test, until failure does not occur in a given number of cycles. (26)

The data is then plotted in the form of an S-N Diagram and the fatigue limit or endurance limit determined. The accuracy of this method is greatly impaired because of the use of only one specimen at each stress level.

This method is used only in cases where a relatively small number of specimens are available. Examples of such situations are: when the fatigue specimens are expensive, when the supply of material is limited, or when machine parts are being tested.

The S-N curve for 50% survival is usually drawn by graphical means. (The 50% survival curve will show the stress and life below which one-half of the test specimens are not expected to fail.) From the 50% survival curve, a prediction of the survival at different levels can be estimated. It must be understood that only an estimation of the probability of failure can be obtained from such limited data. (26)

I-B Group of Specimens Tested at Each Stress Level

The standard test using only one specimen at each stress level will yield very little information concerning the variability of material, component, or the test procedure. It is much more satisfactory to test several specimen at each stress level. The group should consist of at least four and preferably ten specimens.

Using the data obtained, a 50% survival curve is drawn through the median of the groups at the different stress levels. From the 50% survival curve and the scatter band, predictions may be made with up to 98% accuracy, depending on the number of specimens tested. The 98% value only means that 98% of all specimens, of the same material and with the same history, will exceed a given number of cycles at a given stress level without failure.

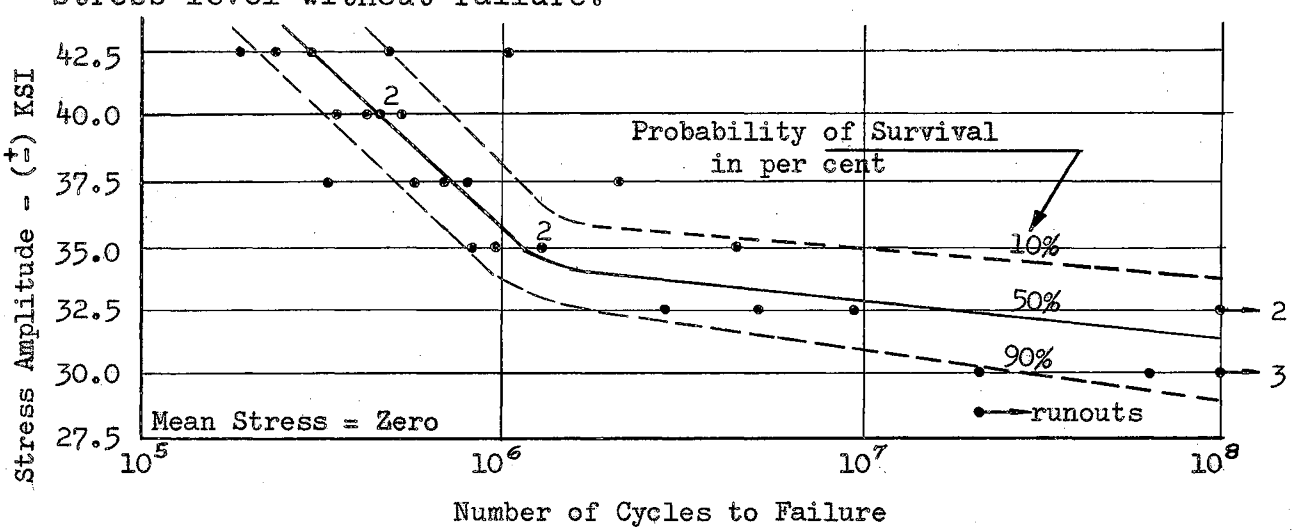

Figure 4. Probability-Stress-Cycle (P-S-N) Curve

Figure 4 is a sample of the type of curve that is generally used to interpret test data obtained for the standard test.

Response Tests (Constant Amplitude)

2-A The "Probit" Method (2)(26)(27)(28)

The "Probit" Method is most commonly used to determine the endurance limit of a material or the endurance limit of a component. The test is conducted in the same manner as the type I-B, standard test, with the exception that all groups are tested in the vicinity of the endurance limit. Such a method is sometimes referred to as "mortality" or "survival" testing. For example, if the average endurance limit of a steel is known to be approximately 72,000 psi, a group of specimens might be tested at stress levels of 68,000 psi, 70,000 psi, 72,000 psi, 74,000 psi, and 76,000 psi (see Figure 5).

In the high stress range, it is expected that most of the samples will fail. In the low stress range, a few specimens will fail, but most will be non-failures or runouts. If the stress level is chosen too low, a 100% runout may be obtained. Such a condition will yield little, if any, statistical information. It is therefore necessary to select a reasonable value for the beginning point of the test and to use proper stress increment between groups. The optimum stress increment will depend to a large degree on the size and number of groups.

From the data obtained by the use of the "Probit" Method, a "mortality" curve may be drawn (see Figure 5), or the Arithmetic Probability Plot of the data is drawn directly (see Figure 6). The Arithmetic Probability curve may be fitted to the data by the least-square procedure, but is generally done by eye. The method used will depend on the accuracy required.

From the straight line representation on normal probability paper, one may easily determine the average endurance limit at a given number of cycles, as it will be the 50% probability point.

It should be noted that this procedure results in the probability of strength at a given number of cycles and not the probability of life at a given stress level.

<u>2-B The Staircase Method (Constant Amplitude) (26)(27)(29)</u>

The staircase or up-and-down method is particularly suited for the determination of the average fatigue strength of a material at a given number of cycles. The procedure is to start by testing one specimen at a given stress level for the required number of cycles. If failure does not occur, a second specimen is tested at a specified increment above the first stress level for the given number of cycles. This is continued until a failure occurs. After the first failure occurs, the next specimen is tested at the specified increment below the stress level that produced failure. The step-down is continued until no failure occurs within the re-

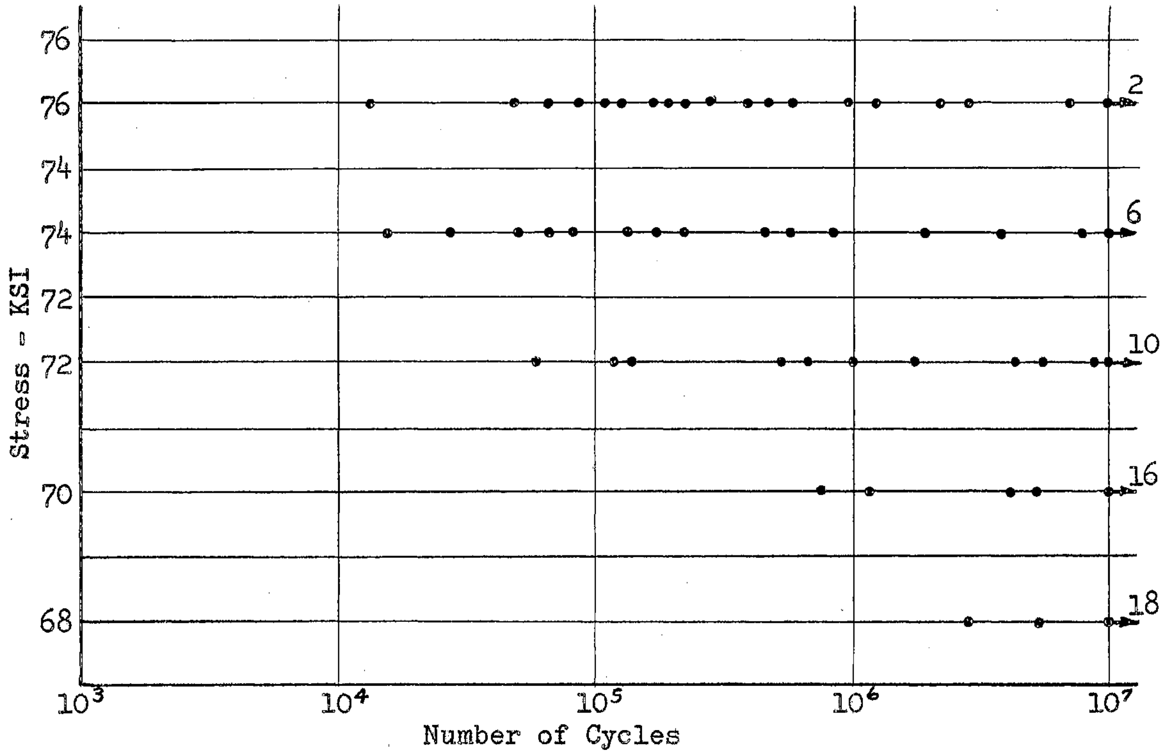

Figure 5. Plot of Mortality Tests

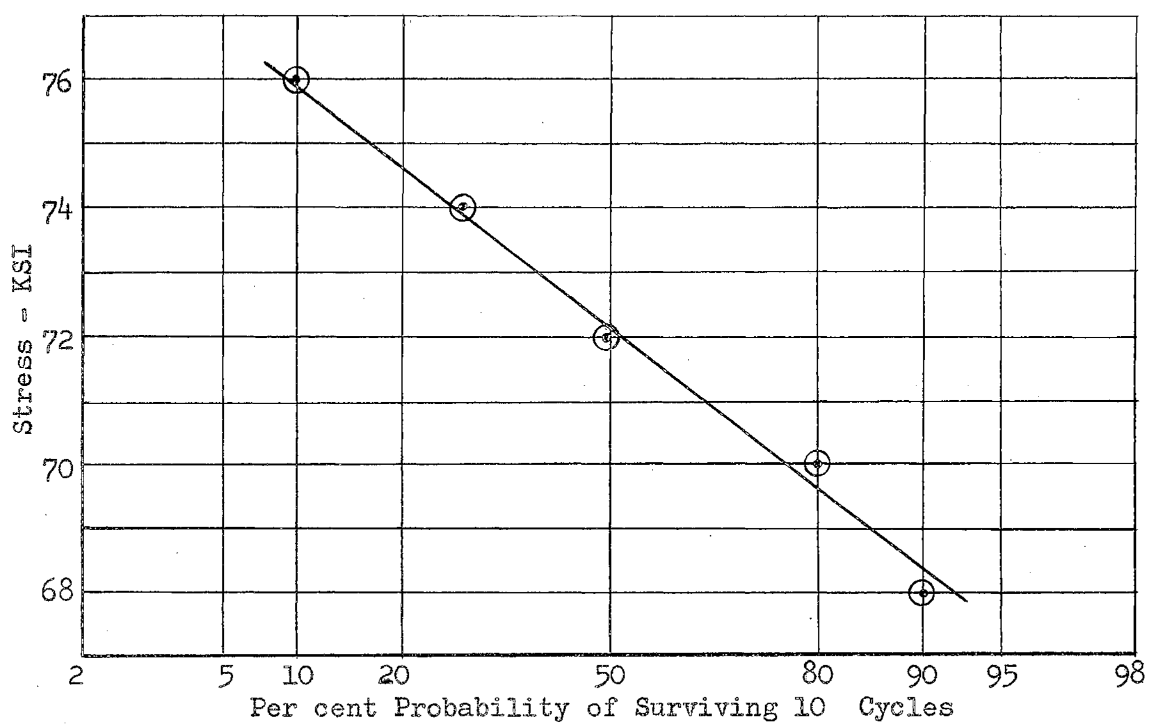

Figure 6. Arithmetic Probability Plot of Mortality Tests

quired number of cycles. The step-up is then started again. This procedure is continued until the completion of the test. The data obtained is plotted as shown in Figure 7.

This method has one major advantage in that the average fatigue strength is automatically concentrated about one stress level, as can be seen from Figure 7. The data obtained, using the staircase method, does not lend itself to statistical analyses and should therefore be carefully examined before attempting the use of any statistical method.

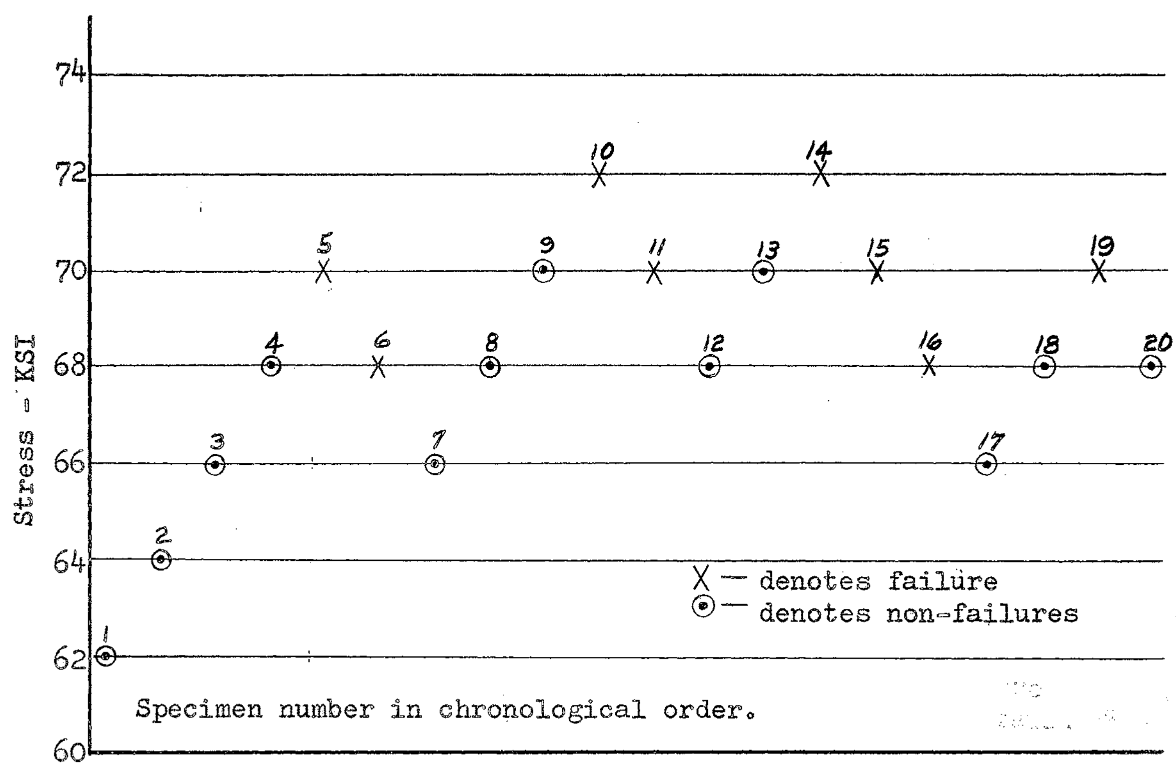

Figure 7. Plot of the Data Using the Staircase Method

2-C Modified Staircase Method (Constant Amplitude)

Due to the time consuming nature of the staircase method described above, a modification of this method has been developed, whereby several machines can be used simultaneously, a short staircase being run on each machine. The set of short staircase tests are then analyzed as one group.

Increasing Amplitude Tests

3-A The Step Method

The large number of samples required in all the tests previously discussed is usually a major cost item. The specimen cost and the fact that in some cases only a limited number of samples are available made it necessary to develop a method in which fewer specimens were required and which would yield useful data for each specimen. Hence, the step method was developed.

In the past, this method was not considered acceptable, because of the effects of strain hardening when the load on the specimen was below the endurance limit of the material. These so called "coaxing" or "under-stressing" effects may be very pronounced (as in some steels), or may be so small that they are lost in the scatter of the data (as in some alloys). The under-stressing effects on the material to be tested must be known before the step method is used. This information may come from previous work or by a few tests.

The step method is started by running a specimen the required number of cycles, at a stress of approximately 70% of the mean fatigue strength. If the specimen does not fail, the stress on the specimen is increased by a specific increment and again tested to the required number of cycles. This procedure is repeated on each specimen in the group and the data plotted, as shown in Figure 6.

In the step method, it is desirable to test at least ten specimens. The probability of failure is computed as the fractional number of failures in all the specimens that occurred below the stress level in question. From the arithmetic probability curve (see Figure 6) of the data, the endurance limit can be directly determined as it is the stress at 50% probability of survival.

3-B The "Prot" Method

The evaluation of the endurance limit of a material usually requires many tests and a great deal of time. Since it is often desired to obtain this information in a relatively short period of time, the Prot method has been developed. The Prot method utilizes a constantly increasing stress until fracture occurs. The rate of increase of the load is carefully controlled and the number of cycles required to produce failure is determined. The test is begun with an alternating stress of 60 to 70% of the endurance limit of the material. Three groups are usually tested at different rates of loading and this is recorded along with the number of cycles to failure.

The endurance limit is estimated by plotting the Prot fracture stress as the ordinate, and some power of the rate of loading as the absissa. After the exponent is properly selected, all points will be on a straight line, and the intercept on the Y-axis represents the endurance limit. An example of this is shown in Figure 8. The problem of computing the exponents such that all points will fall reasonably close to a straight line is usually the most difficult. This is usually done by trial and error methods.

The Prot method cannot be used when the material is subject to changes in fatigue strength by under-stressing effects.

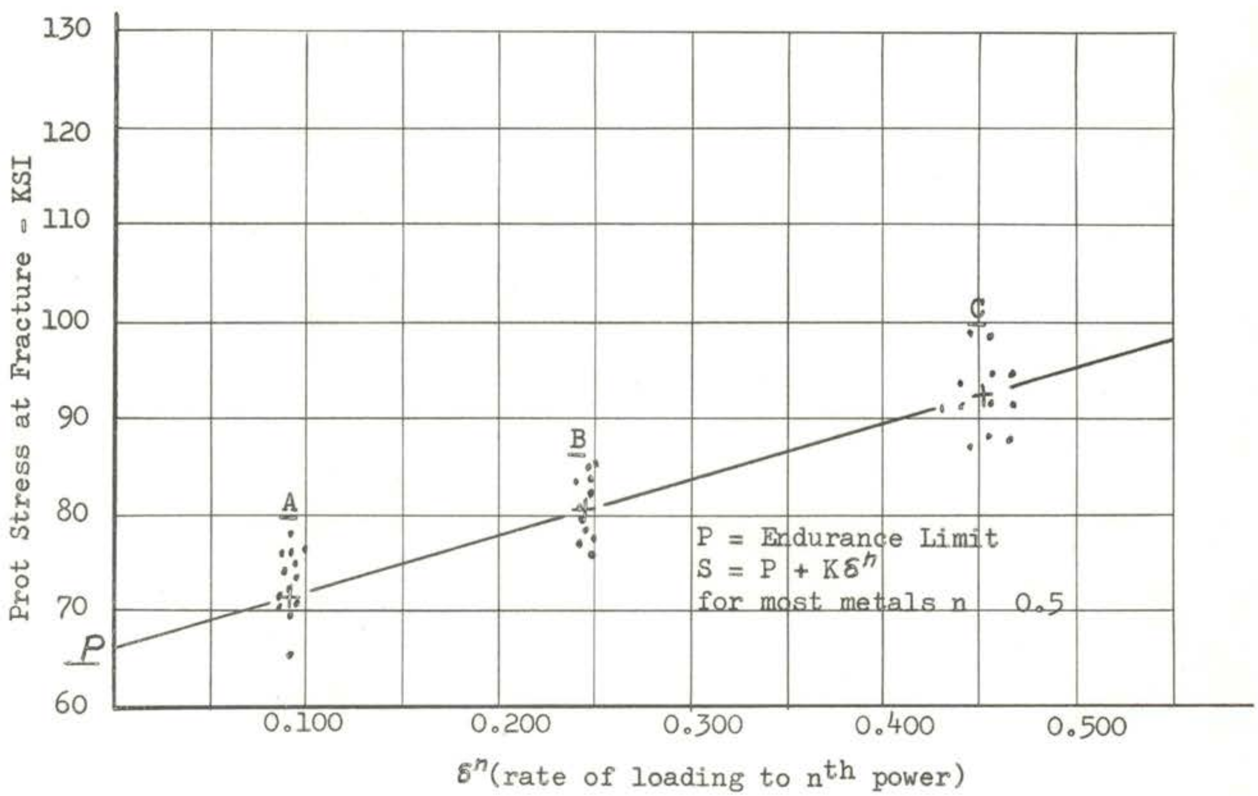

Figure 8. Plot of Prot Data

CHAPTER V

THE BASIC MECHANISM OF FAILURE

The basic fatigue mechanism has been the basis of much study. Several theories pertaining to the failure mechanism have been proposed, but only one has been generally accepted. This report will deal only with the accepted mechanism.

The basic fatigue failure mechanism is usually divided into three phases: (2)(30)(31)(32)

I. The Formation of Slip Bands

II. The Development of the Slip Bands Into Micro-cracks

III. The Merging of the Micro-cracks Into Visual Cracks That Will Produce Failure

I. The Formation of Slip Bands

The slip bands form very early in the life of the specimen, usually between 5 and 10% of the fatigue life. These slip bands form on planes which have low shear resistance and therefore, will usually form at 45° to the axis of principal stresses.

Findley (33), states that slip can occur only in crystals which are favorably oriented in or near planes of principal shear stress and which have relations with neighboring crystals (such as free surface on one side) which permit slip under the applied stress. This is in direct disagreement with most experimental results which show that slip bands form throughout the material. However, it has been noted that for the most part, the actual failure crack will begin at stress concentrations on the surface of the material. For this reason, the assumption made by Findley has some basis.

Shanley (32), in his proposed mechanism of failure, states that in his opinion the formation of the slip bands is due to the unbonding of surface atoms as a result of stress concentration. Shanley requires a free surface as does Findley, but states that the free surface may occur as internal voids, as well as the external surface of the specimen. This, to a limited degree, allows for the formation of slip bands throughout the material.

According to Shanley, the stress on any free surface (due to stress concentrations) may be sufficiently high to overcome the atomic cohesive stress and the original bond is broken. As the load is reversed, the original position of the atoms is again obtained. However, the cohesion between the atoms has been disrupted, and all of it cannot be regained. Continued cyclic loading will increase the size and number of the slip bands.

II. The Development of Micro-cracks

The micro-cracks are formed by development of the slip bands. The time required for this development is mainly dependent upon the mean stress and stress amplitude. In all cases, the majority of the life of the specimen is within this range. It is estimated that at least 75% and possibly as much as 90% of the fatigue life of any specimen is spent in the development of the micro-cracks.

There is sufficient proof of the fact that the slip bands develop into micro-cracks with increasing number of cycles. The exact mode of this transformation is not completely known, and thus many theories have been proposed in an attempt to explain this phenomena. In the following paragraphs, several of these theories will be discussed in limited detail.

Jacquet (34), in an investigation of the micro structure of brass, under reversed bending, concluded that the micro-cracks are developed by a coalescence of holes that are developed at the end of the slip bands. Jacquet makes no attempt to explain how these holes are formed, or why they tend to collect in particular bands. Thompson (35), in his investigations of the fatigue of metals, refers to point defects which appear to be the same as the holes referred to by Jacquet. Thompson states that the micro-cracks are formed in the following manner:

1. Slip bands appear.
2. Dislocation of atomic array due to applied load.
3. Reverse slip, caused by the cyclic loading, creates point defects.
4. These point defects diffuse away from their point of origin.
5. The point defects tend to collect in slip bands, thus giving the material within the band a larger volume than that of the parent material.

6. A process akin to re-crystallization takes place within the slip band. This new material has a smaller volume than that of the material in step 5, and therefore, tensile forces are produced which will open micro-cracks.

There are many who doubt that the process described by Jacquet and Thompson is the process which produces the micro-cracks. The holes or point defects which have been found in soft metals (brass, copper, and etc.) have not been found, in large numbers, in harder materials such as steel. Also, there seems to be no justification of the re-crystallization process described by Thompson, particularly in steel. However, due to the extreme difficulty in locating these point defects, the above described process cannot be completely rejected.

The second theory to be considered is that the micro-cracks are due to "heat-flashes". Freudenthal (36), states that the micro-cracks formed in a material are probably due to localized high temperature (heat-flashes), which is produced by the sharply localized slip. There is little, if any, substantial proof of this theory, other than microscopic examination of the material being tested. The theory does explain, to a limited degree, the discoloration that occurs within the slip bands and may be an explanation of the formation of point defects as proposed by Jacquet and Thompson.

The third theory to be considered is the most widely accepted theory. In this theory, the slip bands are increased in number and size with an increase in the number of cycles. As the plane is weakened by additional plastic deformation, and the break down of the material along the slip plane continues, the principal stresses tend to open a micro-crack within the slip band. With the opening of one micro-crack, a stress re-distribution takes place which will tend to open more micro-cracks in the area of the first. This process continues until the micro-cracks begin to merge into a failure crack.

Regardless of the theories, the end product is always the same, many micro-cracks throughout the entire body of the material. However, not all of these cracks will contribute to final failure. Some of the micro-cracks form, propagate for a short period of time, and then remain dormant throughout the remainder of the test. Such cracks are called non-propagating cracks. Phillips (37), Frost and Phillips (38), in fatigue tests of mild steel and aluminum have shown that both propagating and non-propagating cracks are always formed. The non-propagating cracks are always formed at 45° to the axis of the member and appear to propagate under the influence of shear. The size of the non-propagating crack will increase until the end of the crack reaches the point in the original stress field at which the theoretical stress (Neuber analysis) is equal to the fatigue limit of the material. The crack will propagate no further unless the applied stress is increased.

Propagating cracks begin in the same manner as the non-propagating cracks. The cracks begin propagating under the influence of shear. At some time in the life of the specimen, the propagation changes to the influence of normal stresses. This means that the cracks will begin on planes of maximum shearing stress, but will change to a direction approximately perpendicular to the principal stresses some time within the life cycle. From this, it can be concluded that the formation of the micro-cracks is governed by both shear and normal forces, depending on the stage under consideration.

III. The Formation of the Failure Crack

The micro-cracks continue to increase in number and size under continued cyclic loading. As the micro-cracks increase in length, they must spread from one crystal to another. The spread will take place either through the crystals or along the boundary of the crystals. The direction taken by the enlarging crack is dependent on the relative position of the crystals, the temperature, and the range of loading. At high temperature, the cracks tend to follow the boundaries of the crystals, due to the reduction in atomic bond as the temperature increases. A relatively high stress range will tend to force the cracks to propagate through, rather than around, the individual crystals. The spread of the cracks to neighboring crystals does not begin until very late in the life cycle of the specimen. No marked reduction in the ultimate static tensile strength occurs until at least 50% of the expected fatigue life has been expended.

As the micro-cracks enlarge, they merge. As these micro-cracks become larger, they tend to propagate more rapidly. If a large number of micro-cracks form on one plane of the member, a severe stress concentration is formed which will lead to total failure. In service members, this large number of micro-cracks will only develop on planes near severe stress concentrations (such as holes, notches, bends, and etc.). As has been shown by Cottell (1), poor design is responsible for the majority of service fatigue failures.

CHAPTER VI

FINDINGS AND CONCLUSIONS

Fatigue failures are unique in the engineering field. Under the action of repeated loads, materials will fail at stresses far below those required to produce failure under static conditions. Fracture under the action of repeated loads is a progressive fracture which begins very early in the life of the member and continues to accumulate until the total damage to the member reaches the critical value.

The basic mechanism of failure is reasonably well understood. Due to the action of reverse slip, slip bands are formed within the material. As the slip bands enlarge, micro-cracks are opened within the slip bands. The micro-cracks develop and merge until final fracture occurs. This failure mechanism has been accepted by most investigators.

In this investigation, several points of interest have been noted.

1. There is no direct correlation between fatigue properties and static properties of engineering materials.

2. There is little correlation between fatigue properties of prepared laboratory specimens and the service life prediction of component parts.

3. There is an extremely large number of variables which affect the fatigue strength of any given member.

4. A tremendous amount of time is required to complete a series of fatigue tests.

5. The statistical nature of fatigue test data makes interpretation difficult.

6. There is little correlation between tests performed by different investigators.

7. Little information is available on the fatigue properties of materials, other than metals.

All of these items tend to retard investigation of the fatigue properties of materials.

Future research on the fatigue properties of materials will probably follow along two narrow lines, the so called basic research, and component research. Basic research programs are usually carried out on prepared laboratory specimens, and tests of the metallurgical type will be used. Future basic research can be expected in the following areas: determination of the fatigue properties of new and common materials, investigation into the initiation and propagation of fatigue cracks, and determination of the affect of individual variables on the fatigue strength. Although these three areas have been the basis of considerable study, additional information is necessary if a complete understanding of the phenomena of fatigue is to be obtained.

Component research programs are carried out, using component parts or models of component parts. These studies are usually attempts to evaluate the effects of certain manufacturing processes, and the effects of stress concentrations created by the system used to connect the member to the finished product. In component testing, it is necessary to reproduce the load spectrum to which the component will be subjected in actual service. Future research along this line may be expected in the following areas:

1. Evaluation of the fatigue strength of various materials under a given stress condition.

2. Evaluation of the affect of certain manufacturing processes on the fatigue life of a given member.

3. Investigation of better methods of predicting the service life of members subjected to cyclic loads.

4. Investigation into the cumulative damage aspects of fatigue failure.

There has been a definite trend toward component tests in the past decade. This is largely due to the fact that there is little correlation between laboratory tests of prepared specimens and the fatigue properties of component parts.

It is obvious from this investigation that the entire area of fatigue is open to further investigation. It appears however, that the research work will be controlled by industrial requirements. This is due to the tremendous cost of fatigue research programs. It is very doubtful that a complete fatigue program could be maintained at the Oklahoma State University without substantial aide from industry.

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Master of Science

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