FORMATION AND PROPAGATION OF FATIGUE CRACKS IN METALS AS AFFECTED BY OVERSTRESSING AND UNDERSTRESSING.

Thesis by:

Walter H. Goodwin

In Partial Fulfillment of the Requirements for the Degree
of Mechanical Engineer

California Institute of Technology
Pasadena, California
1947

ACKNOWLEDGEMENT

This investigation was carried out under the general supervision and direction of Dr. D. E. Hudson, to whom thanks are due for the assistance and advice which he has given, and for the interest he has shown throughout. Thanks are also due to Dr. D. S. Clark and Dr. G. W. Housner for their advice and assistance.

The experimental testing machine described in the following pages was constructed with funds provided by the Division of Engineering of the California Institute of Technology.

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APPENDICES

SUMMARY

1. A resumé is given of pertinent information regarding the behaviour of metals under repeated stress, special emphasis being placed on understressing, overstressing and strengthening.

2. The evidence of changes taking place in a metal under repeated stress is examined, and the effects observed, together with the information obtained above, are correlated with the dislocation theory of slip.

3. The data available regarding the visual observation of cracks is studied and correlated with the percent of damage during overstressing. Because there is insufficient data, the correlation is inconclusive. Suggestions are made as to the type and amount of data required, and to how it may be obtained.

4. Considering the above information, two experimental procedures are proposed which will add greatly to the practical knowledge of the effects of slip under repeated stress, a study of these effects leading to a much clearer conception of the mechanisms of slip and failure.

5. A study is made of the properties desired in the test material. Armco iron is chosen because, in addition to having all the requisite properties, it has the simplest structure.

6. A study was made of existing fatigue-test machines and none were found to have the desired facilities for testing and examination. Thus a new type machine has been designed and built to satisfy the requirements of the outlined procedure. In addition, it has also been designed so as to effect a considerable saving in the time required for tests.

INTRODUCTION

Many new discoveries have been made about the properties of metals, but there still remains a great deal of research to be done, especially in order to explain why metals behave as they do under certain conditions. This is true with respect to the changes in properties and behaviour of metals caused by changes in the physical conditions, such as changes of temperature or stress. However, since it is known that physical conditions affect the structure of the metals, the primary problem is one of determining the effect of composition, of structure and of changes in these inherent characteristics upon the properties of the metal.

The inability to answer completely the question of why different metals, or the same metal under different conditions, behave as they do, is evident in our present-day knowledge of progressive failure under repeated stress. In the years of investigation of repeated stress, by far the most work has been done in the field of experimental determination of "fatigue" properties. This is quite simply explained by the fact that industry requires, or rather demands, first to know the "capabilities" of a metal and not why it behaves the way it does. Thus the effects of various physical conditions, such as temperature and heat treatment, upon the failure of metals subjected to repeated stress have been studied and empirical results obtained, but to date no definite information is available about the reason for such progressive failures and why changes in the structure cause changes in the failure. Many theories have been advanced regarding the failure, but as yet there is no definite proof of any of these theories, although each theory is based upon some observation or evidence.

A. An Example of the Problem.

A good example of an experiment in which empirical results, useful for engineering applications, were obtained without the necessity of determining the actual reason for such behaviour was H. F. Moore's Car Axle Experiment.[1,2] In this experiment Moore set out to discover two things: 1, What percent of life was remaining after the formation of a visible crack, and 2, would the metal strength be regained if the crack were removed? The results he obtained in answer to the first question will be discussed later (page 27) but it is the results that he obtained in answer to the second question that are of interest at this point. Briefly his procedure was as follows: Using one and two inch diameter rotating-beam specimens taken from commercial axles, he developed, by means of loading under repeated stress, what he called a standard crack in each specimen. This standard crack was 0.1 inch long as determined by a ten power microscope, detection being aided by use of the oil and whiting test (see Appendix I). The specimen was then turned down on a lathe until the crack was no longer visible with the microscope, the first cut having been made to a computed depth of crack derived from the length of crack and diameter of the specimen. The endurance limit of these turned-down specimens was found to be below that of the original metal and it was not until a further sixteenth of an inch of material had been removed that the specimen regained its original endurance limit.

1 - Numbers refer to references given in the bibliography.

B. The Problem.

What does this mean? It means that industry knows how much metal must be removed beyond the root of crack in order to regain the original strength of the metal. But why does this extra metal have to be removed? It seems obvious that this layer must have been injured in some way, but how? Was this injury a result of a fine crack which was not resolved by the ten power microscope or was it the result of some structural change which had taken place in that layer of metal? Also to be considered is the possibility that the machining has filled in a small crack by plastic flow. But if it can be shown that there is no crack, which is quite probable since the above experiment was carefully carried out, what change has taken place in this thin layer of metal? Is it possible to repair this "injured" layer in any way without appreciably altering the metal? In other words, what change has taken place in the material just below the root of a fatigue crack, causing these changes in mechanical properties?

C. The Purpose of the Investigation.

It is the answers to questions like these which will lead to the determination of what actually takes place in a metal subjected to repeated stresses and during the development of fatigue cracks. Thus, in this investigation, it is proposed to evolve an experimental technique utilizing the known results of behaviour of metals under repeated stress in order to increase our knowledge of what takes place in a metal during the formation and propagation of a fatigue crack. The two chief aims in this regard are; 1, to determine whether or not the formation of a fatigue crack is reversible; and if it proves not reversible, whether or not the injured specimen can be strengthened in any way, and 2, to obtain a clear picture of the relationship between the amount of damage and the formation of cracks.

In order to avoid the difficulties necessarily arising out of the use of a metal having a complicated structure, it is intended to use a fairly simple, well-known metal, Armco Iron, which has a definite endurance limit and the ability to strengthen during understressing (See page 36). Also, upon examining the existing fatigue testing machines, it was found that none had the desired facilities for microscopic examination and all were time-consuming, especially for the tests in mind. Thus, as part of this investigation, a new type of machine was designed in order to eliminate these undesirable features as well as to include other desirable ones. Pictures and a description of this machine are given on pages 38-45.

A BRIEF REVIEW OF PERTINENT INFORMATION REGARDING REPEATED STRESS

For the purpose of presenting a clear conception of the pertinent information about repeated stress, a brief review will be given of the experiments and experimental results upon which the proposed investigation is based.

A. The Endurance Limit.

The most important characteristic of a metal being subjected to repeated stress is what is known as its Endurance Limit. This has been generally defined as the maximum stress at which a polished specimen of a material with no stress concentration can withstand an unlimited number of stress cycles or reversals of stress. Fig. 1 shows the common type of S-N diagram, which is a stress versus number of cycles-to-failure curve plotted on semi-logarithmic paper. The Endurance Limit is indicated on this diagram as the stress at which the curve becomes horizontal. (Fig. 1).

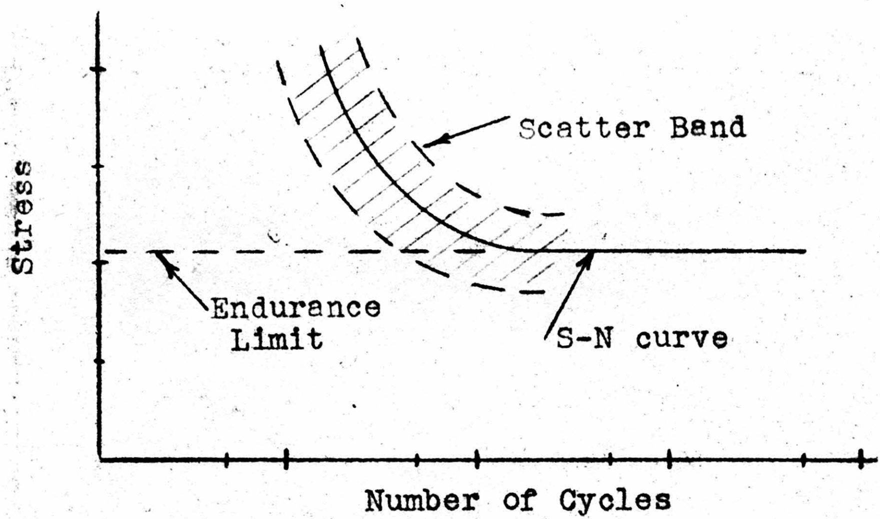

Fig. 1- The S-N Diagram

The S-N diagram is determined by taking a large number of specimens and running them to failure at various stresses, noting the number of reversals of stress at failure. Several determinations are made for each stress and the points are plotted. The S-N curve is then drawn through the mean of these points, the spread of points on either side indicating the width of the "scatter band." This scatter band indicates the variation in number of cycles or in "life" during which it may be expected that the specimen will fail. It is believed that the width of this scatter band is determined to a great extent by the degree of homogeneity of the material and the number of internal and external flaws in the material.[3,30]

It should be noted that in the case of most non-ferrous metals; for example, monel metal and dural, there is no definite endurance limit as defined above, the curves never becoming flat. In these cases the Endurance Strength is defined as the stress which will be withstood for a certain definite number of cycles.

B. Understressing.

During cycles of repeated stress, understressing is said to take place when the maximum applied stress is less than the endurance limit of the material just prior to test. Several investigators, Lea[4], Swanger and France[5], and Kommers[6,7,8] have found that a specimen subjected to from one to ten million cycles of a stress slightly under the endurance limit will be strengthened. Two general methods are used to indicate the magnitude of the strengthening: 1, a new endurance limit is determined and the ratio of increase as compared to the original is defined as the percent of strengthening, and 2, a new determination of the number of cycles to failure

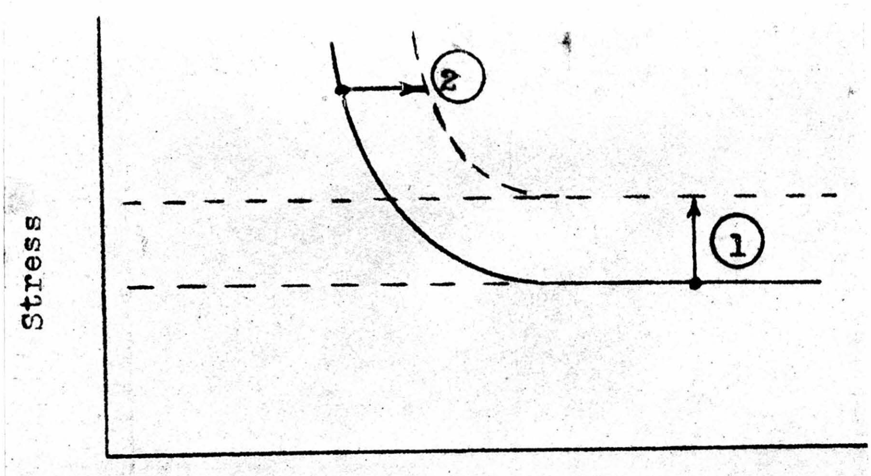

Fig. 2- Strengthening

at overstress is made and the increase of the new life over the original life at that stress is a measure of the strengthening. In figure 2 the arrows show the two methods of determining strengthening, the dotted line showing the S-N curve of the material after understressing.

In addition to increasing the strength under repeated stress (fatigue strength), it has been found that understressing also affects the static properties of the material. Several investigators, Memmler and Laute[3,44], Moore[9] and Kommers[6] have all studied the effects of understressing upon the static properties of a material. Briefly the results of their investigations were that there were increases in tensile strength and hardness and decreases in ductility because of the understressing. It should be noted at this point that these results are analagous to those of work-hardening.

C. Overstressing.

Opposed to understressing, there is what is known as overstressing, which is said to take place when a material is subjected to a repeated stress greater than its endurance limit. In order to determine the amount of overstress and the resulting damage, three terms are made use of:

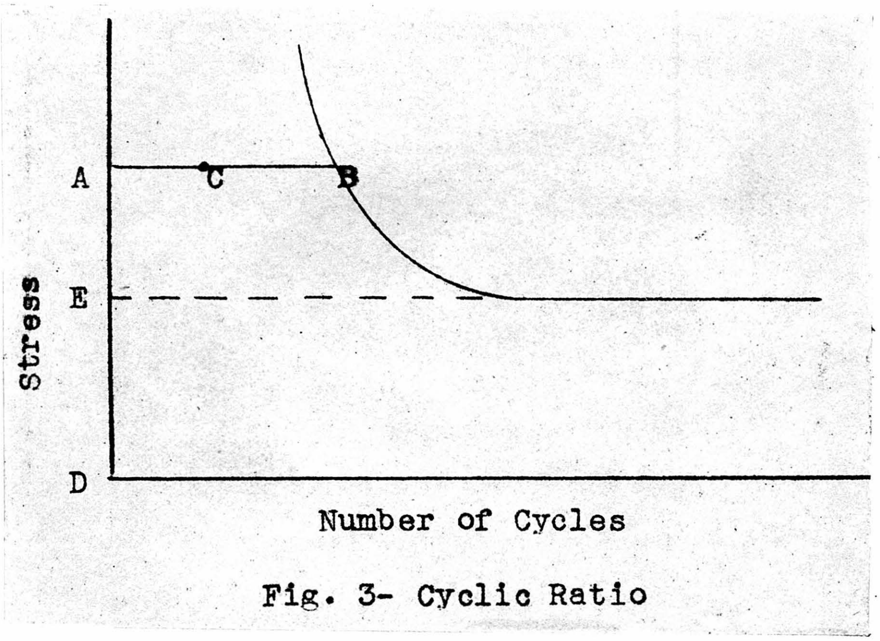

Fig. 3- Cyclic Ratio

cyclic ratio, percent of overstress, and percent of damage. The cyclic ratio is defined as the ratio of the number of cycles for which the specimen has been overstressed to the number of cycles which it would normally withstand before failure at that stress. In Figure 3 the cyclic ratio is shown as AC/AB. The other requirement for determining the amount of overstress is the percent of overstress which may be given either as AD/ED or AE/ED. The percent of damage, however is defined as the percentage reduction of the original endurance limit which has been brought about by a number of cycles of overstress. The percent of damage is determined by running a set of specimens at a certain overstress for a definite number of cycles and then finding the new endurance limit of the set of damaged specimens.

Some typical damage curves are shown in Fig. 4[6] where percent of damage is plotted against cyclic ratio for various degrees of overstress. It may be seen that the percent of damage increases both as the cyclic ratio and the percent of overstress. However, there are exceptions to this general rule as, for example, in the case of 0.49% carbon steel. Here Moore and Kommers[10] found that this steel is strengthened, not weakened, by a few cycles of overstress. This effect is small and is soon overcome as

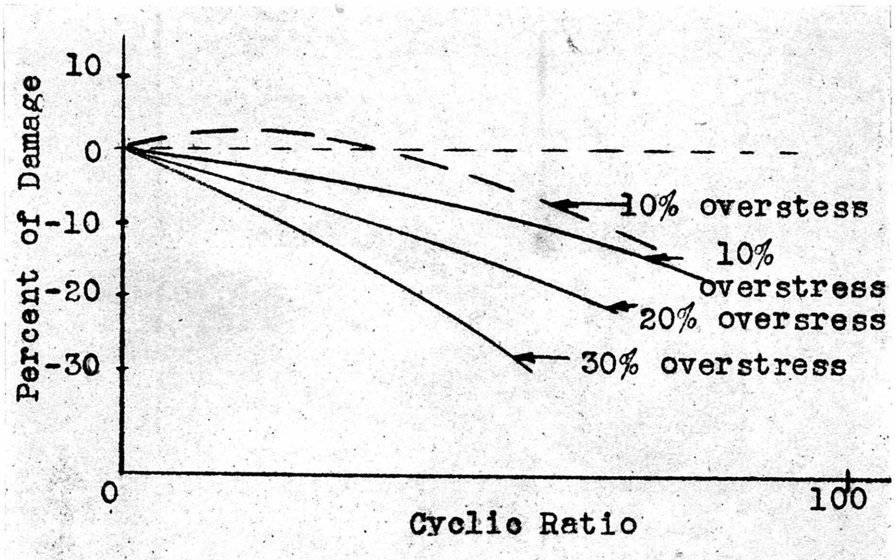

Fig. 4- Percent of Damage

the cyclic ratio or percent of overstress is increased. Some typical values of cyclic ratio and percent of overstress giving this strengthening are: 5000 cycles at 10 percent overstress and 100 cycles at 38 percent overstress[10]. It should be noted, though, in regard to this strengthening that the effect was extremely small, the new increased endurnace limit being just outside the scatter band. In figure 4 the normal damage curves are shown as solid lines whereas a damage curve showing strengthening is shown as a dotted line.

Another method of indicating the amount of damage done was that adopted by Oshiba[28,29], who developed what he called the "degree of fatigue." This he determined by dividing the loss in Charpy Impact value of the specimen subjected to repeated stress of impact by the original Charpy Impact value. Figure 5 shows typical curves obtained by Oshiba for

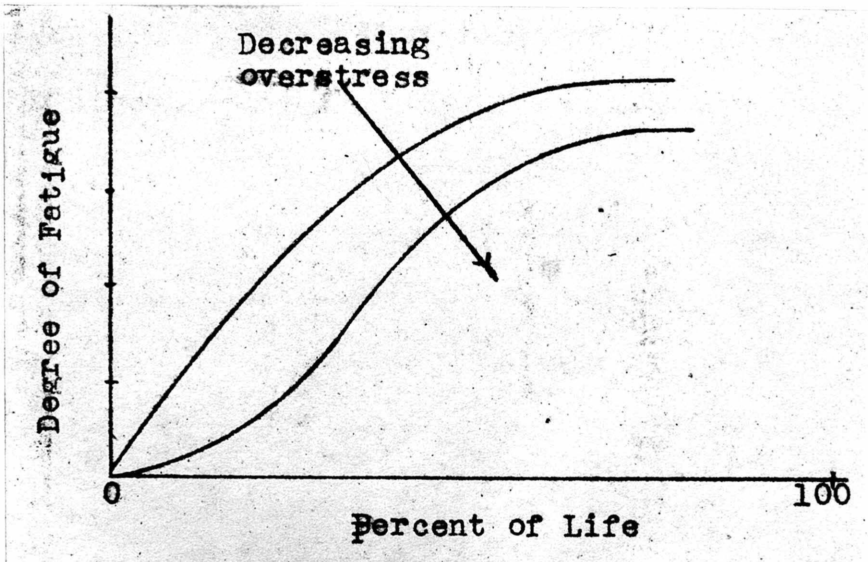

Fig. 5- Degree of Fatigue

a 0.3% carbon steel. He found from his standard curve (lower curve, Fig. 5) that there was first a stage of slow increase in the degree of fatigue. Then the slope of the curve increased rapidly, almost as a straight line, and then finally began to level off. He attributed the slow increase at first to damaging of the specimen without the formation of a crack. Then with the formation of cracks he assumes that the degree of fatigue increases more rapidly until such time as the increase of impact value caused by the refining of the grains during repeated stress (Gough[21]) overcomes to a great extent the effect of the cracks or fissure, thereby causing the curve to flatten off before final failure.* In his discussion he assumes that cracks begin to extend from minute fissures at the lower knee of the curve. The upper curve in figure 5 shows that the initial period of slow damage decreases as the overstress increases, there being no low-slope portion to the curve if the overstress is sufficiently large. During understressing he found that the degree of fatigue increased and then became constant, but that during overstressing the degree of fatigue never became constant. Thus, Oshiba showed in another way that during understressing the metal was strengthened, this time against impact failure.

The damage line is developed from the results obtained from the percent of damage curves as determined above. It is actually a line drawn to the left of the S-N curve through the points at which the endurance limit, when tested after overstressing, is equal to that of the original endurance limit. In figure 6[11] are shown the two different types of damage line resulting

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* It is a proven physical fact that the finer the grains in a metal, the higher the impact value. Here Oshiba makes use of Gough's premise of the formation of crystallites (See page 20), assuming consequent increase of impact value to explain the levelling off of the curve.

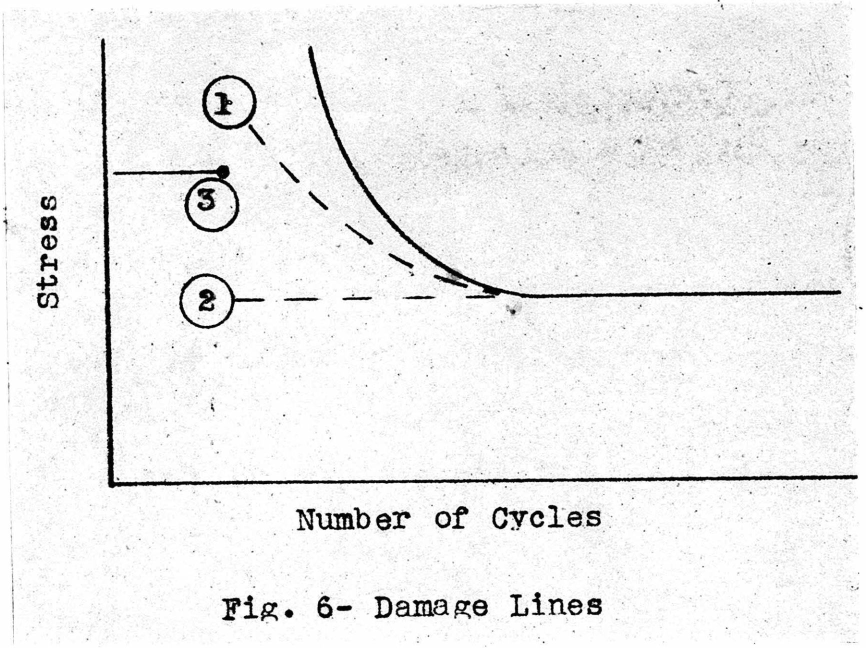

Fig. 6- Damage Lines

from the behaviour of metals under overstress. Line 1 shows the damage line of a metal which shows strengthening during overstressing while line 2 shows the damage line of a metal which does not show strengthening during overstressing.

It should be carefully noted that this line of no damage does not mean that the metal has not been injured, for though the endurance limit has not been lowered, the number of cycles or percent of life remaining to the metal has been decreased. For example, let us consider a metal with damage line 1 and overstressed as shown by point 3 in figure 6. This specimen has been subjected to a number of cycles of overstress just about bringing it to the damage line. This does not mean that the metal is undamaged but only that its endurance limit is still above or equal to the original endurance limit. That is; if the stress were reduced to the original endurance limit, the metal would not fail. However, if the metal was maintained at the same overstress and then run to failure, the number of cycles it would run would be equal to the original life less the percent of life or cyclic ratio already run. In other words, the life of this metal partly overstressed is less than the original life although the endurance limit has not been lowered.

A few determinations have been made of percent of damage curves lying between the damage line and the original S-N curve but these determinations are extremely time-consuming and the results showed nothing other than what was expected; that is, a series of curves conforming to the shapes of the S-N curve and the damage line.

Broadly considering the field of overstressing, we find that if we take a given number of specimens and give them the same amount of overstress, these are then specimens of a different material which has its own endurance limit, its own S-N curve and its own static properties. However, its composition is the same so it is obvious that some change must have taken place in the material's structure in order to give it these different properties. Here again, we are confronted with the problem of what it is that takes place in the material to cause these changes.

D. Strengthening of Damaged Specimens.

Various methods have been tried in order to strengthen or repair this damage which has taken place during overstressing. Some of the experimenters thought that if the metal was "fatigued," that it might be strengthened by "resting." The specimens were rested for various periods of time between various applications of overstress but the results of the experiments showed no improvement of such magnitude as to bring the strength of the metal outside the limits of the original scatter band.[3]

However, Davies, Gerold and Schultz[3] found that by heating a soft steel to 285° F after each 5000 cycles, that they increased the life cycles from the 69,000 to 200,000 range to a range of 360,000 to 440,000 cycles.

In another steel (0.42% carbon) they found that it was necessary to heat the specimen to 285° F for three days after each 10,000 cycles in order to obtain results which were definitely outside the scatter band. It may be assumed that the heating in these cases is an annealing operation, removing the effects of overstressing, which is probably a form of strain-hardening. Also it should be noted that the heating required to reduce the damage is different for different materials, indicating that the effects of overstress are, in each case, a function of the material itself.

Strengthening by heat-treatment, as can be seen above, may only be considered to be effective over small ranges of overstress. On the other hand, strengthening by understressing has been proven to be a much better method of improving the strength of a damaged material. Whether this strengthening is due to the actual repair of the damaged structure or to strengthening around the damaged area is still open to question although the opinion is that the improvement is due to strengthening around the damaged area and not to actual repair of the damage[30]. The usual procedure has been to damage a specimen by overstressing, consequently reducing the endurance limit. Then, after reducing the applied stress to a value just below the new endurance limit, the specimen is understressed and its endurance limit raised from the lower value. The endurance limit has been raised by understressing in this manner up to the original endurance limit and sometimes even above the original overstress. Kommers[6,7,8], Russel and Welcher[12] and Moore[13] have all carried out experiments in which they strengthened damaged specimens by understressing. Usually, though, this understressing was carried out in conjunction with the determination of percent of damage and damage lines, the latter being the prime object of the experiments. For example, Kommers, in his overstressing experiments, always took the damaged specimens remaining after the determination of the new endurance limits and then proceeded to increase the load on these specimens by a pound a day until the specimen failed. He found sometimes that he could in this way increase the applied stress until it was equal to or greater than the originally applied overstress. However, in evaluating these results one must be careful to note that the specimen was run only one day at any understress, thus not obtaining the full benefit of the understressing and using as an arbitrary endurance limit the stress at which failure did not take place during the number of cycles run in one day. This, nonetheless, in no way detracts from the general ability of a specimen to be strengthened greatly by graduated understressing or "coaxing" as it is more commonly called. Also, it is not clear to just what limits the stress of these damage specimens can be raised since no experimental work has been done with this in view, although determinations have been made of the strengthening of undamaged specimens for several metals. It would be very interesting to find out how the maximum value of stress obtainable by understressing compares with the yield and ultimate strengths of the material.

EVIDENCE OF CHANGES IN THE MATERIAL

A. Microscopic Examination of Slip.

But what evidence is there regarding transformations in the material while subjected to repeated stresses? As was natural, the first attempts were made by microscopic examination. Work of this nature was done by Gough[15], Gough and Hanson[16], Moore and Ver[14] and Moore and Howard[17]; to name a few. Briefly the results of their investigations were as follows. It was noted that during understressing of some ferrous metals, traces of slip lines, not extending to the grain boundaries, were observed. However, during the application of an overstress to ferrous metals, the slip gradually became heavier and more extensive until eventaully a fatigue crack of observable dimensions developed out of and passed through areas of maximum slip. Also there was a tendency for the cracks to pass through inclusions and other imperfections in the material. To indicate to what lengths microscopic examination has been carried, Lucas[18] has done considerable work at very high magnifications, having observed cracks of a width of 0.0001 inches at 3500X. At 4200X he reports that a disturbance was visible in the metal ahead of the crack but as to its nature, he was unable to say.

Metals which behave as above; that is, show evidence of slip during understressing, may be classified as one group of metals which also has the ability to increase their hardness during repeated stress. Moore and Ver[14] classify as another group those metals which show little difference in hardness after damage by repeated stresses. Also no slip lines are visible in metals of this group during understressing. This second group may be further sub-divided into two groups, the first of which contains metals, usually alloy steels, which develop slip lines during overstressing before an actual crack is formed and the second of which contains metals such as dural, monel metal and brass, which do not develop slip lines before a crack is formed. As mentioned above, (page 9) it may be stated that generally metals of the first group have a definite endurance limit whereas those of the second group have no definite endurance limit, but rather an endurance strength. These facts seem to indicate that certain metals have the ability to strengthen themselves by plastic deformation, as evidenced by slip, thus preventing the start or spread of a microscopic crack or other inhomogeneity. On the other hand, the metals which have no definite endurance limit show no evidence of plastic deformation and thus no strengthening, allowing submicroscopic cracks to progress to failure, no matter how low the stress, as long as the number of cycles is sufficient.

B. X-Ray Diffraction Examination.

However, because investigation of slip did not seem to be adding any more information about the failure under repeated stress, Gough turned to X-ray diffraction methods for the investigation of the failure.[19,20,21]

In his earlier work on single crystals, he confirmed the fact that slip took place along the operative plane or plane of maximum resolved shear stress. Then in his latest work[21] with a polycrystalline aggregate, he reported that the same three changes took place in the diffraction pattern during static loading and under cycles of overstress. He attributed these three changes in the diffraction pattern, in order, to the following:

1. Dislocation of normally perfect grains into components which may vary in tilt up to about 2° from the orientation of a perfect grain; 2, Formation of crystallites, 10^{-4} to 10^{-5} cm. in size, exhibiting much wider divergence of orientation than parts of the dislocated grains; 3, The presence of lattice distortion in the crystallites. He noted that failure followed the complete breakdown of the crystals, but could not prove whether or not it was related in any way to the three changes, stating merely that they may be associated in some way. On the other hand, he discovered that if a specimen is understressed there is, outside of the initial adjustment to the loading, no change in the diffraction pattern. From these results, he was able to conclude that strengthening by understressing was not the same action as that of damaging by overstress, whereas he showed that in damaging by overstress, the action was the same as when damaging a specimen by static forces. It should be noted at this point that there is, in the first case, a possibility of the actions not being different, but merely the same basic action, the difference being caused by carrying the action to different magnitudes. But whether it is one action of different magnitudes or two different actions, these results can be said to agree with the idea commonly expressed[14,3] that whether a metal fails or not depends upon a sort of balance of power between strengthening and damaging effects. In the first case, it may be assumed that up to a certain magnitude, the action strengthens the material, while beyond this point it will damage the material. In the second case it is merely a balance between the two actions, one tending to damage the material and the other tending to strengthen it. Is there any possible way in which one might prove whether it is the same action or not, as outlined above? One possibility that should

be investigated is to see if the diffraction pattern of a damaged specimen will change during subsequent understressing. If no further change takes place in the diffraction pattern during this understressing, we would be still left with the two possibilities mentioned above. But if there were a change in the pattern, this would not only indicate whether or not a damaged specimen can be repaired, but would also indicate that the action is the same in both cases. Thus these deductions point to a possible method of obtaining further information about progressive failure. However, since specialized and expensive equipment would be required, it was not considered within the scope of this investigation to carry out experiments of this type, but to attack the problem from the same direction, but on a microscopic rather than an atomic scale.

C. Application of Dislocation Theory.

How do the above discoveries regarding slip and progressive failure agree with the recently proposed dislocation theory of slip? This theory has been advanced in order to explain why the force required to produce slip or plastic flow is much less than the theoretical force which would be required to move a plane of atoms past another plane of atoms; as would take place in "block slip", the proposed mechanism of slip in effect up until this time[24]. The question is whether or not this dislocation theory is applicable to the changes taking place during repeated stress as well as for strain hardening by cold-working.

First, however, the question of why slip can take place at stresses much less than the yielding stress of the material should be answered. To explain this Taylor[31] and Orowan[25] have advanced the proposition that in these materials subject to slip, there are certain localities which they have called "plastic inhomogenieties." The individual yield points of these inhomogenieties are lower than that of the material as a whole. Thus, when the applied stress at any time exceeds the yield stress of one of these inhomogenieties, slip will take place in that inhomogeniety with resultant strengthening by strain-hardening. Then slip will next take place at a higher stress in that inhomogeneity which has the lowest yield point after the first inhomogeniety has been strengthened. This process will continue in steps of this sort until either the yield point of the weakest inhomogeneity is higher than the applied stress or the strengthening effect of the strain hardening is not sufficient to raise the yield point above the applied stress, leading to eventual failure of the material.

It will be noted that this theory for fatigue advanced by Orowan explains both strengthening by understressing and failure by overstressing. The portion regarding understressing is completely in agreement with the dislocation theory as outlined by Seitz[24]. In this understressing, slip and the consequent strain-hardening can be explained in exactly the same manner that Taylor[31] explains them in the case of cold-working, Taylor attributing the slip to dislocations and work-hardening to the interference of dislocations as their number increases. He suggests that this interference may be merely caused by attractive or repulsive forces exerted by the dislocations. This is a possible explanation of the effects of understressing but what about the effects of overstressing?

Considering that the first action taking place during overstressing is that of dislocations with their accompanying slip; then, if, as in some cases, the metal is first strengthened, the strengthening by dislocations can take place exactly as in understressing. But let the assumption be made that the attractive and repulsive forces of the dislocations only act in such a direction as to strengthen the metal up to a certain point, beyond which point they act so as to cause weakening because the forces are now acting to force the metal "apart." Then this assumption will explain why, after a certain number of dislocations have taken place, the metal will start to become damaged and the damage will increase as the dislocations progress. A further possibility which may be assumed at this point is that cracks will begin to form when this "destructive force" of the dislocations excedes the cohesive strength of the metal. Those metals which show no strengthening during overstressing may then be simply explained by the fact that the initial stress was great enough to cause damaging dislocations from the start. Thus it may be clearly seen that with a slight extension, the dislocation theory as proposed by Taylor and Seitz may be said to be in accordance with the observed effects of understressing and overstressing. Also, it can be seen that if this theory can be proved to be true, that the question arising in the discussion of Gough's work regarding the action of failure will be answered, the conclusion being that the action in the case of understressing and overstressing is the same but of a different magnitude. Conversely, if by work such as Gough's this fact can be proven, this will lend additional support to the dislocation theory.

CRACK FORMATION

The next step is to examine the data which has been published regarding the point in the life of a specimen at which a visible crack has first been noticed.

A. Detection of Cracks.

In Table I (page 26) has been gathered most of the published data about the initial visual observation of cracks. It should be emphasized that these values of life are those given for the point at which a crack has been detected and may not be assumed to be the point at which the crack has first formed. As can be seen from the table, there are some discrepancies in the results obtained. In order to see whether or not they may be explained, a closer survey of the results obtained should be made with consideration of the means of detection used. We find that Kommers[34] reports that there were no cracks in 0.3 in. diameter specimens up to 90 percent of life, which fact he determined by visual observation as far as we can gather from the literature. DeForest[33], however, found that the percent of life to produce cracks was very consistent. In his experiments he reports that he was able to run his specimens for a definite number of stress cycles and subsequently find a crack almost of the dimensions required. The range given in the table includes tests for various types of surface finish, the range of cyclic ratio for each type of surface finish actually falling within a few percent. He used the Magnaflux method of detection which is described in greater detail in the appendix. With regard to these results, it is of interest to note that the cyclic ratio to crack detection increases as the overstress decreases.

TABLE I

Investigator	Material	Overstress	Crack Detection		Detection
		%	% Life	Cycles	Method
Kommers[34]	Armco, SAE 1030 steel Cast Iron	--	90	Various	Visual
DeForest[33]	SAE 1020 Steel	45	69-85	69-85,000	Magnaflux
		30	73-92	87-106,000	
		18	78-96	390-480,000	
Bacon & Roger[32]	0.27% Carbon steel	32	70-80	70,000	Heat Tint
Moore[1,2]	0.45% Carbon steel	5	39	422,000	Oil & Whiting 10X Mic.
	0.46% Carbon steel (new)	64	87	62,000	
		43	76	146,000	
		36	61	224,000	
		21	27	347,000	
		8	52	1,020,000	
	0.46% Carbon steel (used)	35	49	190,000	
		30	49	100,000	
		19	67	515,000	
		15	70	560,000	
		8	58	350,000	
		2	9	500,000	
		2	5	300,000	
	0.62% Carbon steel	34	55	191,000	
		20	43	333,000	
		6	19	413,000	
		2	31	1,629,000	
Cshiba[28,29]	0.4% Carbon steel 0.7% Carbon steel	Repeated Impact	28-71 degree of fatigue 40-50% " " "		

Bacon and Roger[32] also ran some crack propogation tests in which they give figures showing when a crack first appeared. This given point is definitely located after a crack had formed because the method of detection used was a heat tinting one in which the specimen was tinted to different colors at different numbers of cycles in order to determine the area remaining after various cyclic ratios. Thus the figure given is that of the closest cyclic ratio at which the metal was tested after the formation of a crack.

This leaves to be discussed Moore's[1,2] experiments with specimens taken from commercial car axles. Here cyclic ratios are found all the way from 5 to 87 with a tendency for the cyclic ratio to decrease as the overstress decreases, which is just the opposite to what DeForest found. Also, with overstresses of the same value as the other investigators, he observed cracks long before the other experimenters did. There are two possible expalanations for this; 1, he was able to detect smaller cracks by his method of detection and 2, he used larger specimens, 2 in. in diameter. In explanation of the latter, he states that, roughly speaking, the minimum size of a crack which can be detected is independent of the size of specimen; the proportionate amount of damage done by this size of crack would, however, be greater for a small specimen than a large one.[1] Not too much importance should be placed on his results for 2 percent overstress for this value may be well within the limits of the scatter band.

Examining his results for each material, it can be seen that for the 0.45% Carbon, the 0.46% Carbon (new) and the 0.67% Carbon steels, the results are fairly uniform, with a slight decrease in cyclic ratio, as mentioned above. However, the results for the 0.46% Carbon steel (used) are quite inconsistent. This inconsistancy may be explained by the fact that the specimens had been taken from an axle which had previously been in service so that specimens taken from different parts of the axle would have had different stress "histories" and consequently would not be expected to behave in the same manner, for they would be of essentially different materials.

In column 5, Table I, are given the actual number of cycles run before the detection of a crack. As a matter of interest, the actual number of cycles to failure are plotted on semi-logarithmic paper in order to determine whether or not there is any simple relationship between the actual observation of cracks in different metals and if there is a simple method of indicating crack detection on an S-N diagram (see Figure 7, page ~~27~~ 29). It is of interest to note that most of the plotted points lie within a

TABLE II

From Kommers[7]

Material	Overstress %	Percent Damage C.R. 20	Percent Damage C.R. 50	Percent Damage C.R. 80	Strengthening %	Cyclic Ratios Strengthened
0.27 Carbon Steel	10	3	9	15	7-16	6-96
0.48 " "		10	20	26	9-20	7-74
0.62 " "		5	10	13	11-25	7-71
Cast Iron		1	2	3	10-16	23-72
Armco Iron		1	2	5		
0.27 Carbon Steel	20	4	15	22		
0.48 " "		13	20	28		
0.62 " "		11	18	25	11-25	7-71
Cast Iron		8	8	9	10-16	23-72
Armco Iron		2	7	12		
0.27 Carbon Steel	30	7	18	30		
0.48 " "		20	24	45		
0.62 " "		13	20	27		
Cast Iron		11	14	18	10-16	23-72

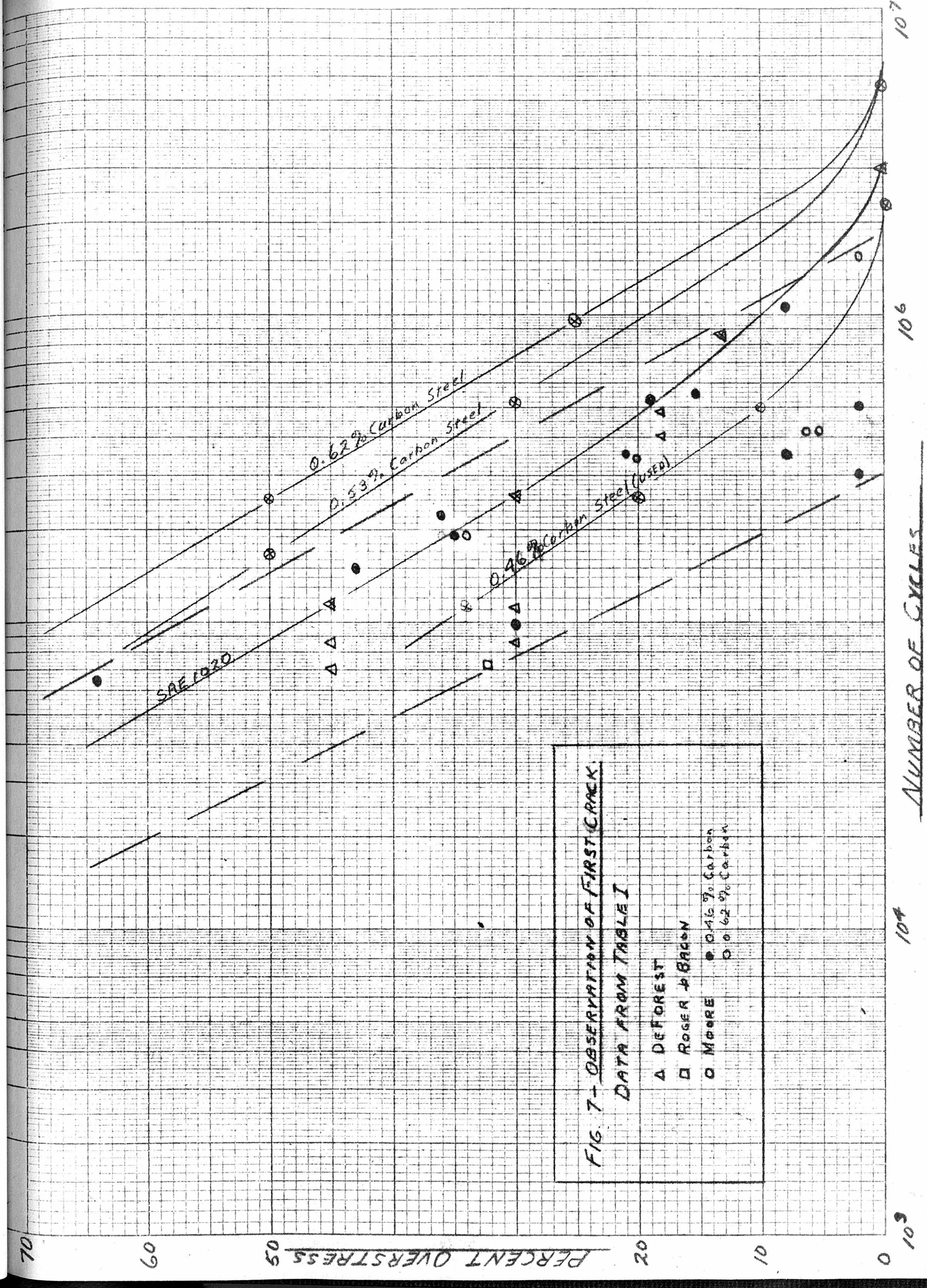

FIG. 7 - OBSERVATION OF FIRST CRACK.

DATA FROM TABLE I

straight band. Whether this is of any significance or not cannot be determined from the data available because it was deemed insufficient to make any conclusions, especially since the values obtained are for different metals. It is possible that if more careful points were plotted one might obtain either a curve similar to a damage line, or a straight line; there being indications of both in the above data.

But what is the percent of damage in such a cracked specimen? There is very little data available on this point but Moore, using 6 specimens of 0.47% Carbon steel, determined that the endurance limit of these specimens with a standard crack of 0.1 in. was between 50 and 65 percent of the original endurance limit, corresponding to 35 to 50 percent damage.

B. Correlation of Crack Formation with Percent Damage.

There is, however, considerably more data available regarding the behaviour of metals subjected to repeated stresses before the observation of a visible crack. This data was obtained mostly by Kommers[7] and Russel and Welcher[12] in their work on percent of damage and damage lines. An extract of some of Kommer's work is given in Table II, page 28. Here, for five different metals, are given the percent of damage at three cyclic ratios and three degrees of overstress. In columns 4 and 5 are given the range of strengthening he observed over various ranges of overstress.

Now, is there any correlation between Tables I and II? Generally it may be said that there are two stages in the life of a material under repeated stress as shown by these tables. The first is one in which the material has been damaged, but no cracks have been observed, whereas the second stage is one in which cracks have been observed. Considerable overlapping of these two stages is found, forming an area in which a visible crack may develop. Since it is in this overlapped area, or perhaps slightly before it, that cracks may be expected to form, it is unfortunate that the data is so confused at this point. For example, Kommers has strengthened specimens which have run up to 96 cyclic ratios, but cracks have been observed long before this by other observers. However, this may not be considered as conclusive evidence of the strengthening of cracked specimens for there is the possibility that different metals will develop cracks at different cyclic ratios. Therefore, this means that the overlapping of the tables does not necessarily indicate that a cracked specimen has been strengthened for it may be only that that particular specimen has not, as yet, become cracked.

A further comparison can be made by using the value of the endurance limit of a cracked specimen as determined by Moore (see above, page 30). The most similar metal in Table II is 0.48% Carbon steel and, taking the value for 30% overstress, it can be seen that it compares favourably with the value for the percent of damage derived from Moore's endurance limit. However, Moore's overstressing was not constant or at any definite value, so that the amount of agreement is a little in doubt. Also, since no other data is available, further correlation is impossible, which fact emphasizes the need of more data if any definite conclusions are to be made.

PROPOSED EXPERIMENTAL PROCEDURE AND EXPECTED RESULTS.

A. Strengthening of a Cracked Specimen.

From the above discussion, it is obvious that the first step should be a further investigation of a cracked specimen during understressing. Though Moore's experiment indicates that there is an endurance limit for a cracked specimen, this should be confirmed for Armco iron, the endurance limit being determined accurately for an arbitrary crack length in preparation for further understressing experiments. If such an endurance limit can be determined, it will indicate the magnitude of the stress concentration factor for a cracked metal subjected to repeated stresses. Further experiments could then be easily carried out to determine the effect of size of crack upon the stress concentration factor.

But the question of whether or not a cracked specimen can be strengthened by understressing is much more important. It is expected from the experimental results and theory discussed above, that if the applied stress is lowered sufficiently to enable the material in the vicinity of the end of the crack to be understressed, then the specimen should be strengthened. This strengthening may not be to the same degree as for an undamaged specimen but it would be expected that they will be in close agreement because Kommers reports[8] that the degree of strengthening of undamaged Armco specimens is 10 percent and that of square-notched specimens is 9 percent. No information is available regarding the degree of strengthening of damaged Armco specimens. Thus if a careful determination is made of the degree of strengthening possible in both damaged and cracked specimens, we may be able to derive some important conclusions. If it should be found that the degree of strengthening is the same for damaged and cracked specimens it would be concluded that it is quite probable that there are sub-microscopic cracks in the damaged specimen. Also, if the degree of strengthening is found to be the same for the damaged specimens as for the virgin metal, it would be an indication that the virgin specimen contained sub-microscopic stress-raisers. However, if the results obtained are not as outlined above, it would be considered that failure under repeated stress does not take place because of the extension of inherent sub-microscopic fissures but is a process involving the formation and subsequent growth of cracks.

If, on the other hand, it should prove impossible to strengthen cracked specimens by understressing, then specimens with smaller and smaller cracks should be understressed until such time as strengthening is observed. If it is found that a smaller crack could be strengthened, a provision would have to be included in the above-mentioned theories indicating that there is a critical size of crack above which the stress concentration factor is greater than the strain hardening effect. However, if it is found that no crack, however small, could be strengthened, then the assumption would be that once a visible crack was formed, the theories advanced for slip and strain hardening break down. This of course, would not give any information regarding sub-microscopic cracks, though a limit would be obtained for the amount of damage above which a metal cannot be strengthened.

B. Extension of Percent of Damage Curves.

If satisfactory results are obtained in the above experimental procedure, the investigation may be continued along the following lines, if so desired and if the results obtained prove it to be practical. Consideration of the correlation between percent of damage in cracked and damaged specimens as outlined in the previous section, leads directly to another procedure which may add greatly to the information regarding failure by repeated stress. If one carefully determined and plotted percent of damage right up to a cyclic ratio of 100, including in this investigation the percent of damage of cracked specimens, one should obtain a continuous curve. This curve should then be observed closely, changes of slope and discontinuities being noted. If a smooth curve were obtained, it would be an indication that the processes of incipient crack formation and crack propogation form one continuous action. The conclusion derived from this observation would therefore be that the observed crack must have started from submicroscopic cracks or fissures which were inherent in the operative planes of the metal, the failure being at first due to submicroscopic extension of the fissures, probably by slip, and later due to visual extension of the fissures.

However, if there were a sharp break or irregularity in the curve at any point, it would indicate that there is a discontinuity at this point in the life of the specimen, the form of which is unknown. The possible reasons for such a discontinuity are either that a crack has suddenly formed giving a stress concentration, or that a crack has reached a stage of development at which its stress concentration becomes operative. Thus, if one did obtain such a curve, one would have to investigate stress concentrations of small cracks in order to arrive at a definite conclusion.

However, there would be two points about which to be very careful if this procedure is followed. The first point to be watched is that the curve, even if smooth, could never be a straight line in the case of either rotating beam or flexural specimens for the following reasons: because there is a variation in stress across the specimen and because the area of the "bonded" material becomes less as the crack or damage progresses. The first of these variations can be eliminated if push-pull testing machines are used and it is assumed that the stress was constant across the area of the specimen. The second point to be watched is that in this curve the effect of the scatter band should be taken into account for if there is a lot of scatter, the discontinuity, if any, might be hidden. For this investigation, the specimens should be carefully finished, sized and polished, thus eliminating most of the irregularities other than those inherent in the metal and consequently reducing the amount of scatter. If it is desired to reduce the scatter still further, the specimens could be given a heat treatment to make them more homogeneous.

Thus the procedure would be to check whether a cracked specimen can be strengthened by understressing and to what degree. Then one could carry on and plot the damage curve. Frequent microscopic examinations will be made during all the steps, slip being noted particularly. Thus this experimental procedure will add greatly to the practical knowledge of the effects of slip and from a study of these effects give a much clearer conception of the mechanism of failure under repeated stress and the part slip plays in it.

CHOICE OF MATERIAL

A. Desired Properties.

In this investigation it is desired to use a metal with a simple structure in order to avoid the effects of a complicated structure which would cloud the fundamental mechanism of failure which is what is actually being studied. In addition it was desired that the metal have as many of the following properties as possible.

1. Has a definite endurance limit.
2. Exhibits slip both during understressing and overstressing.
3. Can be strengthened by understressing.
4. Has a yield point close to the endurance limit.
5. Is easy to machine.
6. Is commercially available.
7. Preferrably has had some previous experimental work done with it.

Armco Iron

It was found that Armco iron satisfies most of these specifications. It has one of the simpler structures, has a definite endurance limit and, in addition is a relatively pure material, thus minimizing the effects of alloying elements.

Regarding the other specifications, Moore and Ver[14] found that Armco iron exhibits slip both during understressing and overstressing. Kommers[8] has shown that it can be strengthened by understressing. Regarding the yield point and endurance limit, Kent gives the same value, 26,000 psi, for each whereas Moore gives the following values: yield point - 20,500 psi, endurance limit - 22,000 psi and tensile strength - 40,000 psi.

Armco iron also satisfies the other specifications given above, especially the last one as is shown by the number of references already given.

Also, if so desired, the effects of the grain boundaries may be studied by using special heat treatments in which the grain size of the Armco is changed.

Thus it can be seen that Armco iron is a simple basic material suitable for the investigation of the behaviour of a metal during failure under repeated stresses without involving the complications arising out of the use of a metal with a more complicated structure.

A NEW TYPE FATIGUE TEST MACHINE

A. Desired Characteristics.

Upon examination of the existing types of fatigue testing machines, it was found that none of them had all the characteristics desired for carrying out the experimental procedures described above. First, since it is obvious that a lot of microscopic examination is anticipated, it is desirable that the specimens be suitable for such examination, and if possible, provision be made for examination of the specimens in the machine. Also, since part of the life of the specimen especially under observation is that when cracks are forming and propagating, it is therefore desired that a constant strain machine be used as opposed to a constant load machine, for the latter type of machine accelerates failure once a crack has formed. Another characteristic which is very desirous to incorporate, is the ability to reduce the time required for the tests outlined on the above experimental procedure if at all possible.

B. A General Description of the Machine.

Two views of the machine designed to incorporate these desired characteristics are shown in figures 8 and 9. This machine was designed by the author with the advice and assistance of Dr. D. E. Hudson and Prof. A. Hollander of the Mechanical Engineering Department of the California Institute of Technology.

It utilizes the reversed bending of flat specimens (see Fig. 10) in order to initiate failure under repeated stress. The specimens are mounted in four banks of six specimens each; that is, holding a total of 24 specimens. The banks are so arranged that maximum utilization is made of both "vibration" eccentrics and space, the whole machine having outside dimensions of approximately 14 x 14 x 5 inches. Adequate provision is made for microscopic examination of the specimens while they are mounted in the machine.

The movement is imparted to the specimen by a ball-bearing mounted eccentric, the specimen being constrained to follow the eccentric by means of a spring-loaded linkage system. These eccentrics are all mounted on a single shaft at angles of 90 degrees to one another in order to minimize the bending stresses on the shaft, each eccentric actuating two specimens in order to further balance the system.

The machine is driven by a V-belt pulley drive (not shown), interchangeable pulleys giving various speed ratios if so desired. The machine has also been designed so that it will operate either on an edge or on a side, whichever happens to be the most convenient.

C. Special Design Features.

This machine was designed to incorporate several special features which would be of great assistance in carrying out the outlined investigation.

Since it was expected that a great amount of microscopic examination would be required, it was first decided to use flat specimens, as opposed to round specimens, in order to facilitate such examination. These flat

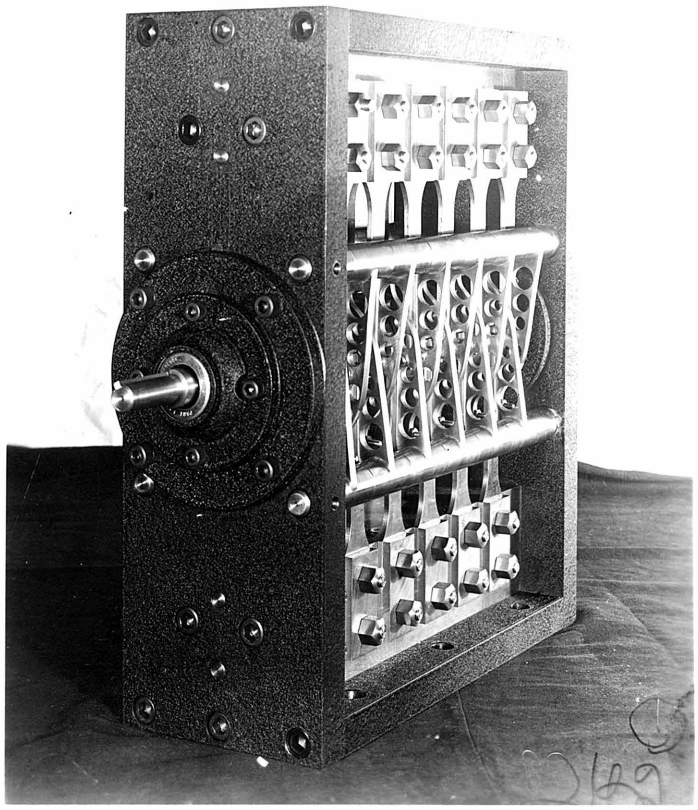

Fig. 8- New Type Fatigue Machine. View from drive end showing mounting of specimens and linkage system.

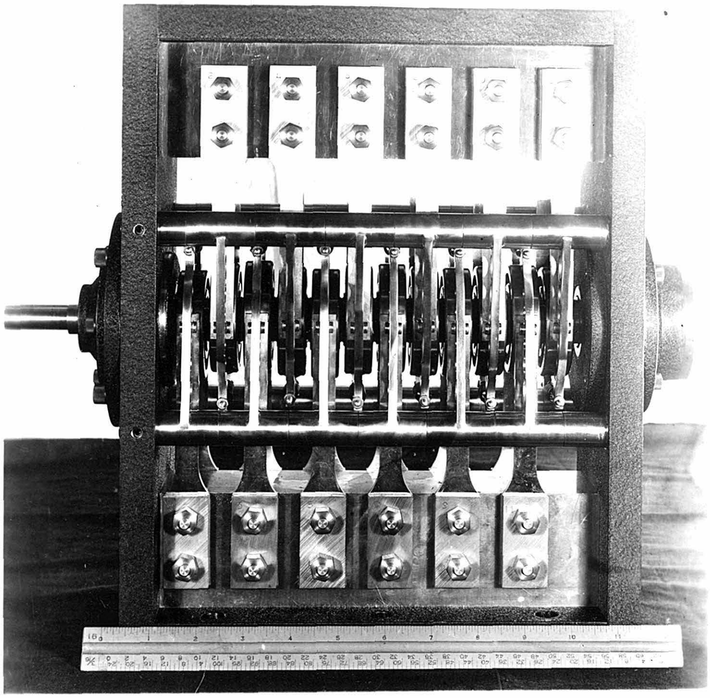

Fig. 9- New Type Fatigue Machine. Side view.

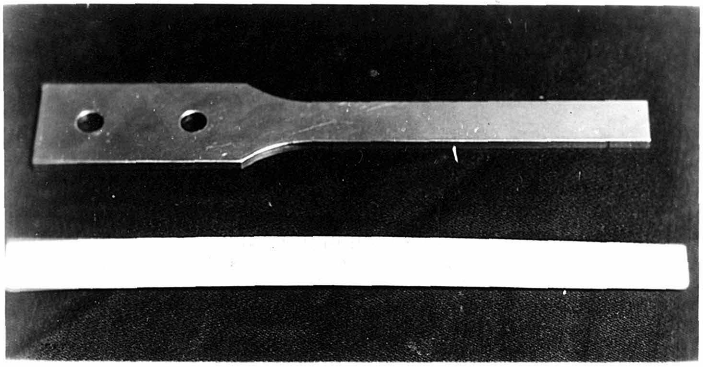

Fig. 10- Specimen for Fatigue Machine.

specimens require no special mounts and present a flat objective plane. It was felt, however, that a great saving of time and energy could be made if the specimens were so mounted that they could be examined in the machine. Thus the machine was so designed that the critical area of one side of each specimen was left open to facilitate microscopic examination. In order to facilitate examination in position, a microscope mount with suitable adjustment screws has been designed for attachment to the machine. Since this piece of equipment has not as yet been made, no photographs are available.

In this investigation a great number of the specimens will be run at or close to the endurance limit. Since the ordinary ~~machines~~ machines turn only at about 1700 RPM, it can easily be seen that the time required for each test would be very great unless the machine were speeded up. Since Moore and Krouse[25] report that speeds up to 30,000 cycles per minute cause very little difference in the endurance limit, this machine has been designed to run at speeds much greater than the ordinary machine, thus reducing the time required for running tests. At first, until the effect of speed on the endurance limit of flexural specimens has been determined, for precise results the speed at which the tests are made should be specified. Since the machine was so complicated as far as loading is concerned and since the loading will change with each variation of stress, it was considered impractical to try and theoretically determine the critical speeds. Instead, it was decided to determine the critical speeds experimentally, finding a suitable non-critical speed close to the desired speed.

A further method of saving time is to design the machine so that several specimens are tested at the same time. However, one of the greatest improvements this machine has over other multi-specimen machines is that several specimens can be tested at different stresses at the same time on the one machine. This is accomplished by the use of a set of removeable eccentrics of varying eccentricity. Thus with a complete set of eccentrics, any desired combination of stresses can be set up in the machine. For example, this machine was designed for 24 specimens with a maximum of 12 different stresses. Thus, by the use of appropriate eccentrics, it is possible to get a complete S-N curve in just one run of the machine, the curve being determined by six stresses with four specimens at each stress or twelve stresses with two specimens at each stress. Many other combinations can be made up and if desired all the specimens can be run at the same stress. A further advantage of this machine is that, by changing either the set of eccentrics or the thickness of the specimen, it is suitable for any material.

Another simple adaptation possible with this machine is that by the use of shims under the specimens, failure under various ranges of stress may be studied. Also the machine is designed so that by the simple addition of cover plates it may be used for testing under controlled conditions.

Thus, it can be seen that the above machine is simple and adaptable to most testing conditions as well as being able to reduce by a considerable amount the time required for fatigue tests and for determination of S-N curves.

Appendix I

Detection and Observation of Cracks.

This is not intended to be a detailed statement and discussion of each of the methods but rather a general statement of each method and the results obtained, with references supplied for further information.

Methods of Detection.

1. Oil and Whiting Method.

The specimen is first coated with a thin oil and then rubbed dry. It is next coated with whiting which is allowed to dry. Then any oil retained in the cracks will not allow the whiting in the area of a crack to dry, thus bringing emphasis to that area. Sometimes the specimen is stressed for a few cycles after the whiting has dried, the stressing tending to force the oil out of the smaller cracks.

A modification of this procedure is to use gasoline as a wash and then to stress the specimen for a few cycles. Bubbles will then tend to form along the cracks, bringing them to notice.

No limits are given as to the size of crack which may be detected in this manner.

References: 1 and 2.

2. Magnaflux.

In this method the specimen is magnetized and then coated with a dry or wet para-magnetic powder. Solvents used for the wet powder are carbon tetrachloride and kerosene. The relative times of application of powder and magnetizing current is different for different procedures. A variation of this method is to use a fluorescent para-magnetic powder in solution and then observe the specimen with the aid of ultra-violet illumination.

By means of this method, cracks of a depth of 0.008 inch have been detected by the flux.

References: 23, 35, 36, 37, 38.

3. Magnetic Means.

Using the same principle as the magnaflux; that is, the disturbance of eddy currents by cracks, but in this case the crack is located and measured by a calibrated change of the current in a surrounding coil.

Cracks to depth of 0.0005 inch have been detected by this method. However, for this apparatus the material being tested must be in strip form and of constant cross-section.

Reference: 39

4. Electrical Resistance.

This method utilizes the change in the resistance of a specimen taking place some time before its failure. Associated with this change in resistance are; a rise in temperature, a change in deflection, a change in natural frequency and amplitude of vibration and a change in the power input to the testing machine. However, these methods all seem to indicate the initiation of slip or damage and the change comes some time before the initial visual observation of a crack.

References: 40, 41

5. X-ray Diffraction Methods.

Changes of diffraction pattern have been noticed during the damaging of a metal and during the formation of a crack as mentioned in the text of the thesis (page 20). This method discloses changes of atomic dimensions if changes in the pattern are correctly interpreted.

References: 19, 20, 21, 22, 42

6. Supersonic Methods.

In this method sound waves are sent into the metal being tested. Any flaws in the material will reflect these sound waves before the remainder of the waves ~~is~~ are reflected from the end of the specimen. Actually this is the same principle as was used in Asdic and Radar during the war.

The smallest hole determined in this way was one of 0.005 inches in diameter at a distance of three inches from the end of the specimen. However, a lamination of 0.0001 inches will give a reflection but this lamination must have considerable area perpendicular to the path of the waves.

Reference: 43.

7. Visual and Microscopic Methods.

Since this was the method adopted, it is discussed in greater detail below under Methods of Observation.

Methods of Observation

1. Electron Microscope.

This method of examination was not investigated closely because it was felt that during the early stages of the investigation such precision was not required and because special techniques and equipment were required. It is expected that several specimens will be given to a competent operator for examination early in the investigation in order to determine the possibilities and limitations of this tool.

2. Microscopic Examination.

Little need be said about this means of observation for the characteristics and capabilities of the microscope are well known. Lucas has reported the observation of a crack of 0.0001 inches in width,[18] but this was only obtained with great difficulty and the use of special equipment.

In this investigation, it is desired to re-examine the specimens, perhaps many times each. In order that no change might take place in the material because of the examination, most of the aids to detection are eliminated. Anything applied to the surface of the specimen would work its way into the cracks, causing changes in the later behaviour of the specimen. Also, since the specimen is of irregular shape, magnetic means cannot be used. X-ray diffraction methods could be used but, in spite of the expensive equipment, they would not add greatly to the results which could be obtained by microscopic examination. This means that cracks should be detected by visual and microscopic examination. In order to minimize the tedious searching required, the specimens are so shaped that the critical area in which cracks are expected is reduced to a minimum consistent with not introducing any serious stress concentrations.

Upon laboratory investigation of polishing and etching methods for microscopic examination, it was found that the polishing and etching of a specimen changed the nature of the crack. Polishing tends to "burr" the edges and fill in the crack while the etching tended to eat away the edges of the crack, making it wider and probably deeper. Thus it was decided that, for at least the first stages of the investigation, the specimens would be polished and etched before it was placed in the machine and to carry out detection and examination by means of the microscope, using powers suitable for the size of crack being looked for.

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