THE MECHANICAL BEHAVIOR OF MATERIALS

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Introduction

Nowhere in all the areas of advanced structural materials technology do we feel there is a more emphatic need for imaginative development of knowledge than in the area we have generalized here as the mechanical behavior of materials. It sooner or later develops that this side of a material's personality becomes the dominant criterion with which success or failure to meet requirements is ultimately measured.

The truth of this statement has surprisingly enjoyed little recognition until relatively recent times - within the last decade. At one time, off-the-shelf materials were abundantly available to meet the requirements of a new design. Today however, a new design is often limited by the lack of materials with the desired combination of properties.

In general, our drive for higher performance has cost us the luxury of having so called infinite life systems. Modern design is, almost without exception, based on the concept of a limited life of operation. The more complex the system and the more demanding the mission, the shorter the design life invariably becomes. Higher performance thus demands more efficient application of materials and at the same time introduces more severe environments in which materials must satisfactorily function.

The intrinsic mechanical properties of structural materials form only part of the story, however, and in the case of modern materials and applications, do not necessarily play the most important role. The optimum exploitation of materials properties through the knowledge of a material's compatibility with the operating environment and its continued performance therein, become key factors. Important here, then, is not only the knowledge of a material's ability to perform its assigned function, but the knowledge necessary to reliably predict its useful life early in the design stage.

This approach definitely has gone against the conservative tradition which characterized the materials as well as the design aspects of aeronautics of the past. Not too many years ago, as an example out of context, it was a firmly established opinion of most of those in the design fraternity that fatigue was a phenomenon observable in the laboratory but of no concern in a flight vehicle properly designed by static load criteria. Commercial as well as military equipment safety and maintenance records since the early 1950's certainly repudiate that opinion.

Because operating conditions have become so severe, we have had to pass from an era where "economic feasibility" dominated materials selection into one where "scientific feasibility" will dictate. It is necessary for the designer to pay considerably more attention to the sometimes independent-minded materials behavior than ever before. The characteristic feature of this trend in mechanics is the recognition that knowledge of the influence of imperfections of the submicroscopic, atomic and molecular structure of materials forms the basis from which the microscopic and macroscopic behavior of materials can be explained, predicted and exploited. Indeed, this is a time for an effective interplay between design and materials development.

The Metals and Ceramics Laboratory program of research in materials mechanics has been for several years carefully oriented to meet the needs of the changing requirements just described, both through internal programs and those performed under sponsorship. In general, the total program has followed along the guidelines outlined below:

1. Development of new and refined materials behavior concepts leading both to more efficient use of and performance of "standard" materials.
2. Maximum use of limited property materials through improved design concepts.
3. Development of failure concepts for "standard" and new materials.
4. Employment of new concepts to tailor multi-material systems with combined properties and develop knowledge of their performance characteristics.

In the discussions that follow, some of the programs being conducted by our Laboratory along the above lines will be described. For the sake of clarity, the discussion is presented in three parts each of which treat related areas of work. They are: materials dynamic behavior, creep, buckling and stress-relaxation and finally brittle behavior in materials.

Materials Dynamic Behavior

The area of materials dynamic behavior is recognized as being very broad, encompassing such occurrences as fatigue, damping, resonant vibrations, rapid loading, shock and impact. However, in this discussion, rapid loading, shock and impact will not be considered. The areas which remain might be categorized as dealing with forced stressing and stressing through resonance vibration.

Due to their very nature, forced vibrations are in most respects considerably easier to deal with than is the case of resonance vibrations. This is because the stress response of a resonant system may be highly non-linear and uncontrollable and therefore difficult to predict, whereas, forced vibrations follow a linear relationship between force input and resulting stress.

Fatigue

For many years, the fatigue phenomenon per se has been the subject of considerable research at all levels of observation, from a study of the basic mechanical metallurgy concepts to the accumulation of masses of design data. As for a discovery of an ultimate "solution of the fatigue problem", it seems unlikely that one will ever be found. It is clear now that the logical approach is one of reducing the problem to a level at which accurate control and prediction of performance is possible. In its simplest form the fatigue process is at best, only partly understood. On the introduction of operating environments, the total process can be tremendously influenced by many factors and become very complex indeed.

There are many important studies in progress today to increase our understanding of the basic fatigue process. In general, the work is devoted to the two major steps recognized in the process, 1) studies of fatigue hardening of metals and 2) studies of fatigue fracture.

As for fatigue hardening, experiments by Broom and Ham (1) of Birmingham University in England have demonstrated the difference between fatigue hardening and tensile work hardening. Thin film transmission electron microscopy has shown how fatigue stressing uniquely produces prismatic dislocation loops and that it is these loops which contribute to the fatigue hardening process (2). Loop formation and the subsequent hardening are essentially completed after the first 100 to 1000 cycles of reversed stress if the stress is of such magnitude as to produce failure in one million or more cycles. It is these changes, incidentally, which are responsible for the rather large increases observed in resistivity which accompany fatigue stressing at low temperatures. If the fatigue stressing is carried out about a mean stress other than zero, it is known that an additional subgrain structure is superimposed on the hardened matrix. The formation of this structure is also essentially completed after the first 1000 cycles of stress have been introduced. The major changes observed in internal friction and damping are completed during this early hardening period as well.

The mechanism associated with ultimate fracture becomes operative in the small fraction of the volume of metal being stressed which softens. This softening occurs with the accumulation of slip, first on single planes, then intensified into striations or bands. Crack initiation then occurs in the work softened material of the bands. Our Laboratory is currently supporting studies of this cracking process. We have seen that the propagation of the crack is limited to the areas and direction of intensified slip and it passes from one band to the next by cross slip. Once it is better understood, it follows that the effect of various factors, such as vacuum, temperature, strain rate, and others, can be studied in greater detail.

A review of the effect of vacuum on the fatigue process, indicates the important experiments of Wadsworth and Huchings as being classical in demonstrating that most metals exhibit longer life (3). They found that the fatigue life of copper was 20 times longer and that aluminum exhibits a life 5 times greater when tested in vacuum. Experiments in our laboratory on PH 15-7 Moly stainless steel about the same time, as well as experiments by the Navy, illustrated similar results. The life exhibited by PH 15-7 Moly was on the order of 20 percent higher. The explanation of the phenomenon seemed to be in the reduced rate of crack propagation in the absence of oxygen. Later experiments by Wadsworth showed that the amount of oxygen present, and not the existence of a vacuum per se, was responsible for the crack propagation behavior and the fatigue life exhibited. The degree of increase in fatigue life was shown to be dependent on the number of oxygen molecules in a partial vacuum. It is postulated that a chemical attack of some kind occurs at the tip of a crack and that it occurs only while the crack is growing. Samples removed from the test chamber during fatigue testing were subsequently unaffected by the exposure.

Crack initiation, on the other hand, was found to be independent of the atmosphere. It seems that cracks are initiated very early in the fatigue life of a material, and that they grow quite slowly during the first 25 percent of the life (4). Many cracks are initiated which never grow at all, only a few become large enough to be easily seen, and usually only one crack is operative at the time of failure. The situation is somewhat different in vacuum however, where it is found that even though the cracks grow at a slower rate, more of them are operative for a longer time.

It has been found that a vacuum coaxing effect exists. That is, the fatigue life of a sample in air may be increased by first stressing the sample in vacuum for a short time.

As stated above, current experiments being performed to study the process of crack initiation and propagation are being extended to include observations of the influence of various amounts of oxygen. Experiments in our Laboratory are presently underway to observe this effect on the fatigue behavior of refractory metals since oxidation rates are so much higher in their case. It is expected that fatigue life here will be affected on the one hand by strain hardening or coaxing, while on the other by more rapid oxidation in the propagating crack to decrease life.

The influence of temperature on fatigue behavior is another significant factor although it has not received much consideration so far in fundamental work. The room temperature process has occupied most of the attention focused on the general problem until recently since the introduction of temperature complicates matters tremendously. Aside from the general reduction of static elastic properties as might be expected with temperature, an increase occurs in the plastic component of the fatigue cycle and damage accumulation can take on a new dimension. Additionally, the damage process is susceptable to other alterations because metallurgical changes brought on by temperature, such as aging, local oxidation, stress relief, and the like, may change structure to which fatigue is sensitive.

Because of the increased plastic component of deformation under cyclic loading, fatigue at elevated temperatures is usually accompanied by some creep, the amount of mixing being dependant on the value of the preload. The specific amount of creep damage occurring during fatigue damage is a function of the temperature, the stress - both mean and alternating, the test frequency (the time at temperature and load), the nature of the test material, and probably other factors. Creep, on the one hand, is generally a continuous deformation process under load and occurs more abundantly at high temperatures. The rate of creep is influenced by many variables, but under a given set of conditions at elevated temperature, the rate controlling process is commonly considered to be the climb of dislocations. This implies that the glide of edge dislocations is hindered, or that the number of edge dislocations is limited. It seems likely that the initial rapid deformation which occurs after loading accounts for most of the unhindered dislocation glide.

The fatigue of metals, on the other hand, occurs at any temperature. The rate controlling process, if there is one, has to do with crack propagation since the specimen spends most of its total life in the cracked condition. Vast numbers of dislocations, vacancies and interstitial atoms are generated during the early part of the fatigue process. Their effect on crack propagation is not well established.

If we superimpose an alternating stress on a material exposed to creep conditions, or vise versa, we would expect an increase in the rate of damage in the material. However, this is not necessarily the case as is shown in figure 1. It is seen that the superposition of creep and fatigue stresses can sometimes promote a strengthening of the metal, apparently by means of a work hardening process. An exceptional degree of strengthening is shown in the case of Waspaloy by the shaded areas of the stress range diagram (5). Research in this area has been sparse, and what has been done has not been on a fundamental level. Variables such as atmospheric effects, metallurgical instabilities, non-uniform stress distributions, and the like, must be considered in proposing a comprehensive failure mechanism.

Our Laboratory is supporting research in this general area. In this work, pure aluminum will be fatigued under various combinations of load and loading rate at temperatures ranging from room temperature to that of liquid helium. It is expected that this work will provide some insight as to how damage is partitioned between deformation due to stress activated and thermally activated dislocations and point defects. It may be found that loading rate is of fundamental significance as well as temperature, mean load, ultimate load, and the like. In addition to this, tests, are being made on long, thin-walled tubes of brass to establish the relationship between cumulative plastic strain and stress history. It has been found that plastic strain is dependent on stress path as well as the more obvious variables of temperature, maximum stress, number of cycles, etc. The culmination of this work should have fundamental significance in the field of theoretical and applied mechanics. The mathematical model should be an improvement over some of the older theories of classical plasticity.

Acoustical Fatigue

In regard to the question of resonant vibrations, one of the most powerful tools found to cope with attendant problems has been damping. For a number of years our Laboratory supported research which developed and refined damping concepts largely responsible for solutions being applied today. Our initial interest was stimulated by vibration problems associated with early jet engine designs, particularly critical in the case of turbine buckets and compressor blades. Here, materials self-damping, as well as Coulomb or friction damping at connections, offered an important solution.

In the early 1950's the sudden development of the acoustical fatigue problem gave impetus to a structural concept of damping in which non-load carrying materials, having very high damping characteristics, would be used in a structure to reduce resonance stresses in loaded materials rather than the loaded materials provide their own damping (which is insufficient to cope with the acting energies).

Actually, since the early days of aircraft design, there have been cases of airborne excitation of structures such as flutter of wings and control surfaces or excitation of fuselage components generated by propellar pressure pulses. However, in these cases only under specific and rare circumstances was there enough energy available to cause structural damage of the energy absorbing structure.

With the advent of supersonic flight and high thrust propulsion systems, pressure pulses or noise levels became high enough to excite continuously and maintain serious structural vibrations. Structural failures caused by these vibrations have been termed acoustical or sonic fatigue failures, implying that their source is airborne energy in the form of pressure fluctuations. Figure 2 shows typical examples of this type of failure. These pressure fluctuations may either be periodic or random. If they are periodic, excitations are relatively easy to cope with by means of appropriate frequency adjustments of the receiving structure or use of the interference phenomenon of sound waves. However, the reduction of random excitations or elimination of random resonance fatigue, associated with high intensity noise, cannot normally be avoided by the same means because both jet exhaust and boundary layer "noise" spectra have a frequency bandwidth which includes most of the natural frequencies encountered in conventional structural components of aerospace vehicles. Figure 3 shows a typical sound-pressure-frequency distribution for pertinent systems and sources to illustrate this. Figure 4, in which power level measurements made on an F-100 aircraft are plotted over Mach number, makes a comparison of in-flight noise.

Since random resonance is therefore a most difficult problem, the gathering of information on noise sources and characteristics of the environment they produce, which is essential in design of exposed structures and in prediction of structural life, has been one of our efforts in this area in recent years.

A great variety of aero and thermodynamic conditions are involved in noise generations; however, since this subject is amply covered in earlier publications (6, 7) it will not be treated in the present paper.

The general problem of acoustical fatigue can be broken down into three component parts:

1) the acoustic environment to which the structure is exposed,

2) the response of structures to this environment, and

3) the structural fatigue life at specified cyclic stresses.

Our chief activities in recent years besides the study of the acoustic environment have been concerned with the response of structural components and the increase of acoustical fatigue life.

The main difficulties in this work is posed by the fact that most structures have a nonlinear response characteristic. Panels, for instance, display a high degree of nonlinearity in stiffness at large amplitude, which causes their natural frequency to be highly dependent on amplitude.

Considerable knowledge has been gained in recent years and more accurate expressions of acoustical fatigue strength derived through experimental studies of response characteristics and the behavior of basic components as well as response correlation studies on a combination of these components or whole structures under acoustical service and laboratory conditions.

Four properties of materials and configurations govern acoustical fatigue strength: 1) random materials fatigue strength, 2) natural frequency of the configuration, 3) static stress produced by unit pressure, and 4) structural damping. It is obvious that the last two offer the greatest potential for an improvement. Significant gain can be realized in acoustical fatigue strength by careful detail design in order to minimize the maximum statically-induced stress. However, the conventional design concepts are inadequate to deal successfully with the fatigue problem associated with resonance amplification. Although "beefing-up" a structure for increased strength and stiffness has "fixed" resonance fatigue difficulties in some cases, this approach cannot be considered a long-term engineering solution. Not only is the weight and cost penalty large in this approach but it is also totally inadequate to meet the problems encountered in many of the new types of aero-space vehicles. Consequently, the utilization of the fourth property, structural damping, as an engineering property to control acoustical excitation is a necessity. In the future it will still be necessary, of course, to reduce the maximum statically-induced stress by using heavier members or build-ups. However, if maximization of damping is also considered to be a design objective in addition to the static strength increase, then a much larger gain in acoustical fatigue strength can be realized than using either criterion alone.

Whereas in the past the damping of a structural assembly may have been increased by the addition of separate energy absorbing means such as use of dashpots or surface layer treatments such as coatings and tapes, this approach no longer provides an engineering solution for the newer types of configurations and acoustical conditions. Instead, the design concept of optimizing a configuration for maximum inherent structural damping must be emphasized. The experimental and analytical knowledge which we gained through our research efforts in the recent past on the major sources of inherent structural damping such as hysteresis in structural materials, interface slip and interface viscoelastic shear, has now reached a point where application to structural design is practicable.

Of these possible damping types only the interface visoelastic shear damping was found to be reliable and effective enough to make a worthwhile contribution to the increase of the acoustical fatigue life of structures. And it is for this reason that our Laboratory has devoted considerable effort to the realization of viscoelastic damping both in optimized structural configurations and in surface layer additions.

Figure 5 shows some of the basic ideas used in this concept. Sketch a) of this figure demonstrates interface shear damping of a sandwich panel; Sketch b) shows shear damping at a panel connection initiated by membrane action; and Sketch c) shows an example of panel damping by surface layer addition with restraining metal foil.

Looking at the overall acoustical fatigue problem, it becomes apparent that knowledge of its individual components - noise environment, response and damping-is necessary for a satisfactory solution and the continuation of research along these lines is in order.

Viscoelasticity

The very early efforts to seek improvement in the dissipative character of structures through damping treatments with viscoelastic media were largely by trial and error. To optimize an application however, it became evident that only by approaching a solution on the basis of viscoelastic theory was an effective result to be had.

In the last decade a great deal of work has been done in the development of linear viscoelasticity of a homogeneous and isotropic material and many technologically important problems have been solved. However, if viscoelastic effects appear in a non-linear manner, a solution becomes very difficult and it seems likely that only the simplest problems can be handled completely satisfactorily. In many cases, linear viscoelasticity can provide a sufficiently good approximation to the solution of non-linear problems and offers numerous mathematical methods of attack. Because of the basic difficulties encountered in non-linear analysis, it has become extremely important to exploit linear viscoelasticity theory to the utmost extent.

Our Laboratory is providing support of research to extend, where possible, certain aspects of linear viscoelasticity. This work is divided into two parts. First, research is progressing to extend the state of the art with particular reference to Lagrangian Methods. The partial mode analysis is emphasized and material anisotropy is being considered. The second part of the research considers specific cases of current technological interest, including viscoelastic damping phenomena, sound and energy absorption in laminated beams, plates and shells. Although many applications can be described as direct applications of the basic theories, additional work will be necessary to clarify approximate procedures that can be used in the solution of engineering cases. Problems involving beams, plates and shells are being studied with various boundary and loading conditions as well as different material properties.

Dynamic Modulus

In the stress analysis of vibrating members, it is usually desirable to know the dynamic modulus of elasticity which is higher than the modulus of elasticity obtained in static tests. Several explanations have been given for this difference. Fine (8) offered an explanation on the basis of thermodynamic behavior at various speeds of stressing, reasoning that when a tensile or compressive stress is applied to a material, there is a production or absorption of heat. In static tests, time is sufficient for a heat exchange with the surrounding medium so that the test is isothermal. However, time is not sufficient in a dynamic test for such a complete heat exchange so that this test is considered adiabatic. Fine expressed the relationship between isothermal and adiabatic modulus values as

$$\frac{1}{E_{is}} - \frac{1}{E_{ad}} = \frac{T\alpha^2}{\rho c_p}$$

where:

E_{is} = isothermal modulus of elasticity

E_{ad} = adiabatic modulus of elasticity

T = absolute temperature

α = coefficient of thermal expansion

ρ = density

c_p = specific heat at constant pressure

Zener (9) has explained the difference in terms of the time dependence of the relationship between stress and strain. He showed that there is an instantaneous stress-strain relation - called the "unrelaxed elastic modulus" and another relationship occurring after a finite relaxation time called the "relaxed elastic modulus" which has a lower value than the unrelaxed modulus. Hence, the behavior of a material depends on the speed of stress application with respect to the mean relaxation time for the material. In dynamic modulus tests (or for example, in the case of acoustical vibrations), the stressing speed is high enough for the unrelaxed modulus to be operative.

Our Laboratory has developed apparatus for making dynamic modulus measurements at room and elevated temperatures in either a longitudinal or bending mode and has recently published data for a representative group of materials (10). The sensitivity of the apparatus is such that the effect of metallurgical changes, such as alloying, aging, recrystallization, etc., on the dynamic modulus have successfully been observed (11). In figure 6 is shown examples of the influence of some representative metallurgical variables. Our current apparatus development work is geared to higher temperatures in a set-up which excites the bending mode of a sample. The apparatus will provide a vacuum at temperatures to 1600°C for additional research on mechanical metallurgy questions.

Cumulative Damage

Forced as well as resonance related structural vibrations can be produced by energies generated either mechanically or aerodynamically. The mechanically generated energies are almost exclusively transmitted through the structure itself whereas aerodynamically generated energies are either structure borne, or airborne when they originate from gust or maneuver activities. However, if they originate from turbulence created by jet engine or missile exhaust or boundary layers they are almost entirely transmitted by air in the form of pressure pulses (noise).

For several years our Laboratory has been actively concerned with devising a more realistic account of the damage which accumulates due to different stress levels and histories imposed by the spectra of such vibrations.

In recent years use of Miner's linear damage rule (1946) has been almost universal in aeronautic design circles. However due to its inability to cope with more complex stress histories and mixing of extreme values of stress, interest grew in a more descriptive damage criterion. Research work of Freudenthal and Heller (12-16) has developed conclusive evidence that "stress-interaction" takes place which appears to be responsible for the discrepancies in the linear damage hypothesis. In other words the effect of introducing high stresses is to increase in some materials the potential damage of heretofore "non-damaging" low stresses so that damage proceeds under low-level stressing which is not accounted for and causes "premature" failure. On the basis of this damage mechanism Freudenthal devised his semi-empirical quasi-linear damage rule which is illustrated in its effect in figure 7.

The noted deviation from a constant rate of damage accumulation, described by a linear rule, is due to the dependence of the damage rate on the applied stress levels which themselves are varying randomly. For a stress sequence containing predominantly high stresses and consequently having lower life, a smaller degree of stress interaction occurs because of an abundance of cyclic plastic deformation taking place. Stress spectra containing mostly low stress peaks of similar value in considerably greater quantity than higher peaks, result in a more linear damage accumulation rate. Of course, the nature and extent of the deviation from linear behavior varies with the material considered and the "shape" of the spectrum. Now that basic concepts have been established the more complex conditions representative of actual service conditions are being introduced such as effects of mean load, structural redundancy, type of loading, etc.

Since most of the load spectra to which aeronautical systems are subjected are largely random in nature, which means they do not occur in an established sequence, the problem is largely a statistical one. The aim in our work towards the solution of the problem is the establishment of a more uniform cyclic loading with a damage potential equivalent to the given random load spectrum. The statistical part of this problem is at present being conducted for us by Dr. Weibull of Sweden (16). Dr. Weibull also in recent years has been studying a problem for the Air Force which is of particular interest to aircraft structures test people. Prompted by the lack of large numbers of specimens for fatigue reliability tests of components and whole structures, studies were made of the possibilities of arriving at a probability of failure with an accuracy sufficient for the prevailing case, using a small number of test samples. Encouraging progress was made which allows interpretation of fatigue test results from a small or reasonable number of test points distributed evenly over the whole range of the S-N curve (18, 19). Also under consideration are the problems of small sample statistics for extreme values such as are prevalent at the so called fatigue limit.

Reliability

When one considers the total picture of the reliability of a complex, long but finite life mechanical system, the task of making an accurate quantitative prediction of life seems awesome, and at first glance, it seems hopeless that one is possible without introducing safety factors which are orders of magnitude too broad. The overall deterioration of a finite life mechanical system is governed by so many individual deterioration mechanisms with different rates, each perhaps sensitive to various changes in operating environment, that system failure can often appear to be ''chance'' failure. However, this has generally been shown to be fallacy and that the prediction of fatigue life for example, can be put on firm statistical grounds (20).

Although the methods of stress analysis have been greatly improved and refined through the use of computers, and our knowledge increased in the use of materials, the methods of safety and reliability analysis have not improved significantly, and in general are still based on the use of more or less arbitrary safety factors that can neither be justified by rational argument nor related to a probability of failure (20). In short, the principal tool needed is an analytical technique which would first establish the expected life of a system, related to a probability of failure and a risk function, and which could re-estimate a new value of life when a new set of operating conditions are introduced, such as a change in the mission profile of a flight vehicle from the original design specifications. Important research along these lines has been underway recently under the support of our Laboratory showing considerable promise (21). The first phase of development involved the establishment of the risk function describing the increasing risk of fatigue failure as damage accumulates together with the evaluation of the chance of ''premature'' failure from a sudden high overload. This phase was based on laboratory test data. This work is continuing under plans for studying data from extensive aircraft structures test programs and flight records both from this country and several foreign countries and making final adjustments in the statistical theory.

Creep, Buckling and Stress-Relaxation Behavior of Materials

Creep

In high performance systems, structures are subjected to stresses at elevated temperatures over varying periods of time. Under these conditions the materials from which the structures are made undergo creep deformations or are subject to the phenomenon of stress relaxation. Designers of structures for such applications are interested in producing designs with emphasis on reliability and most efficient use of light weight structures in order to maximize performance. In order to optimize the design it is necessary to predict the creep and stress relaxation behavior of materials, under varying conditions of stress and temperature, within fairly close limits of reliability. It is also necessary that such predictions be based on test data which is obtained under more limited conditions of stress, temperature, and time than those incurred in service. Practically all data, on which to base predictions are obtained from creep tests conducted under conditions of constant load and constant temperature. Attempts in the past to develop purely empirical formulations to predict creep behavior of materials under varying stress, and temperature histories have met with little success. And it has been shown that the conversion of creep data into relaxation data does not provide reliable information on the stress relaxation behavior of materials. Since the empirical approach to prediction of creep and relaxation behavior has not been successful, it is necessary to acquire more fundamental knowledge in these areas, by using a physical or phenomenological approach to determine the basic laws governing such behavior, and to use these laws as a basis of predicting design criteria.

After a rather unsuccessful attempt several years ago to establish empirically the creep behavior of engineering alloys under conditions of intermittant stressing and thermal cycling, our Laboratory initiated a basic study of creep behavior based on a physical approach. An investigation of the creep behavior of pure polycrystalline aluminum was initiated. The pure aluminum was selected as a starting point because of its relatively simple structure and the fact that mechanisms such as aging would not complicate the analysis of creep behavior. It has been established that the creep rate of the high purity metal may be represented by the equation:

$$\dot{\varepsilon} = Se^{-\frac{\Delta H}{RT}} \phi(\sigma) \qquad \text{Eq. (1)}$$

where:

S is a structure factor dependent on stress and strain history

ΔH = activation energy for creep

R = gas constant

T = absolute temperature

$\phi(\sigma)$ = function of stress

σ = stress

Initial work in the investigation studied the effect of temperature on the creep behavior of pure aluminum. By holding the stress constant and introducing slight changes in temperature, the relative creep rates before and after the temperature step were used in equation (1) to determine the activation energies for creep (22-24). Figure 8 illustrates the activation energy for creep of high purity aluminum in the temperature range 0 to 900°K which were established in this manner. The activation energy for creep increases from about 4000 to 28,000 cal/mol over the range 78 to 240°K, in a manner which has been explained as simultaneous operation of the Peierls process and cross-slip; from 240 to 370°K the activation energy remains constant at the 28,000 cal/mol value for cross-slip; it then increases to 35,500 cal/mol and remains at this value for all temperatures above 500°K. This value of 35,500 cal/mol is associated with the process of dislocation climb.

Having established the effect of temperature on creep behavior of pure aluminum the next step was to attack the problem of determining the contributions of stress and the structure factor on creep over the temperature range of application of the material. It has been demonstrated (25) that during primary creep where S, the structure factor, is changing constantly with strain, the stress effect cannot be represented by a unique function ϕ (σ) but is also implicit in S. This result has complicated the analysis for the effect of stress upon the creep rate.

During creep under cyclic stressing, recovery or softening of the material may occur during the period of the cycle when the stress is reduced. The manner in which recovery affects the creep rate must be investigated throughout the range of temperature of application of the material.

In order to make use of the basic information on creep, which is being obtained on a pure material, it will be necessary to investigate the effect of alloying additions in engineering materials on the basic factors involved in creep.

At the present time our program in the investigation of fundamentals of creep behavior includes studies of the following nature:

1. A study of the recovery of creep resistance in the cross-slip region of temperatures.
2. An investigation of the effect of stress changes in the cross-slip region of creep.
3. Research on the effect of alpha solid solution alloying on recovery.
4. A study of the effect of alpha solid solution alloying on the creep curve following a drop in stress.
5. A study of dislocation locking in alpha solid solutions of aluminum.
6. Research on the mechanism and rate of sub-boundary movement.
7. A study of the effect of stress increases on the permanent plastic straining during primary creep in the dislocation climb region.

The trend of work in the area of fundamental studies of creep behavior is oriented toward progressively more complex problems eventually to deal with engineering cases. The transition must be slow however so that we can carry the fundamental knowledge with us.

Since at best it may be quite some time before we have sufficient fundamental knowledge to be able to predict reliably the creep behavior of materials, most current designs consider the commonly available constant load-constant temperature creep information when it is necessary to consider the effects of time at elevated temperature. Even in the case of common test information, we are faced with a gap in the knowledge when it is necessary to design for extremely long life at elevated temperatures as is the case in supersonic transport aircraft, manned satellite systems, engines for sustained operation, etc. Practically all available creep information on materials of interest in the design of such systems is limited to information determined at times of 1000 hours and less. Since the acquisition of creep information for extremely long time periods, up to 30,000 hours and longer, is quite expensive and involves unacceptably long lead times for materials, it becomes necessary to develop a reliable method of predicting long time creep behavior of materials from relatively short time tests. Efforts in the past in extrapolation of long time creep data have involved: First, the use of fundamental knowledge to predict behavior, and second the use of various graphical presentations in the correlation and extrapolation of creep data. We have seen earlier that the state of the art in the fundamental knowledge has not advanced to the point where it may be used in the prediction of creep behavior of engineering materials. Most of the graphical methods of extrapolation which are based on a master curve associated with some time-temperature parameter fail in the extrapolation of long time creep data because they fail to consider materials instabilities.

Our Laboratory has initiated a program which by means of a phenomenological approach will develop an extrapolation method for predicting long time creep behavior which considers the various materials instabilities encountered in engineering alloys. The program will also include a study of the inherent scatter of creep deformation and rupture life data to establish the reliability of extrapolated data.

Stress-Relaxation

The characteristic of most metals to relax part of an applied load at elevated temperatures due to a form of creep has become a major concern to designers of high temperature systems. Phenomenologically, the process of stress-relaxation is explained as the conversion of the initial elastic strain in a material into irrecoverable strain of the same magnitude through inelastic deformation of the medium under decreasing stress. The reliable evaluation of the relaxation behavior is rather cumbersome because of the difficulty of applying initial strain rapidly enough to ensure elastic response and subsequently controlling the strain accurately enough during the test. Because of these difficulties and because of the relative simplicity of creep testing equipment it has been a widespread practice to interpret the relaxation characteristics of a material from creep data. The assumption is made that the inelastic strain, which is produced during a relaxation test, proceeds by the same mechanism as the creep test. Thus, neglecting the effect of creep-recovery, the rate of stress decay is expressed as:

$$\dot{\sigma} = - E \dot{\varepsilon}'' \qquad \text{Eq. (2)}$$

where

$\dot{\sigma}$ = time rate of change of stress

E = the elastic modulus

$\dot{\varepsilon}''$ = time rate of change of inelastic strain (which is a function of time, initial strain and stress)

Using this relation, the relaxation function σ (t) can be obtained by simple, though frequently cumbersome, integration.

Through our support, Professor Freudenthal analyzed the conventional approach to the conversion of creep data into relaxation data, and he demonstrated several discrepancies arising in this conversion with the aid of Eq. 2 (26). First, creep tests are practically always performed under constant load and therefore (because of lateral contraction accompanying extension) under slightly increasing true stress ("loading"), while stress-relaxation of course takes place under decreasing stress. In other words, creep in a crystalline aggregate proceeds under conditions of changing structure, while relaxation proceeds with practically no structural change. Therefore, part of the deformation process which occurs in the normal creep test is blocked because of the decreasing stress during relaxation ("unloading"). The temporary blocking of the creep rate by a decrease in stress has been confirmed experimentally by several investigators (27-29). As a result of this blockage, the use of converted creep rates will result in the prediction of higher relaxation rates than actually occur. A second discrepency arises from the use in the conversion process of the elastic compliance rather than the sum of the elastic and tangent compliance for a given strain on the true isochronous stress - strain diagram (not derived from creep data). A third discrepency arises from the neglect of the effect of creep-recovery in the conventional procedure.

Freudenthal has approached the problem of relaxation on the basis of an assumed ''mechanical equation of state'' leading to a four element non-linear viscoelastic model which is assumed to be the simplest possible representation of the stress-strain relation of a volume-constant material (30). In the case of linearized materials, the required elastic and viscous coefficients necessary to solve the model equations can be obtained from constant stress tests and directly applied to cases of continuously changing stress. In real non-linear materials the conversion procedure becomes more cumbersome. Experimental evidence has been obtained to illustrate the ability of the model to represent actual material behavior under linearly decreasing stress, constant stress and linearly increasing stress. Figure 9 shows the agreement between theory and experiment for 2024-T4 aluminum alloy tested at 375°F. This research is intended to establish a workable relation between the physically and mathematically simple condition of linear stress variation and the experimentally difficult condition of true stress-relaxation in which the strain has to be kept constant. Further, the effect of intermittent temperature, multidirectional stress and boundary conditions are to be studied.

Our Laboratory is performing an internal research study on relaxation behavior in support of the above work. A standard commercial relaxation testing machine has been modified to incorporate a specially designed precision extensometer capable of sensing and recording strains of the order of one micro-inch. Using this equipment, the stress-relaxation behavior of high purity recrystallized aluminum is being investigated in the temperature range of 75° to 200°F. The objective of the program is to evaluate the temperature dependence of the relaxation rate, and to compare the relaxation activation energy with activation energies obtained for creep of aluminum in the same temperature range. It is hoped that additional information on relaxation mechanisms will be learned.

Thermal Deflection and Buckling

The desire to operate flight vehicles at higher velocities has brought with it a host of new and complex problems to the structural designer and analyst, not the least of which is the introduction of the temperature parameter.

For example, aerodynamicists have shown experimentally and theoretically that a detached curved shock will always exist in the upper stream of a conventional wing with a round leading edge at all supersonic speeds. Down stream of the curved shock the flow is subsonic and may extend to the trailing edge. It is then evident that this subsonic flow will produce a great deal of drag, and it is the reason that supersonic wings are made comparatively thin with sharp leading and trailing edges, which in turn have given rise to new structural problems.

A second problem is the thermal heating of the structure due to aerodynamic friction, requiring that plastic flow and creep conditions be considered in the design.

Thirdly, non-uniform temperature distributions in the structure will cause thermal stresses in addition to the stresses from mechanical origin. A non-uniform temperature distribution may easily be developed in a structure as complicated as a flight vehicle wing even under uniform heating rates. This problem is more complicated in supersonic flight since leading edges of the wing are exposed to much higher rates of heating than the rest of the structure. Therefore, special attention has to be given to the structural design of the leading edges for supersonic flight.

Finally, the instability of the structure in the presence of thermal stresses has to be considered. For example compressive stresses will always be developed in a panel or shell under non-uniform temperature distribution even if it is not supported. Instability of the structure will reduce the overall strength but may not yield the overall collapse because of the additional constraints. However, the buckling of the external surface of a flight vehicle will reduce the aerodynamic performance due to waviness which of course is not desirable.

In order to overcome difficulties mentioned above the structural designer has to make the best choice of available materials for various operational conditions, and materials specialists must continue to develop new materials with emphasis on better high temperature characteristics. Another line of attack is to find the best combination of different materials to form an integral unit to partly satisfy all the required conditions. For this purpose sandwich panels have been used in elevated temperature, high strength and high stiffness applications for various flight vehicles. Their light core reduces weight and increases stiffness properties compared to any high strength sheet material construction. Furthermore, better performance could be obtained from sandwich panels if their faces are chosen of different materials and thicknesses.

Unfortunately, presently available sandwich panel theories can not be used for arbitrary temperature distributions and dissimilar face materials. For this reason, a general small deflection theory for a sandwich panel with an orthotropic weak core has been developed as an internal research program in our Laboratory and has been applied to various practical problems (31). It is shown that general thermoelastic equations for a sandwich panel consist of five differential equations in terms of the displacements of faces and appropriate boundary conditions. These equations have been reduced to the solutions of two independent systems of equations, with a suitable transformation of the unknown functions. These equations are shown in figure 10 in generalized form. The explanation of notations are omitted here but fully explained in reference (31). One of the systems consists of two differential equations, and its solution determines the components of the stresses in the plane of the panel. A second system consists of three differential equations and their solutions determine the deflections and corresponding displacements. The latter differential equations can be reduced to the equations derived by Reissner (32), Hoff (33) and Chang - Ebcioglu (34) under particular assumptions.

Other research supported by our Laboratory has been centered on the use of short-time buckling theories for predicting creep buckling failures of longer time duration through the use of more abundant short time data. It has been found that end shortening measurements, heretofore generally neglected in most other investigations, are significant for relating the creep buckling behavior of columns to the creep properties of the column material (35). Center lateral deflection measurements also exhibited a definite relationship with failure time data. It is now considered possible to extend short time theory to creep buckling by considering the strain value corresponding to the short time buckling stress as the critical strain in creep buckling (36). In general, additional improved analytical techniques for describing and predicting elevated temperature structural behavior are needed.

In discussing brittle behavior it must be kept in mind that there is no universally acceptable definition for such behavior and the identification of "brittle fracture" must be made for each particular case under consideration. This implies that there are many factors which influence the extent to which a fracture is brittle. These factors range from a minute consideration of the mechanics of microcrack nucleation to the more gross consideration of continuous stress state. If a careful examination is made, it is generally possible to associate with "brittle fracture" some degree of yielding or plastic flow. Under these conditions it is not unreasonable to study and define "brittle fracture" as it competes with plastic flow. Our programs then are aimed toward identifying some of the factors which influence "brittle behavior" and explaining how these factors contribute to "brittle behavior" separately or in combination. They are primarily concentrated on three categories of materials - high strength to weight metals, refractory metals and ceramic type materials. The types of approaches being used are to study external parameters which induce brittleness such as state of stress, chemical environments, and low temperatures, and also internal material parameters such as grain size, impurity content, and dislocation interactions, as they effect brittle behavior in both metals and ceramics.

State of Stress

One of the first factors recognized to contribute to the embrittlement of metals was the effect of stress state. Many investigators have studied the effects of stress state as induced by notches, on the fracture of metals but, as yet, these effects on the strength properties of a metal part are only partially recognized.

A theory of brittle failure that is now well known and universally recognized was developed 40 years ago by Griffity (37). The Griffity crack concept, originally proposed for the failure of glass, has since been modified by Orowan and Irwin and his co-workers (38), to apply to structural metals. The Griffity-Irwin theory, however, applied only to sharp cracks and has no bearing on the behavior of a material in the presence of a stress concentration of a definite magnitude. Therefore, in order to better understand the nature of fracture of engineering materials in the presence of mechanical notches a program supported by our Laboratory has been underway to study the effect of stress state on the strength properties of sheet materials (39).

The primary purpose of this program was to study the principal factors known to affect the strength of sheet materials in the presence of stress concentrations as caused by notches. These principal factors are the strength level of the material, and the stress distribution along the notched cross section. Significant in this study was the fact that the stress concentration factor calculated according to Neuber-theory was held constant. On the other hand, a variable which has received little consideration in previous studies, the stress gradient, has been varied for different notch depths and section widths. The stress gradient at the root of the notch was determined analytically from the notch geometry according to elastic theory.

The results of tests on an extremely brittle titanium sheet alloy indicated that the stress gradient is the predominant factor that influences notch strength. For a truly brittle material, it appears that the stress concentration factor, the depth of a notch, and the specimen width are significant only insofar as they contribute to the magnitude of the stress gradient and the maximum stress at the notch root. This is illustrated in figures 11 and 12.

As a result of these findings further studies are being conducted to determine the effect of stress gradient on the strength of brittle sheet materials.

The results of these studies are hoped to contribute to the understanding of the effects of strain state and stress gradient on the fracture of both brittle and ductile materials.

In this area of investigation another program is being conducted to study fracture initiation in notched tensile specimens. The effect of notch severity and grain size on the flow pattern in notched sheet tensile specimens of commercially pure molybdenum are being studied. Zones of initial yielding and patterns of plastic flow accompanying fracture are being analyzed as an elastic-plastic interface in order to ellucidate the location and mode of fracture initiation.

Stress Corrosion Cracking

Included in the subject of brittle behavior in materials is the area of environment induced brittleness. By environment induced brittleness we mean the apparently brittle failures which occur in normally ductile metals in the presence of a chemical environment. These failures usually occur as delay type failures when the metal is under applied stress in the environment. Included in this area are the subjects of hydrogen embrittlement, surface absorption, liquid metal embrittlement, and stress corrosion cracking.

Although all of these causes of embrittlement are important, the area of stress corrosion cracking is probably the most troublesome at present, in terms of failures in flight vehicle structures.

Although the phenomenon of stress corrosion cracking has been with us for the past 50 years, we still know very little about the basic nature of stress corrosion cracking. In order better to understand the effects of certain environments on various structural materials and their related mechanisms several research programs are underway.

In laboratory tests, titanium alloys have been found to be susceptible to stress corrosion at temperatures between 550°F and 900°F and under stress in the presence of inorganic chloride salts. Limited experience in the laboratory suggested that other metallic materials such as nickle, cobalt-base alloys, and aluminum may also be susceptible to this type of corrosion. The purposes of the program (40) were: (a) to learn more about the chloride salt stress corrosion of titanium alloys with particular emphasis on how the protective character of the oxide film is lost; and (b) to explore the susceptibility of representative jet aircraft structural materials to elevated-temperature stress corrosion in the presence of chloride salt, and jet engine fuel or fuel residue.

In regard to the elevated-temperature chloride salt stress-corrosion of titanium alloys, experiments were conducted to determine whether the protection of the oxide film is lost by direct chemical reaction, or by dissolution, i.e., oxygen diffusion into the base metal. These experiments showed conclusively that film protection is lost not by dissolution but by chemical reaction of the chloride salt with TiO_2.

Several of the alloys investigated were found to be sensitive to stress corrosion cracking in the presence of a salt environment, at both room and elevated temperatures.

No detrimental effects of any of the test materials were found in the presence of JP-4 fuel, tested either in tension static fatigue at room temperature or in elevated-temperature creep tests.

As a result of these findings, further studies are being conducted in order to determine the basic nature of the stress corrosion failures in the alloys investigated.

Before completely satisfactory solutions to stress corrosion problems in the field can be obtained, a basic understanding of the mechanisms and causes of stress corrosion must be obtained. In this light, another more basic research program has been undertaken under our sponsorship. The purpose of this program is to determine the mechanism of stress corrosion cracking in face-centered-cubic metals. In this program ternary iron-nickle-chromium alloy single crystals are being investigated. The stress-corrosion susceptibilities of these austenitic single crystals will be correlated with strain-rate-sensitivity measurements as a function of composition. It is hoped that the strain rate dependency of yielding can be expressed directly in terms of dislocation velocities. The long term problem is to elucidate mechanisms which can give reduced dislocation velocities, and to see whether low velocities correlate with stress corrosion susceptibility.

Ductile Brittle Transition

At elevated temperatures, the usefulness of a material usually is limited either by strength considerations or by oxidation protection problems. However, if the material is used at low temperatures, or is subjected to a multiaxial stress system, it may display a pronounced tendency toward brittle behavior. Usual design criteria cannot predict failure adequately under these conditions. The classic example is the catastrophic failure of Liberty ships during World War II when the calculated stresses were far below usual design limitations. The normally ductile structural steels used in these ships became quite brittle when under the combined effects of low temperatures and multiaxial stress systems. The refractory metals, in fact all body-centered-cubic metals, tend to exhibit this marked decrease in ductility and susceptibility to cleavage fractures at low temperatures. Therefore, the theoretical knowledge gained in the investigation of the brittle failure of steels can profitably be applied to the fracture study of the refractory metals.

One such program which we have (41), utilizes notched and unnotched tensile tests to explore the ductile to brittle transition temperature of the refractory metals tungsten, molybdenum, columbium and tantalum. These metals have been studied in the wrought and recrystallized condition over a total temperature range covering the ductile-brittle transition and are now being studied as a function of interstitial content. From these tests, relations such as are illustrated in figures 13 and 14 can be determined. These figures indicate the very broad temperature range, within which the refractory metals display a transition characteristic. By making strength and ductility measurements, and fracture appearance observations as a function of such variables as temperature, stress concentration factor, strain rate etc. a relatively quick, general and practical definition of ductile to brittle transition can be established.

While the above approach provides a broad view of the transition characteristics of the refractory metals and gives qualitative agreement with fracture mechanics, a more refined and concentrated study is needed to understand the contributions which metallurgical variables are making in the ductile to brittle transition. To do this a more basic approach has been adopted, with dislocation theory providing the basis for the fundamental studies. In these studies Petch (42) and Cottrell (43) models, describing transition behavior, are used to study the various microstructural variables. Investigations, using such models, are being carried out in order to answer such questions as; why tantalum is resistant to brittle fracture while tungsten is not. Continuation of this line of approach should provide some basis for control of brittleness in refractory metals and their alloys.

The strain aging tendencies of columbium are being investigated (44) using yield point return and dynamic modulus measurements to study the aging process, as a function of hydrogen content. Comparison of activation energies for strain aging with those for interstitial diffusion revealed that hydrogen could be responsible for dislocation locking in columbium at low temperatures. The temperature dependence of the yield point and dynamic modulus recovery was found to be adequately expressed by an Arrhenius type rate equation. The activation energies found by the yield point and dynamic modulus recovery techniques bracketed that of 9,370 cal/mol given by Albrecht for diffusion of hydrogen in columbium. In order to obtain a measure of the degree of dislocation locking as a function of hydrogen content, the tensile lower yield stress of columbium was determined as a function of grain diameter using constant strain rate and test temperature. The locking strength, was found to increase with increasing hydrogen content. In further work on columbium the strain rate and temperature dependencies of low temperature deformation behavior of fine grain columbium were investigated. An apparent activation energy of 8300 cal/mol for the early stages of low temperature deformation indicates that stress induced diffusion of hydrogen may be the rate controlling mechanism of the early stages of low temperature deformation of columbium. Increasing the strain rate causes a decrease in the ductile-to-brittle transition temperature of fine grained arc melted columbium, for constant hydrogen content. This decrease in transition temperature may be due to slow strain rate hydrogen embrittlement. Raising the hydrogen content of columbium causes a measurable increase in the ductile-to-brittle transition temperature and also has slight solid solution strengthening effects.

The conclusions of the above work indicate that a hydrogen-dislocation interaction can influence the mechanical behavior of columbium at low temperatures.

Ceramic Materials

A large effort, which is centered around single and polycrystalline Al_2O_3 and MgO, is being devoted to the study of brittle behavior of ceramic materials (45). The program is designed to give consideration to the many factors which contribute to brittle fracture and the mechanisms which can be controlled to introduce plastic behavior. Because of the broad scope of this program only a superficial treatment will be given in order to bring out the salient features of the approach.

The program is broken down into eleven different areas of investigation. Several of these areas will be briefly outlined below:

Static Fatigue: Delayed Fracture

A study is being made of the corrosion processes which may be of importace in controlling the long-term strength of single crystals of Al_2O_3 and MgO, and polycrystalline aggregates of these oxides. It is desired to obtain information on the identity of the corrosion reactions, their mechanisms, and their effect on the rupture strength of these ceramics.

Internal Friction Studies

This study seeks to determine the effect of defects and vacancies upon the fracture dyamics of brittle materials. This aim is to be accomplished by mechanical loss measurements (damping), in order to correlate them with dynamic effects occurring during defect motion.

Effect of Microstructure

The success of current theories by Stroh, Cottrell, Petch, and others dealing with the atomic mechanism of cleavage fracture in metallic lattices has promoted an extension of this thinking to a study of fracture behavior in ceramic materials. This approach is being used to study the deformation behavior of polycrystalline alumina and magnesia. This work will study the influence of grain size on yield and fracture strength over a temperature range covering both ductile and brittle behavior.

Effect of Impurity Content

Work is being directed toward the understanding of the effect of impurities on the mechanical properties of alumina and magnesia. Impurities will be introduced into the polycrystalline alumina and magnesia by two methods: either by adding them to the starting powder, or by diffusing them into the finished specimens from the outer surface. The mechanical properties will then be evaluated as a function of impurity content.

Effects of Structural Size

This area seeks to resolve the problem of the effect of structural size upon the fracture strength of brittle materials. The approach to the solution is based on Weibull's "Statistical Theory of Failure". The work consists of studying the fracture characteristics of two grades of Al_2O_3 and MgO at various temperatures and atmospheric conditions. The statistical failure variability will be obtained from testing identical specimens. The size effects will be observed from experiments using specimens of similar geometrical shape by varying size. The purpose is to obtain an insight into the effects of varying conditions and size on the fracture strength. An attempt will be made to formulate a design equation for service application of brittle materials from the empirical constants determined during the course of this work.

The above abstracts of work in the ceramic area are supplemented by other studies dealing with such subjects as effect of thermal-mechanical history, effect of strain rate, effect of non-uniform stress fields, effect of surface energy, surface active environments, and fracture mechanisms.

Summary

The material presented in the foregoing sections has by no means covered completely the area of mechanical behavior, nor have those aspects treated here been given a full measure of attention. Time and space limitations of course prevent a full treatment. We hope, however, that we have successfully and effectively underlined the point that our advancing aerospace technology has forcibly established and defined imposing performance requirements for materials development and their proper use in present and planned aerospace enterprises. The fact has become quite clear that we can no longer study phenomena singly and out of context and expect a total solution by merely summating the individual effects. It seems imperative to study materials characteristics in their relationship with one another in order to understand their total nature and response to a set of environmental circumstances.

In reviewing areas in which additional work is needed for the future, one could easily generate a list of research without an end. However, from a weapon systems development point of view, we feel there are certain gaps in our knowledge of materials behavior which warrant particular attention at the moment. Some of these areas are enumerated as follows, although again, we are not all inclusive here:

1. Development of improved observational techniques such as x-ray and electron microscopy, etc., for observations of mechanisms.

2. Additional research on the mechanisms of fatigue and creep geared mainly toward the interpretation of these phenomena in terms of bulk behavior.

3. Research on corrosion-fatigue from a basic electro-chemical and physical viewpoint as opposed to a test data correlation procedure.

4. Expansion of research on spatial and temporal pressure and stress correlations across structural airframes leading ultimately to reliable scaling laws.

5. Additional research on the chemistry of viscoelastic materials aimed specifically at optimum dynamic mechanical properties over broad temperature and frequency bands for energy dissipation purposes.

6. Investigation of viscoelastic materials subjected to thermal gradients with particular reference to the physical properties. Modification and improvement of design procedures under extreme thermal conditions.

7. Development of non-linear viscoelasticity theory with particular emphasis on the stress-strain relations and their application to structural design problems.

8. Research on non-linear theory of elasticity, with reference to shells, and application to stability problems in composite structures.

9. Development of "equivalent damage level" load spectra to simplify random loading problems (this requires both statistical and experimental input).

10. Additional studies of long time temperature and strain effects on structural materials properties.

11. Research on plasticity theory which takes into account the thermal stresses due to non-uniform temperature, fields and improvement of concepts of design to account for thermal stress gradients.

12. Research on aerothermoelastic effects on high speed flight structural components by considering them a combination of aeroelasticity and thermoelasticity.

13. Research on stress-corrosion, directed particularly along fundamental lines, in order to support solutions of problems on sound metallurgical bases rather than apply stop-gap measures such as shotpeening, anodizing, stress-relief or redesign.

14. Research designed to elucidate the influence of microstructural variables on fracture behavior of materials with particular emphasis on understanding the complex fracture problem in engineering materials as compared to pure model materials.

15. Additional research in the general area of the anelastic behavior of materials including delayed yielding, elastic after effects, internal friction, stress-relaxation, etc.

16. Development of new techniques for measuring deformation behavior of metals, including notch root strain rates, high temperature strain, etc.

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STRESS RANGE DIAGRAM FOR 6.3% Mo - WASPALOY
at 1500°F

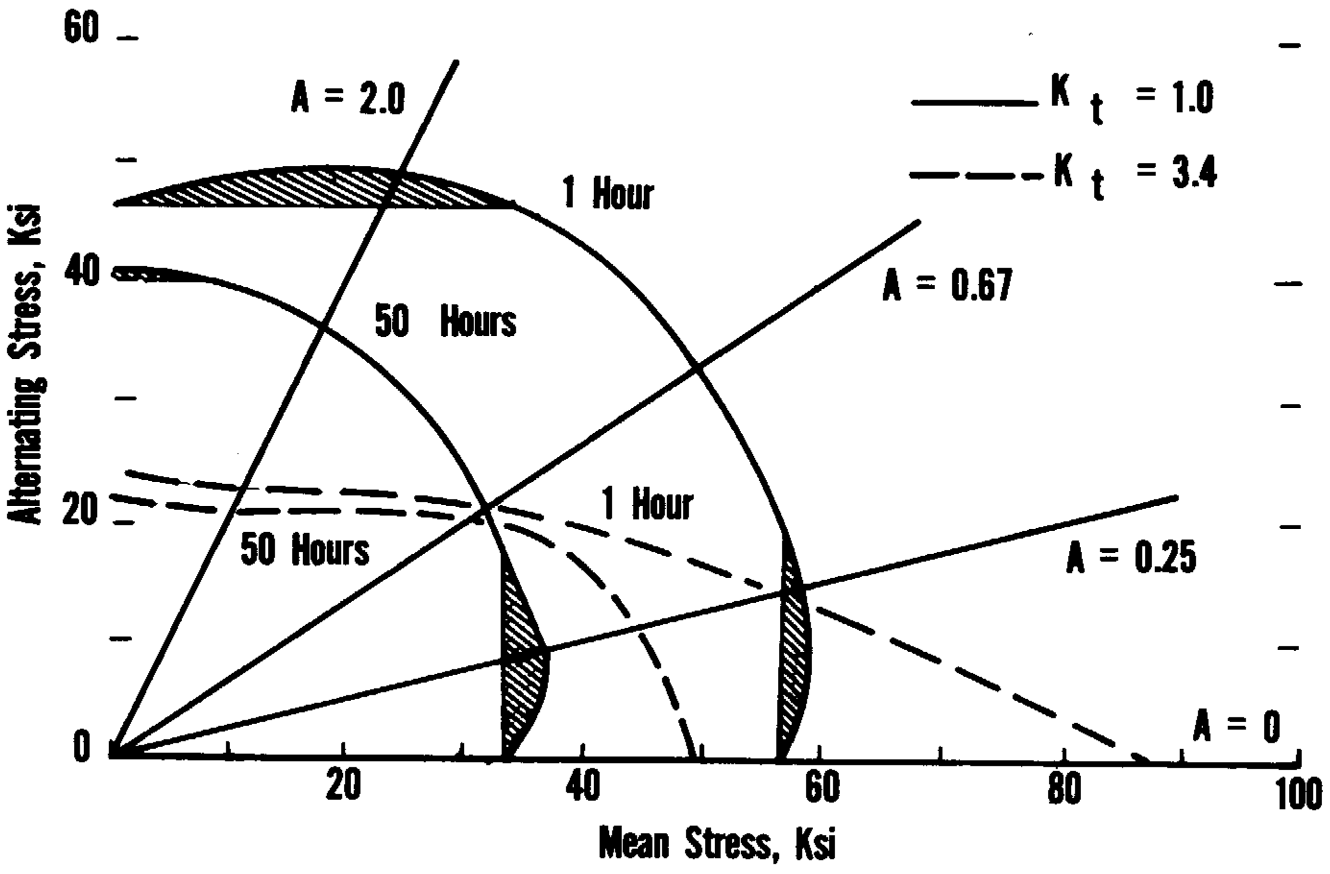


Figure 1.

ACOUSTICAL FATIGUE FAILURES

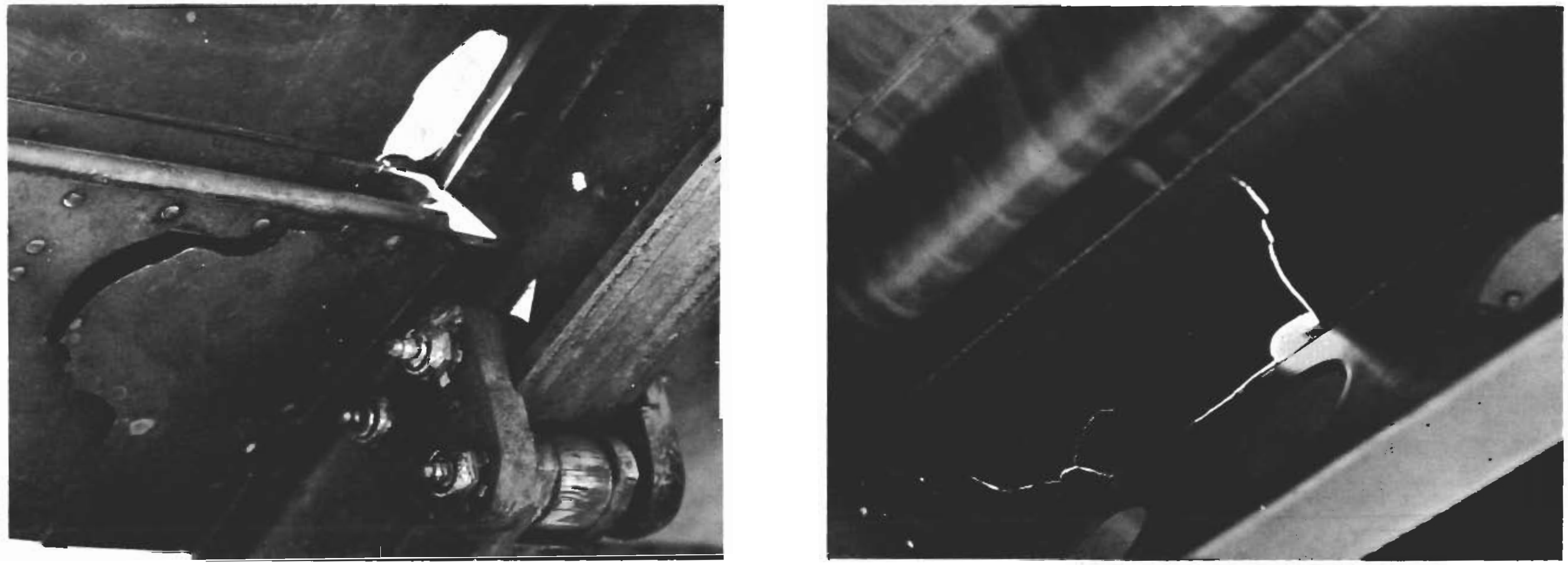


Figure 2.

TYPICAL SOUND PRESSURE - FREQUENCY SPECTRA

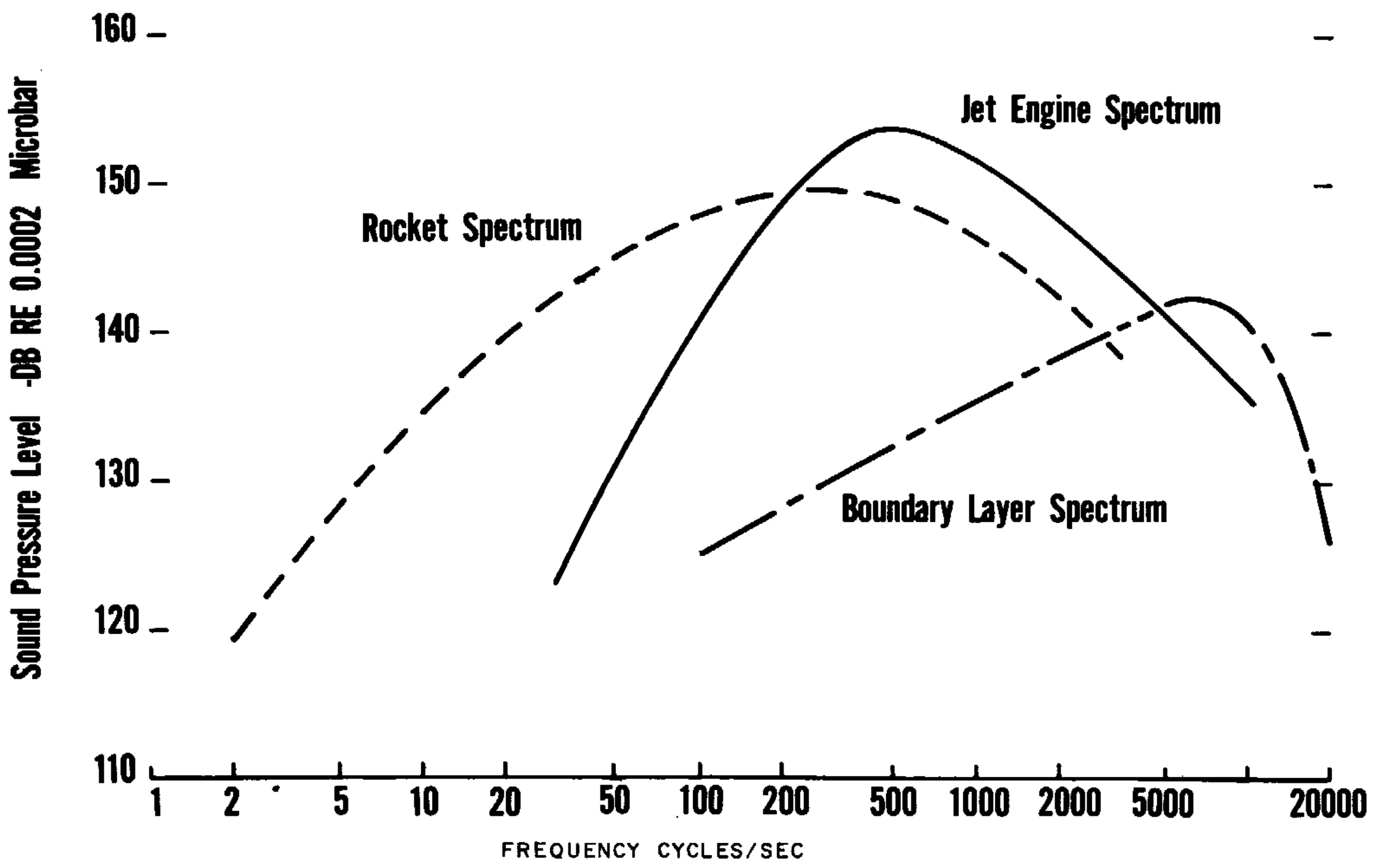


Figure 3.

ACOUSTIC POWER LEVELS FOR F-100 AIRCRAFT IN FLIGHT

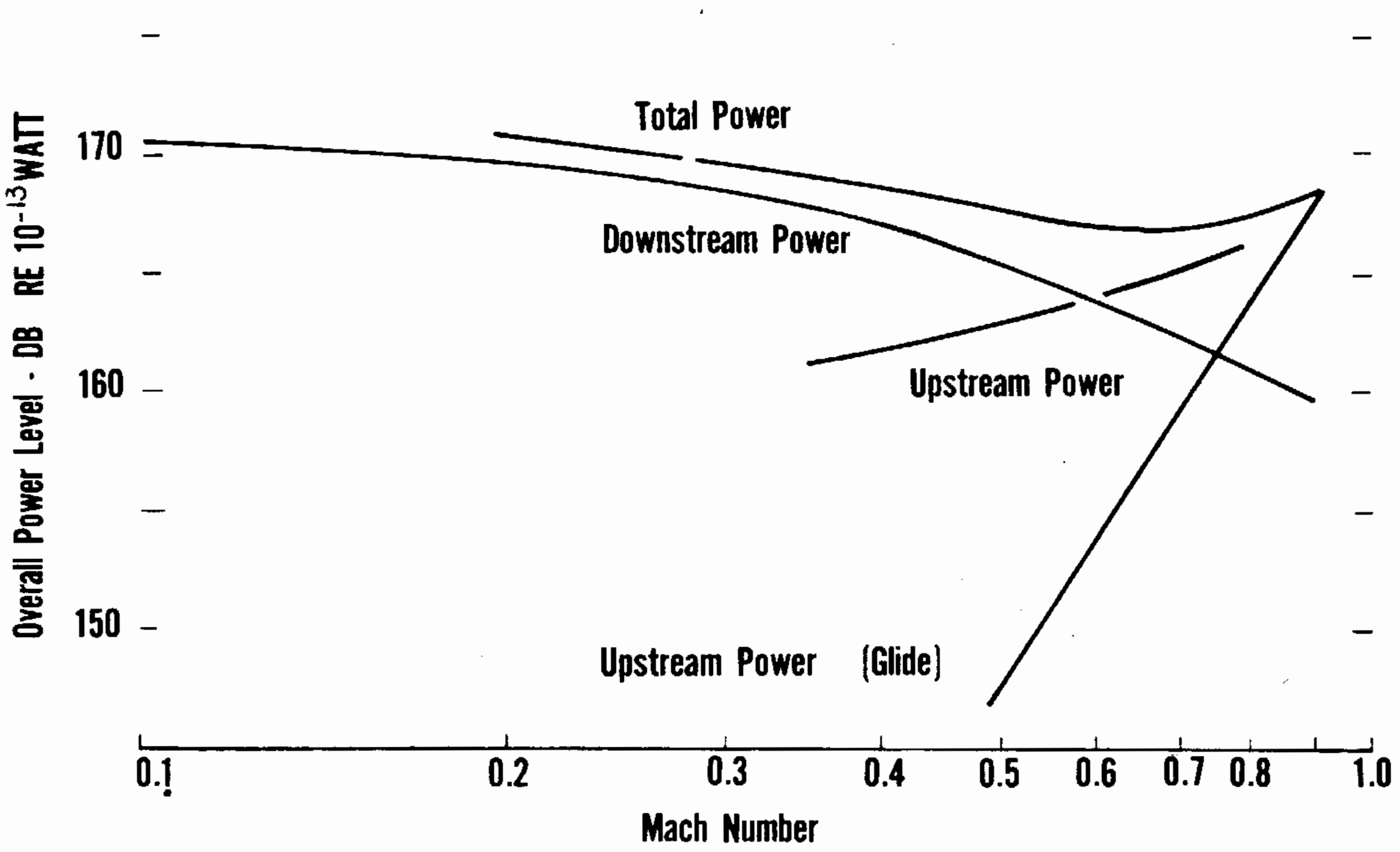


Figure 4.

EXAMPLES OF CONFIGURATIONAL DAMPING

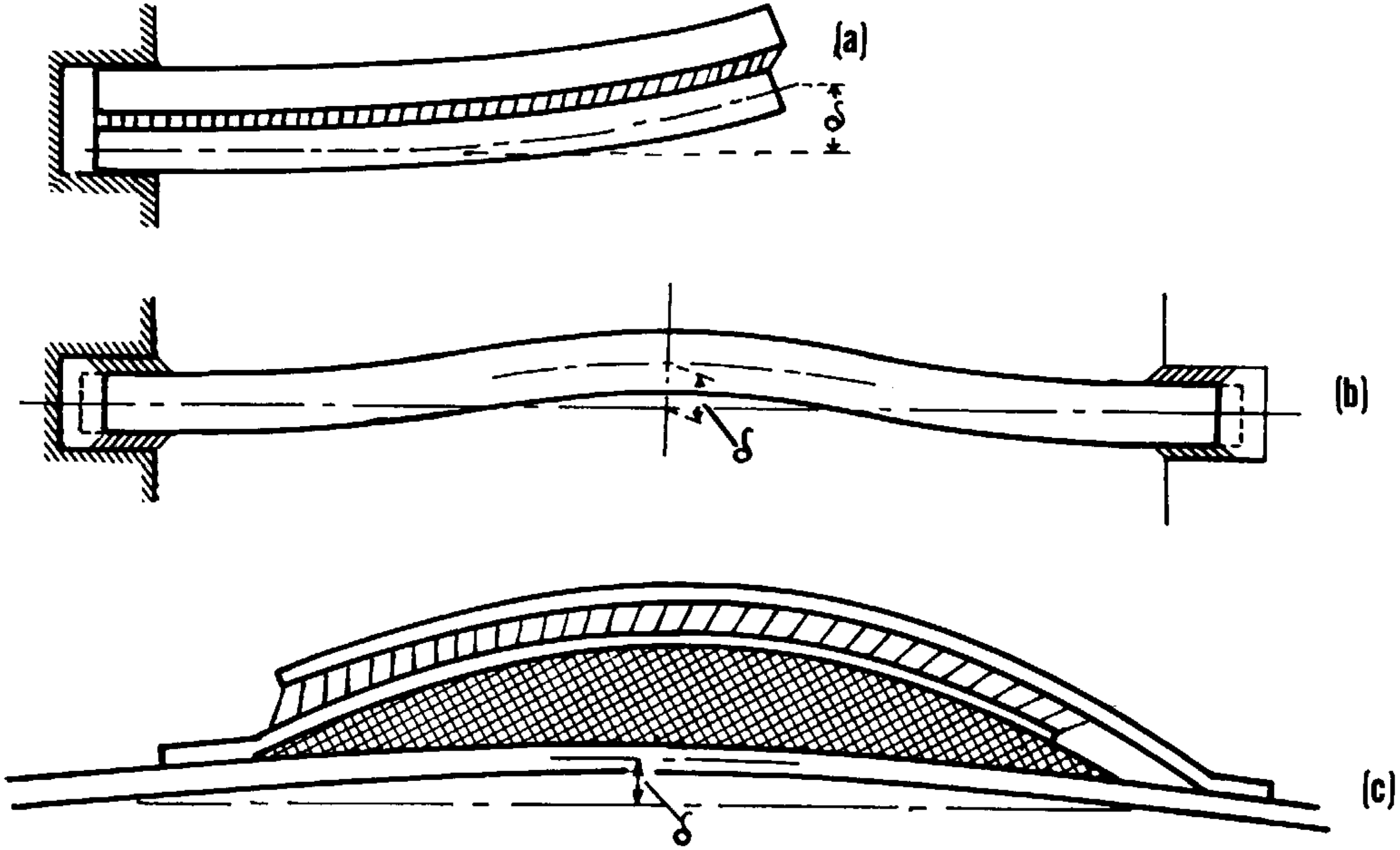


Figure 5.

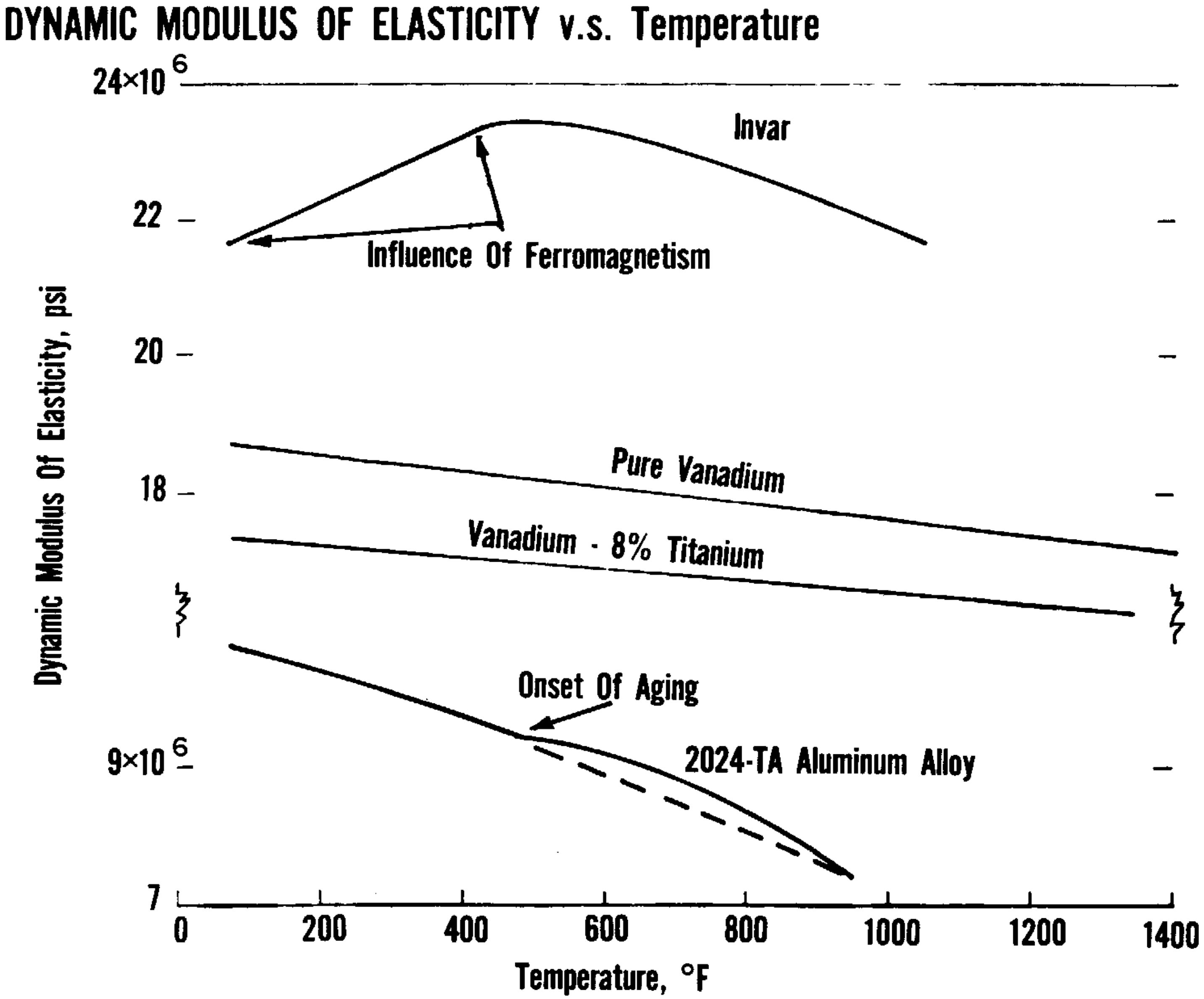

DYNAMIC MODULUS OF ELASTICITY v.s. Temperature
Dynamic Modulus Of Elasticity, psi
24×10^6
22
20
18
9×10^6
7
0
200
400
600
800
1000
1200
1400
Temperature, °F
Invar
Influence Of Ferromagnetism
Pure Vanadium
Vanadium - 8% Titanium
Onset Of Aging
2024-TA Aluminum Alloy

Figure 6.

TRUE RANDOM FATIGUE LIFE AS FUNCTION OF LINEAR LIFE

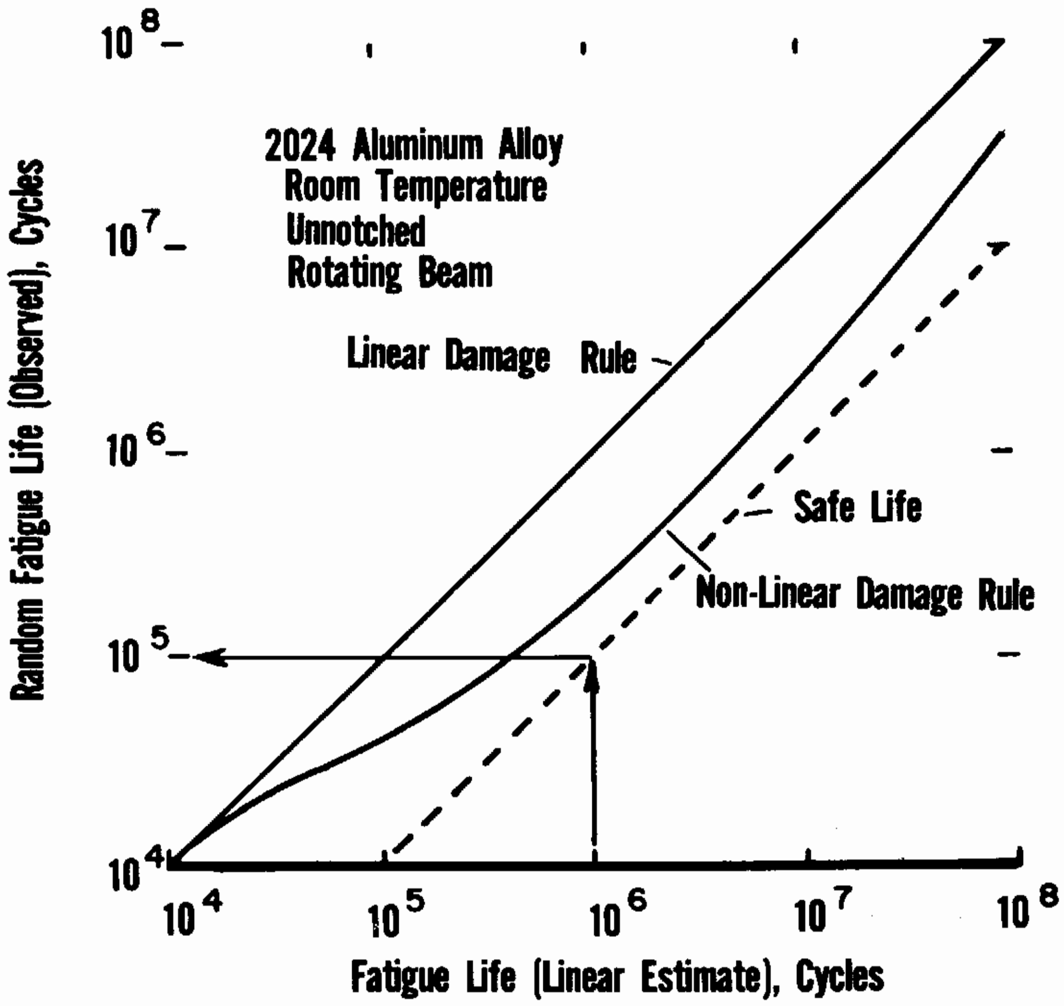


Figure 7.

ACTIVATION ENERGIES v.s. TEMPERATURE FOR PURE ALUMINUM

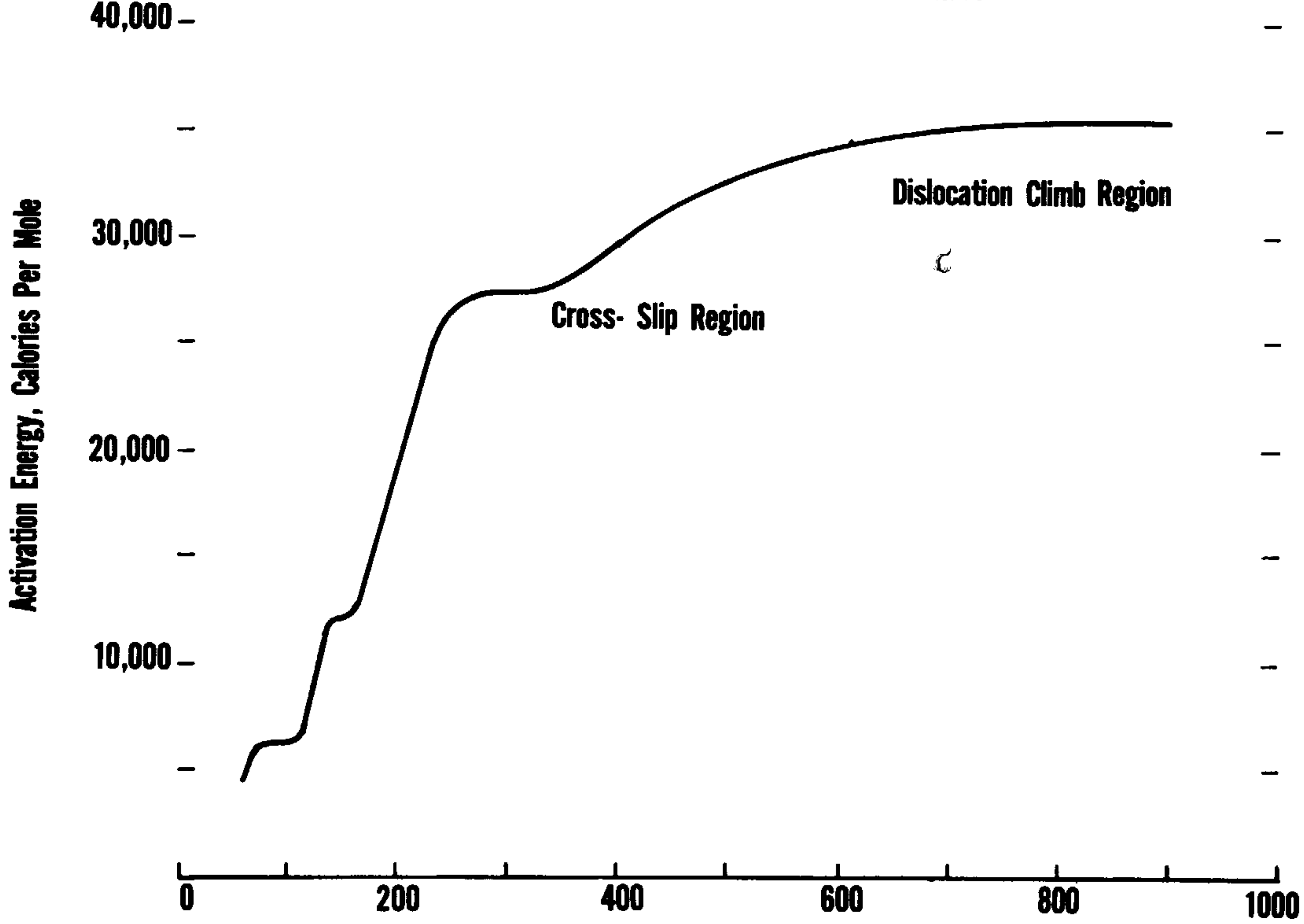


Figure 8.

STRAIN - TIME CURVES FOR 2024 - T 4 ALUMINUM

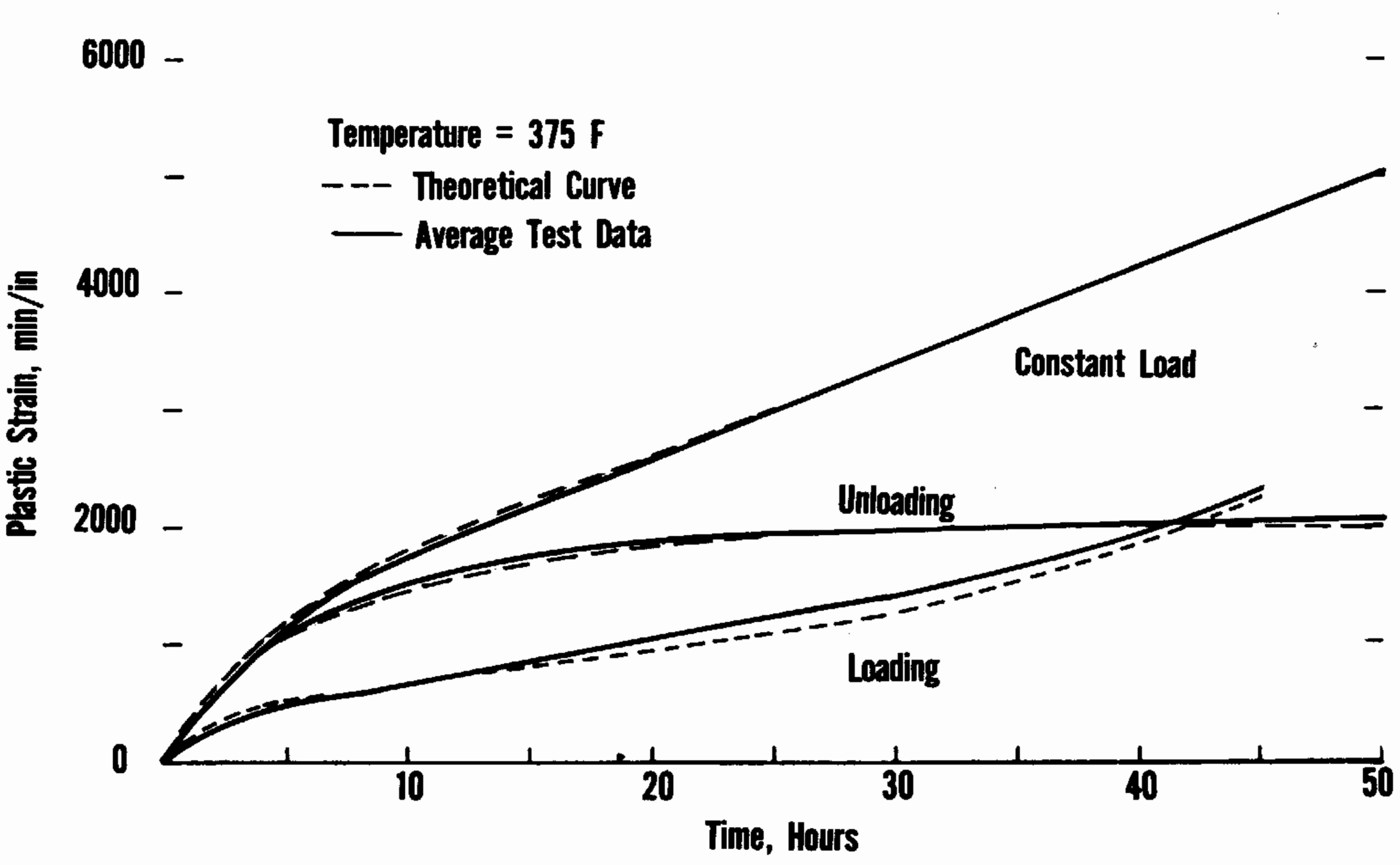


Figure 9.

DIFFERENTIAL EQUATIONS

$$\frac{(1+m)E't'}{2m(1-\mu^2)}\left[2\bar{u}_{,xx}+(1-\mu)\bar{u}_{,yy}+(1+\mu)\bar{v}_{,xy}\right]=\frac{1}{1-\mu}\left(E't'\alpha'T'+E''t''\alpha''T''\right)_{,x}$$

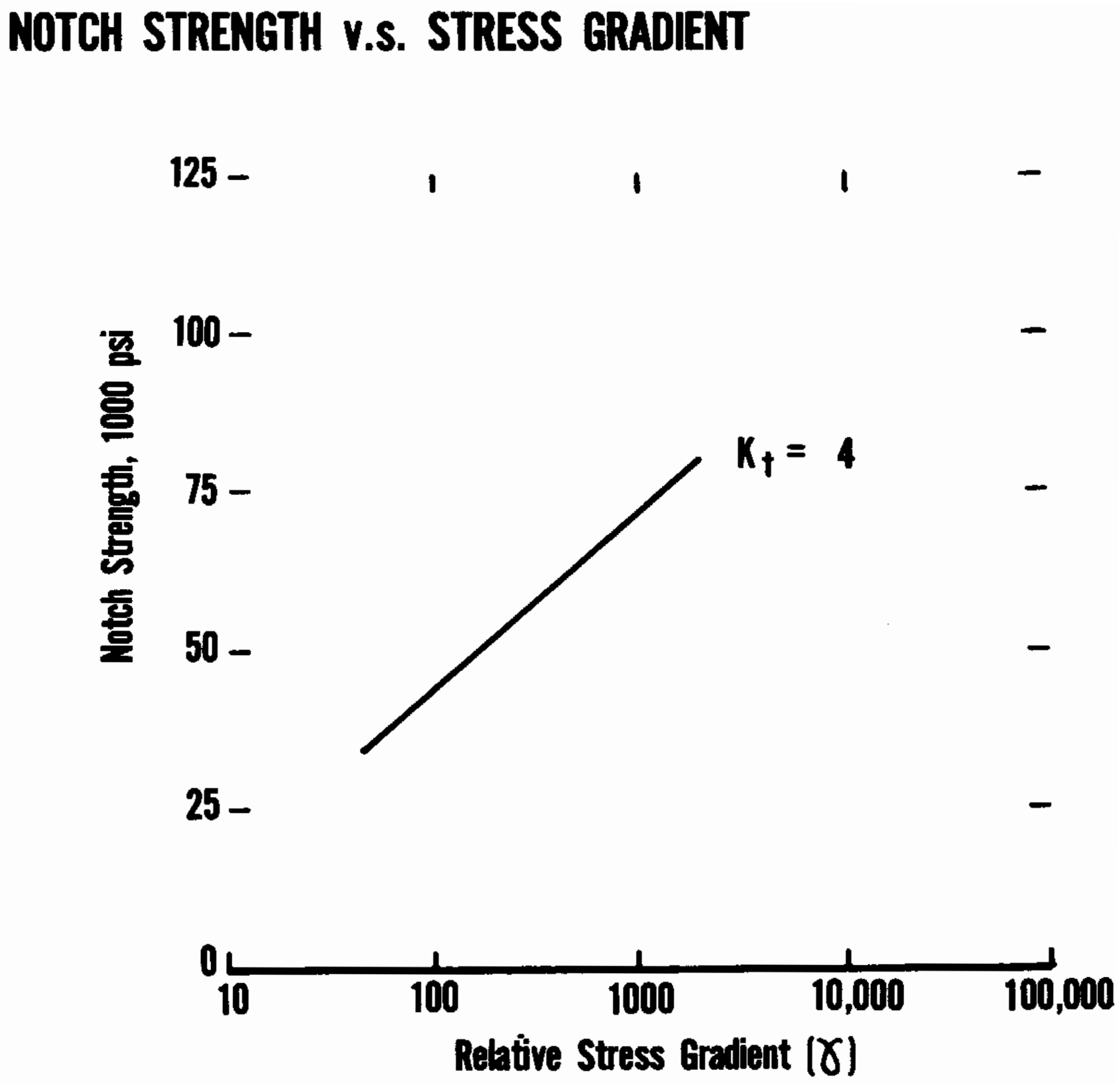
$$\frac{(1+m)E't'}{2m(1-\mu^2)}\left[2\bar{v}_{,yy}+(1-\mu)\bar{v}_{,xx}+(1+\mu)\bar{u}_{,xy}\right]=\frac{1}{1-\mu}\left(E't'\alpha'T'+E''t''\alpha''T''\right)_{,y}$$

$$\frac{(1+m)E't'}{2m(1-\mu^2)}\left[2u_{,xx}+(1-\mu)u_{,yy}+(1+\mu)v_{,xy}\right]-\frac{1+m}{\bar{t}}\bar{H}_x\left(\frac{1+m}{m\bar{t}}u+\hat{t}\,w_{,x}\right)=\frac{E't'}{1-\mu}\left(\alpha'T'-\alpha''T''\right)_{,x}$$

$$\frac{(1+m)E't'}{2m(1-\mu^2)}\left[2v_{,yy}+(1-\mu)v_{,xx}+(1+\mu)u_{,xy}\right]-\frac{1+m}{\bar{t}}\bar{H}_y\left(\frac{1+m}{m\bar{t}}v+\hat{t}\,w_{,y}\right)=\frac{E't'}{1-\mu}\left(\alpha'T'-\alpha''T''\right)_{,y}$$

$$-\frac{E't'^3+E''t''^3}{12(1-\mu^2)}\nabla^4 w+\hat{t}\,\bar{H}_x\left(\frac{1+m}{m\bar{t}}u_{,x}+\hat{t}\,w_{,xx}\right)+\hat{t}\,\bar{H}_y\left(\frac{1+m}{m\bar{t}}v_{,y}+\hat{t}\,w_{,yy}\right)+N_{xx}w_{,xx}+2N_{xy}w_{,xy}+N_{yy}w_{,yy}+q'+q''=\nabla^2(M'+M'')$$

Figure 10.



NOTCH STRENGTH v.s. STRESS GRADIENT

Figure 11.

NOTCH STRENGTH v.s. NOTCH DEPTH

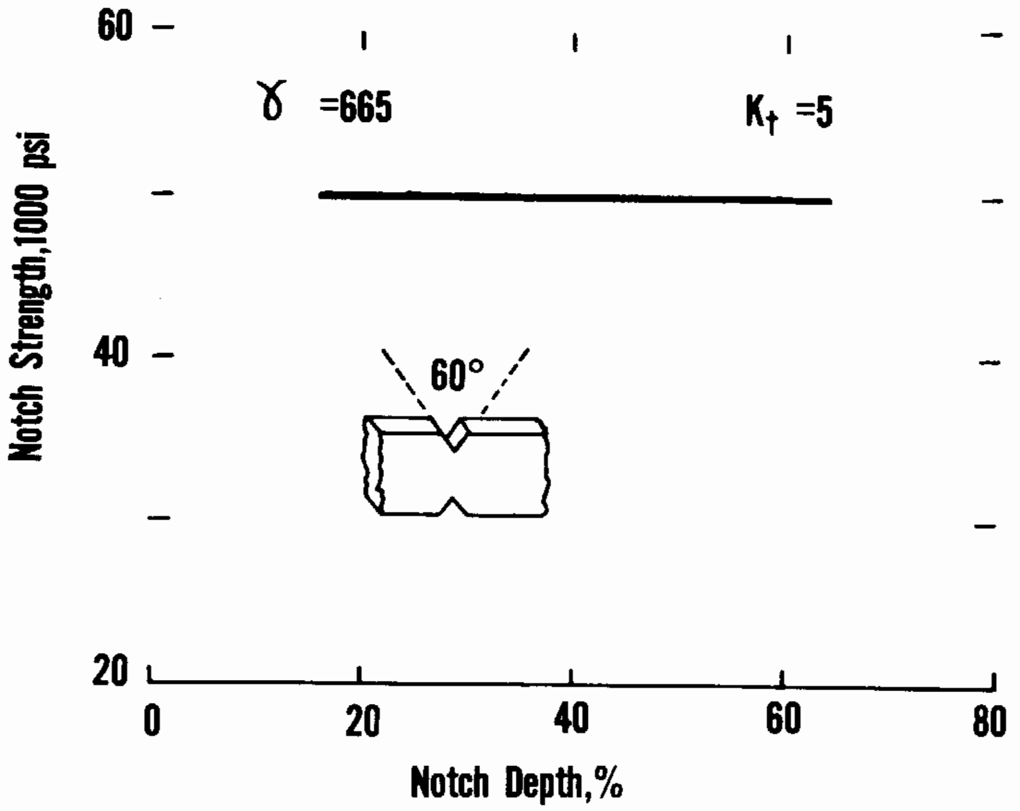


Figure 12.

NOTCH-UNNOTCH STRENGTH RATIOS FOR THE RECRYSTALLIZED MATERIALS

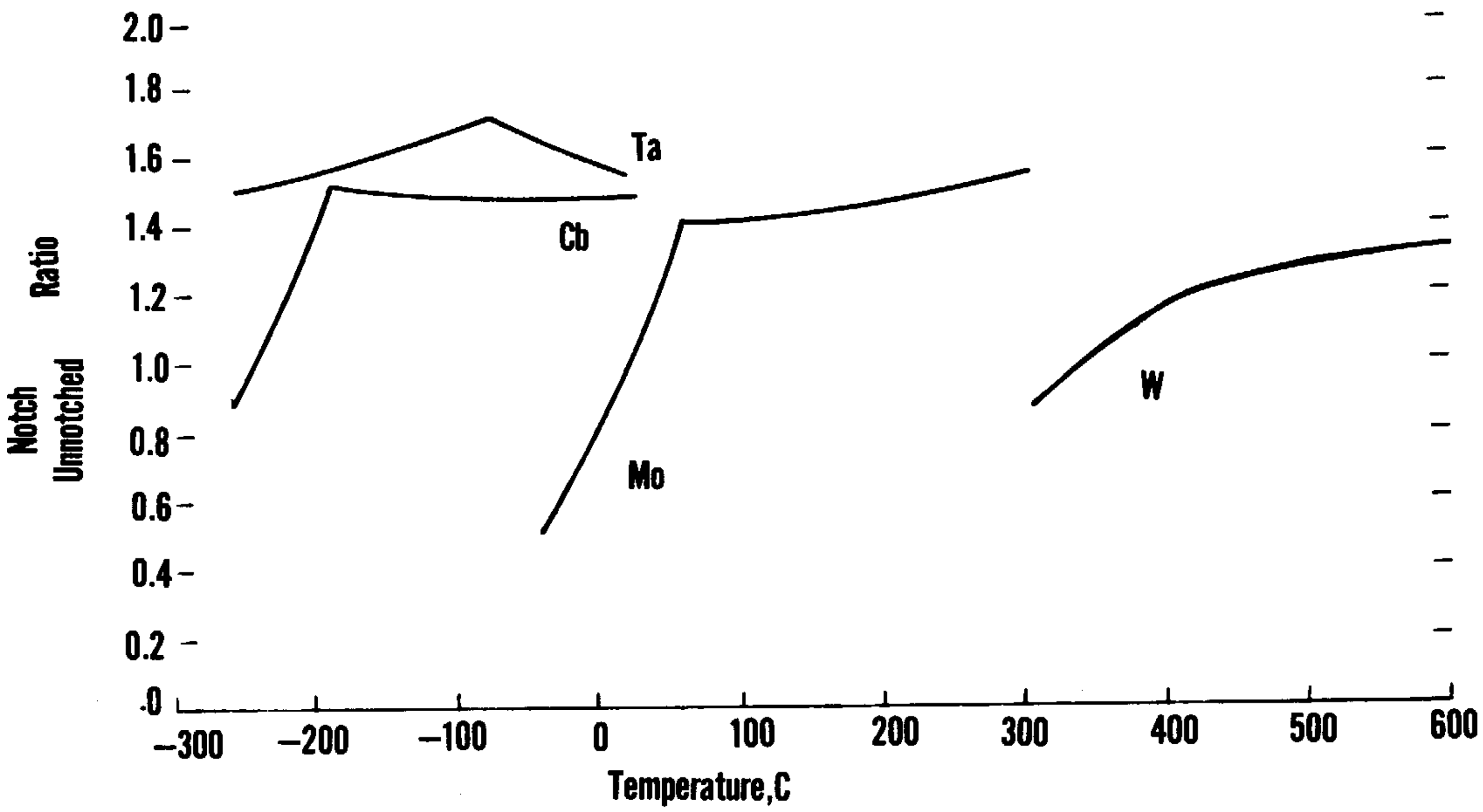


Figure 13.

DUCTILITY FOR RECRYSTALLIZED MATERIAL

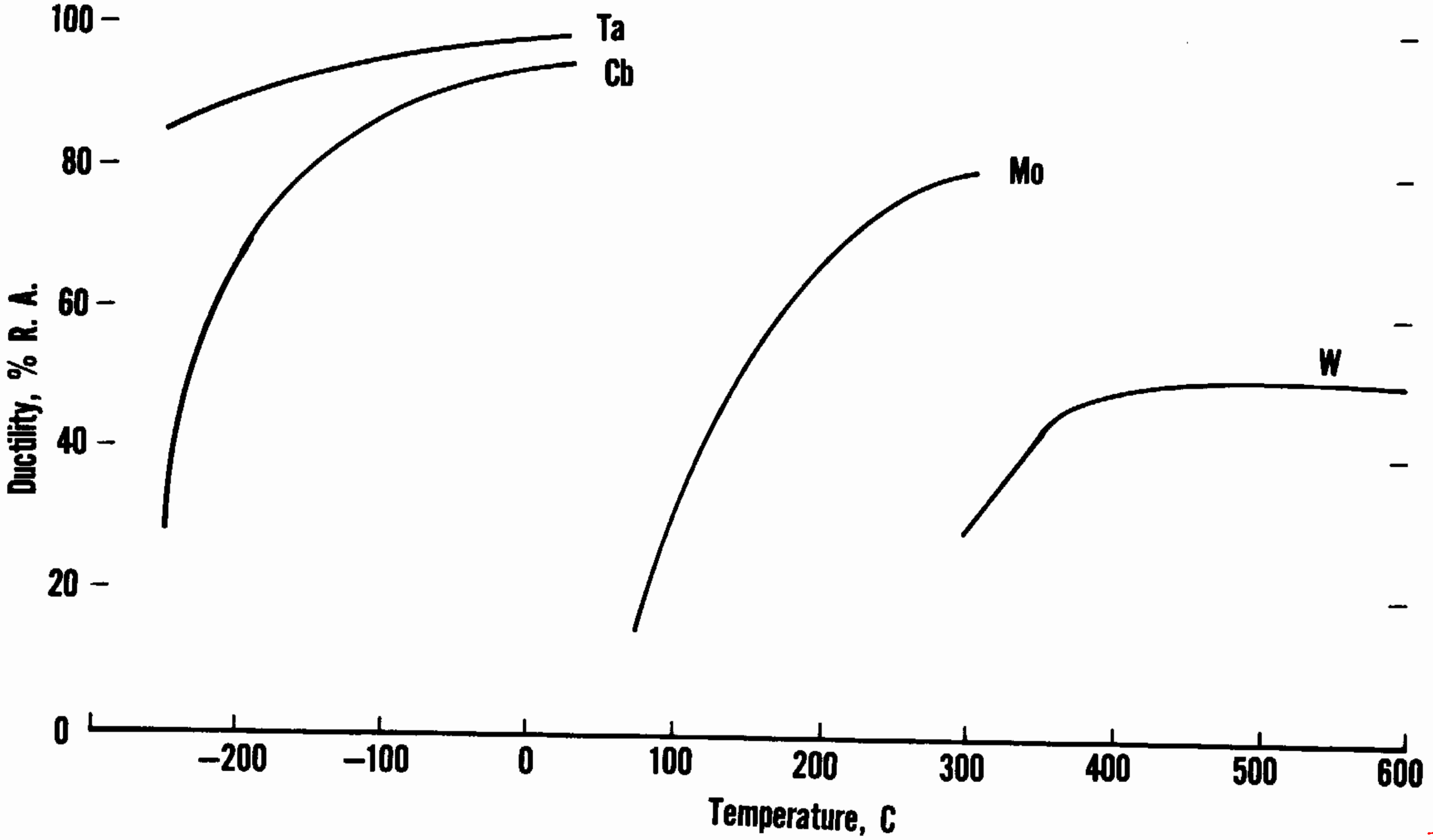


Figure 14.