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AERODYNAMIC HEATING AND FATIGUE

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SUMMARY

A review of the physical conditions under which future airplanes will operate has been made and the necessity for considering fatigue in the design has been established. A survey of the literature shows what phases of elevated-temperature fatigue have been investigated. Other studies that would yield data of particular interest to the designer of aircraft structures are indicated.

INTRODUCTION

The frontier of manned flight has reached speeds higher than 2,000 mph and altitudes over 125,000 feet. This has been done with small experimental planes carrying a large store of fuel, with little room for desirable instrumentation and no room for payload. These planes have been released at high altitudes for flights of short duration. The experimental plane of tomorrow will be built with the expectation of pushing the frontier to ever greater speeds and higher altitudes.

The military aircraft (fighters, interceptors, and bombers) will be made to carry useful loads at the speeds and to the altitudes of flight attained by the experimental plane. Future aircraft will have to take off under their own power and to be able to fly long enough to complete their missions. Before these aircraft can become a reality, however, some perplexing problems of thermal stresses, materials, structures, and so forth must be solved. Only if these military planes prove feasible and able to carry large loads will commercial planes be built for flight at such high speeds and high altitudes.

The purposes of the present investigation were: (1) To consider the subject of aerodynamic heating with a view to outlining some of the structural fatigue problems, if any, resulting therefrom, (2) to determine from a survey of the literature what data on elevated-temperature fatigue are available, and (3) to outline fields of study for future research.

This survey will not consider fatigue problems of missiles. Missiles are in the class of one-flight aircraft and, although they will be subject to aerodynamic heating, there is believed to be no necessity for considering fatigue in their overall design.

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STRUCTURAL FATIGUE PROBLEMS

In subsonic flight, fatigue of the aircraft structure is attributed to the fluctuating loads imposed by maneuvers, by atmospheric turbulence, or by sound-induced vibrations from jet engines. At the higher speeds of supersonic flight, aerodynamic heating occurs and not only complicates the fatigue problems arising from these sources but introduces additional ones as well. Fatigue failure at elevated temperatures can be said to be due to thermal fatigue resulting from fluctuating temperatures, to material fatigue resulting from cyclic loads, or to both.

Thermal Fatigue

The temperature gradients caused by aerodynamic heating produce thermal stresses in the airplane structure. Some of the conditions under which they may be produced are described below.

If an airplane flies for an extended period of time at supersonic speed, parts of the external structure become heated. It takes time for this heat to reach the interior structure. A result of this thermal gradient is the creation of thermal stresses. As the temperatures throughout the structure equalize, the thermal stresses decrease and may become insignificant. The opposite occurs if the plane decelerates rapidly. The exterior surfaces cool and thermal stresses result until the interior structure, at some later time, also cools.

In high-speed flight, some parts of the airplane such as the leading edges of the wings and of the tail surfaces are heated to higher temperatures than the rest of the airplane. These temperature gradients produce thermal stresses. Thermal stresses may also be created in structures that are fabricated from materials having unequal coefficients of thermal expansion. The magnitude of these stresses depends upon the difference between the operating temperature and the temperature at which the structure was assembled.

Temperature gradients are produced in aircraft structures by rapid changes of ambient temperature. Such a condition may be experienced by an airplane which takes off on a hot summer day and quickly climbs to a high altitude. The change in ambient temperature in this case may be 200° F or more. Thermal stresses would exist until the interior structure reached the temperature of the exterior structure.

The structure near an engine may also be subject to thermal stresses if there is excessive running of the engine before take-off or after landing. The air flow is expected to cool the engine in flight; when the engine is run for periods of time with the plane on the ground, cooling is insufficient and the engine and the neighboring structure are overheated. Thermal stresses result from the temperature gradient between the heated and unheated parts of the structure and decrease only after the plane is airborne.

Thermal stresses, superposed on the flight loads, might exceed the yield condition and cause residual stresses in the structure. The residual stresses could be either beneficial or detrimental (ref. 1). If the residual stresses were large and increased in magnitude as a result of subsequent flights, the resulting deformations could lead to incremental collapse of the airplane structure as pointed out in references 2 and 3.

Thermal fatigue may be defined as the type of failure caused by thermal stresses, either tensile or compressive, which vary about the flight load as a mean. The rate of thermal cycling would depend upon the airplane's mission, being one per flight if the plane were to go from one base to another on a routine flight or several per flight if the plane were an interceptor and engaged an enemy.

Material Fatigue

The other type of fatigue to which supersonic airplanes may be subjected is material fatigue. It was once thought that turbulence was practically nonexistent at altitudes above 35,000 feet where high-speed airplanes are expected to fly (ref. 4). However, data that have been obtained over the United States indicate that, although there are large reductions in the number and intensity of gusts for high-altitude operation, gusts do occur frequently enough to warrant consideration (refs. 5 to 7). The turbulence may exist in clear air and be unavoidable since there is no visual warning of its presence. In addition, it is anticipated that high airspeeds will be used during the climb and descent through low rough altitudes which will mean more severe gust loading (ref. 8).

Thus the material used in the construction of the supersonic airplane will be subjected to fatigue due to

(1) More severe gust loads at normal temperatures while the airplane is taking off or landing at higher speeds

(2) Gust loads superposed on higher mean loads consisting of flight and thermal loads while the airplane is accelerating to high speeds

(3) Fewer and less severe gust loads while flying at supersonic speed, and therefore at elevated temperature, at high altitudes

The flight history of the airplane will present a complicated fatigue pattern based on a composite of the loads described above.

It is evident from the foregoing discussion that fatigue-producing conditions will be encountered by the supersonic airplane.

LITERATURE SURVEY

Research in fatigue at elevated temperatures has been carried on for a number of years. The need for information on the effect of thermal cycling to which the materials in equipment in some manufacturing processes are subjected is evidenced by the studies reported in references 9 to 13. This work was carried out on stainless steels, AISI Type 347 and Type 304. Localization of the cyclic strain as a consequence of thermal fluctuation was found to be a principal cause for thermal stress fatigue failure of structures fabricated from austenitic steel. Other studies in the field of thermal fatigue are given in reference 14.

Prior to this work, studies were made to determine the effect of temperature on the fatigue strength of materials used in gas turbines and other equipment (refs. 15 to 17). Many of the present special high-temperature alloys were developed for use in blades and other parts of gas turbines and jet engines (refs. 18 to 21). The fatigue properties of these materials, however, were usually investigated only over the temperature range at which they would be used.

With the problems raised by supersonic flight where it was foreseen that the high speeds would result in heating of the airframe (refs. 22 to 25), an evaluation of the elevated-temperature properties of the materials used in the construction of subsonic or low supersonic aircraft had to be made to determine their limitations. Results of some of these investigations are given in references 26 to 29. Aluminum alloys lose much of their strength at temperatures of about 400° F. Some of them also lose their high-strength properties at normal temperatures after being exposed to elevated temperatures for extended periods of time (refs. 30 to 32). It is doubtful, therefore, if the aluminum alloys can be used in the same way they are now as structural materials for airplanes that are to fly much over Mach number 2 because, for sustained speeds of Mach number 2 at altitudes between 35,000 and 105,000 feet, portions of the airplane structure will be heated to approximately 200° F. At speeds of Mach number 3, the temperatures will range from 450° to 600° F and at Mach number 4, from 800° to 1,000° F (ref. 24).

For airplanes that are to fly at speeds well over Mach number 2, it is natural that the designer turn to the materials developed for other high-temperature conditions or to new alloys (refs. 33 and 34). In the structure of the supersonic Bell X-2 airplane, for example, nickel-strengthened alloys were used. The fuselage skin was of a copper-nickel alloy and the wing and tail sections were of chromium-nickel stainless steel.

In addition to the work in thermal fatigue, fatigue tests have been made for the primary purpose of evaluating materials under conditions of temperature and pulsating loads. They may be grouped under the following broad headings:

<u>Aluminum alloys</u>.- In references 35 to 48 the fatigue strengths of some of the high-strength aluminum alloys, 7075-T6, 2024-T4, 2014-T6, 2618-T61, are given for temperatures of 75°, 300°, 400°, 500°, and 600° F. These results were obtained on various forms of the alloy and from different types of fatigue tests.

The values given in references 37 and 39 are considerably higher than those of reference 40. (See fig. 1.) This is attributed to the fact that the results in reference 40 are for specimens heated for long periods of time at the test temperature and would, therefore, have reduced strength properties. No indication is given of scatter in presenting the S-N curves

The results of fatigue tests on sintered aluminum products indicate that, although they have only about one-half the fatigue strength of the high-strength aluminum alloys at 400° F, they maintain this strength for temperatures as high as 600° F. Preliminary work on a sintered aluminum product, reference 38, indicates that it still has some fatigue strength after prolonged heating to 500° C. In addition to greater fatigue strength, its thermal conductivity is higher and its thermal expansion is lower than that of the conventional aluminum alloys.

Magnesium, titanium, and other nonferrous alloys.- Magnesium, titanium, and other nonferrous alloys are discussed in references 15 to 20, 35, 36 (vol. III), 40, and 49 to 62. The fatigue properties of these materials are given, for the most part, in company reports. Few test data are given, and the endurance limits are specified over a rather short temperature range.

For magnesium alloys the test temperatures vary from 300° to 650° F and for titanium alloys, from 200° to 1,000° F. The temperature range for the high-strength alloys is from 1,000° to 1,500° F. A particular material, however, was usually tested only at two or three high temperatures. Representative unpublished data on some of the newer alloys are given in figures 2 to 5.

Reference 15 gives the fatigue strength in bending under completely reversed stress at 1,200° and 1,500° F for alloys of different trade names which can be grouped as chromium-nickel-cobalt alloys, nickel-molybdenum alloys, titanium and aluminum hardened nickel-chromium and nickel-chromium-cobalt alloys, nickel-chromium-iron alloys, chromium-nickel-iron alloys, and precision cast specimens of various compositions.

Steels.- Data for a large number of special steels are given in references 35, 36 (vol. III), 40, 48, 54, and 61 through 72. The steels, primarily of the stainless type, were tested over temperatures ranging from 500° to 1,200° F. The temperature range investigated for a particular steel, however, is relatively narrow and the data rather meager.

Effects

Notches and surface finishes.- At high temperatures and low ratios of alternating stress to mean stress, notches may have no effect or may have a beneficial effect; at high ratios of alternating to mean stresses, notches are detrimental to fatigue strength. Surface finish may not be important at high temperatures. (See refs. 64 and 73 to 82.)

Loading frequency and endurance limit.- On the basis of the S-N curve (refs. 41, 83, and 84) materials tested at low frequency have a lower fatigue strength than those tested at high frequency. However, if data are plotted on stress versus time basis, the opposite is true.

Load cycling and temperatures.- For a particular material, rupture may be accelerated or retarded depending upon the temperature, the static stress level, and the level and frequency of the cyclic stress (refs. 60 to 62 and 85 to 91).

Grain size.- Fine-grained materials have superior unnotched fatigue strength up to certain temperatures after which a coarse grain size appears to be advantageous. For notched specimens, grain size apparently has no effect on the fatigue strength. References 92 through 96 are basic studies which should lead to a better understanding of the mechanism of fatigue failure.

Bonded and sandwich construction.- Tests at 50° C of a Redux-bonded 7075 Alclad lap joint cured for 1/2 hour at 160° C indicate that the fatigue strength does not change from the room temperature value (ref. 97).

Excellent summaries of the work that has been done to date are found in references 98 to 100. Attempts have been made in these papers to piece together the limited data available so that some understanding of the general problems of elevated-temperature fatigue can be obtained. Trends are indicated which must be validated by more extensive test data. Some of these trends have been given above.

DISCUSSION

The first requirement of any structural material is that it be able to support the static loads that will be applied during service. For this reason, the creep strength of metals at high temperature was considered of primary importance. Only if a material had desirable creep properties was its strength under fatigue or dynamic loading determined. Most of the elevated-temperature fatigue data have been obtained with this objective in mind. The specimens have usually been small and the tests few in number because of the small amounts of a newly developed alloy available for this purpose. This evaluation testing is continuing as new alloys are developed.

The search of the literature has revealed few systematic studies in the field of elevated-temperature fatigue.

Fatigue at elevated temperatures is more complicated in nature than fatigue at ordinary temperatures (refs. 101 and 102). Results of tests on aluminum alloys indicate that the decrease in fatigue properties at high temperatures may be partly due to overaging but that the fatigue process itself is altered by high temperatures (ref. 42). The fatigue strength determined by testing at elevated temperatures is considerably lower than that obtained on material soaked for an equivalent period of time at the same high temperatures and then fatigued at room temperature. This parallels the results of static tests of materials exposed to elevated temperatures.

In fatigue fracture at both elevated and ordinary temperatures there may be an absence of apparent deformation; fracture surface may show characteristic conchoidal markings distributed about the point of beginning of fracture, but in other instances fatigue fracture may apparently be preceded or accompanied by creep. This may occur when the stress is not completely reversed as would be the case if a vibrating stress were superposed on a steady stress. Fracture appearance and time to failure under vibratory stress are probably functions of alloy and of stress and temperature (ref. 103).

Even though, as previously pointed out, supersonic airplanes will encounter conditions leading to fatigue loading at elevated temperatures, the question arises as to whether this will be a necessary design condition. Moore, reference 104, states that, for plain carbon steel at temperatures above 1,000° F, for 18 CR-8-Ni steel at 1,200° F, and for stronger steels at somewhat higher temperatures, the fatigue strength is higher than the stress that produces an appreciable rate of creep, indicating that creep strength will be the controlling factor in design. Below these given temperatures for particular alloys, however, the elevated-temperature fatigue strength or the strength under combined fatigue and creep will determine the alloy to be used in a structure.

For ordinary temperatures, fatigue is considered to be a cyclic-dependent phenomenon but at elevated temperatures fatigue seems to depend also on time. Regarding his studies of carbon steel, chromium steel, and molybdenum steel under static and alternating stresses at temperatures of 550°, 600°, and 650° C, Wever in reference 64 said, "The question arising from these results as to whether the time against fatigue strength can reach, or even exceed, the time against creep strength has not yet been clearly solved by the tests carried out up to date." However, figure 6 taken from reference 64, would indicate that the alternating or fatigue stresses causing failure in a certain number of hours are considerably smaller than the static stresses causing rupture in the same time for times of 1,000 hours or less. Plots of rupture stress versus fatigue stress for various materials ruptured in equal times at equal temperatures as given by Allen and Forrest in reference 98 would, for the most part, substantiate this.

The apparent dependence of elevated-temperature fatigue on time may be due to creep occurring under the cyclic loading. Most of the analyses made of the elevated-temperature fatigue data have been based on a time-under-load parameter (refs. 62, 98 to 100, and 105 to 107). The cycles-to-failure are converted to equivalent time under load and the data are then correlated with creep data for the material. Statistical methods, reference 108, have also been used to analyze data from fatigue tests. In the work on thermal fatigue (refs. 9 to 12), relationships between plastic strain change and cycles-to-failure to be used in design are given for strain-cycled and thermally-cycled 347 stainless steel.

Methods of analysis for the fatigue strength of an airplane have been compiled in reference 36 (vol. II). Few data are available to evaluate these methods for applicability to the design of subsonic aircraft, a step which should precede consideration of their use in the design of supersonic aircraft.

It should be borne in mind that conventional methods of fatigue testing, using small machined and polished cylindrical specimens or coupons, can give results which may indicate too high a fatigue strength of the unmachined sections from which they were cut (ref. 109). In addition to the need for standardizing the specimens for fatigue tests, the methods of testing, and the presentation of data, a reappraisal of fatigue testing and its purposes is necessary if there is to be any hope of correlating the large amount of fatigue data being obtained. Much of the fatigue testing that is done yields qualitative information as to the relative strengths of materials under cyclic loading and stated conditions of temperature, type of cyclic loading, and so forth. Other fatigue testing can be classified as basic research to determine the causes of fatigue failure, the mechanism of fatigue failure, and so forth. The structures engineer, on the other hand, would prefer to have fatigue tests made with specimens that are larger and more representative of the structures in which the material will be used. Unless this is done, it will be difficult if not impossible, to relate the results of fatigue tests to the fatigue strength of a fabricated structure.

RECOMMENDED FIELDS OF STUDY

While the picture of temperature and stress conditions that confront the high-speed, high-altitude airplane seems a gloomy one that would limit drastically the speeds and altitudes it might attain, there are apparently alleviating conditions as pointed out in references 110 to 112. No doubt the temperatures will be extremely high at the nose cone and on leading edges of wings and tail surfaces which will call for special consideration. On the other hand, parts of the airplane structure will be heated only moderately high. It would seem then that aluminum alloys need not be considered as completely obsolescent materials for future aircraft, but use should be made of them in conjunction with newly developed heat-resistant alloys and new structural designs (ref. 34).

As pointed out previously, the studies in the field of high-temperature fatigue have, for the most part, been very limited as to scope, number of tests, and applicability to general design.

Fatigue properties of various alloys have been investigated over temperature ranges from 75° to 1,600° F. It should be borne in mind, however, that a particular alloy will probably have been tested only at the two or three temperatures at which it was expected to be used in a special application such as in gas turbines or jet engines. Figure 7, taken from reference 98, gives the fatigue strength of different alloys at various temperatures. The basis of the fatigue strengths in figure 7 varies from 10^7 to 10^8 cycles. A definite number of cycles are chosen as there is no true endurance limit; the S-N curve at elevated temperatures for most materials continues to decrease with increasing number of cycles.

Other factors must be considered if certain materials are to be used in an airframe. The airplane structure must be as light in weight as is compatible with safety. The structural materials must have reasonably high endurance limits and will, therefore, not be usable at as high temperatures as the same material might experience in an engine, for example. The fatigue properties of many of the alloys of current interest for airframes have not been investigated over the lower portion of the elevated temperature ranges. In some of these alloys there may be little change from the room temperature fatigue properties but it is doubtful if this can be assumed to be true generally.

Data are needed on materials suitable for the airplane structure under test conditions that will reflect the use to which they will be put in service. It would seem that results similar to those reported in reference 62, where tests were made with various ratios of alternating stress to mean stress of 0 (static tension), 0.25, 0.67, 2.0, and ∞ (reversed axial stress), would more nearly reflect the type of fatigue loading to which an airplane structure would be subjected. The loading on an airplane would usually vary due to aerodynamic heating and/or flight through turbulent air superposed on a mean or level flight load. Projects with the following objectives should provide information needed for the design of supersonic-speed airplanes:

(1) Establish S-N curves for high-strength aluminum alloys, high temperature alloys and steels over the temperature range of their usefulness as structural airframe materials.

(2) Obtain data on the fatigue strength of joints or other structural elements at elevated temperatures.

If the study of the fatigue properties of materials is to be useful in design, there must be correlation between the results of tests of the material and of structural elements made of the material. If there is no correlation, these data obtained on structural elements will be much more useful to the designer than will the fatigue properties of materials.

(3) Obtain data on the fatigue strength of sandwich construction at normal as well as elevated temperatures.

Sandwich construction has been advocated for use in designing thin wings for high-speed aircraft as it is a comparatively lightweight type of structure and provides a means of stabilizing the airplane surfaces. Some investigations of the behavior of sandwich material under shear fatigue loadings have been reported in the literature (refs. 113 to 115). Other evaluation work (ref. 116) is being done on sandwich material suitable for supersonic aircraft.

(4) Determine the conditions of load, time, and temperature under which the fatigue strength rather than the creep-rupture strength of the materials used should govern the design of structures that will be operating at elevated temperatures.

(5) Determine the interaction between fatigue and creep at elevated temperatures.

Some investigators believe that there is always some creep occurring during cyclic loading at elevated temperatures. If it is the first stage of creep, the fatigue strength may be increased; if the second stage, there may be no effect; and if the third stage, the strength may be reduced (ref. 88). Another investigator reports no effect of creep strain on fatigue properties (ref. 42).

(6) Establish the relationships between length of time at high temperature and the fatigue strength of the material.

Some indication of the effect of length of exposure to elevated temperature on the fatigue strength of 2024-T4 aluminum alloy is evident from the results given in figure 1 and discussed previously. No time at temperature for these tests is reported, however.

(7) Determine the effect, if any, of fatigue at normal temperatures on the fatigue strength at elevated temperatures.

An airplane, climbing at subsonic speed, and then flying at altitude at supersonic speed, might have such a history of fatigue loading.

(8) Determine the effect of fatigue at elevated temperatures on the endurance limit at normal temperatures.

This should supplement data in item (8) in attempting to evaluate the fatigue life of a structure under various flight histories.

(9) Determine the effect of thermal stresses on fatigue strength of a structure.

Thermal stresses would result in a variation of the mean stress until the temperature conditions stabilized. Investigation should determine if a cumulative damage analysis is applicable.

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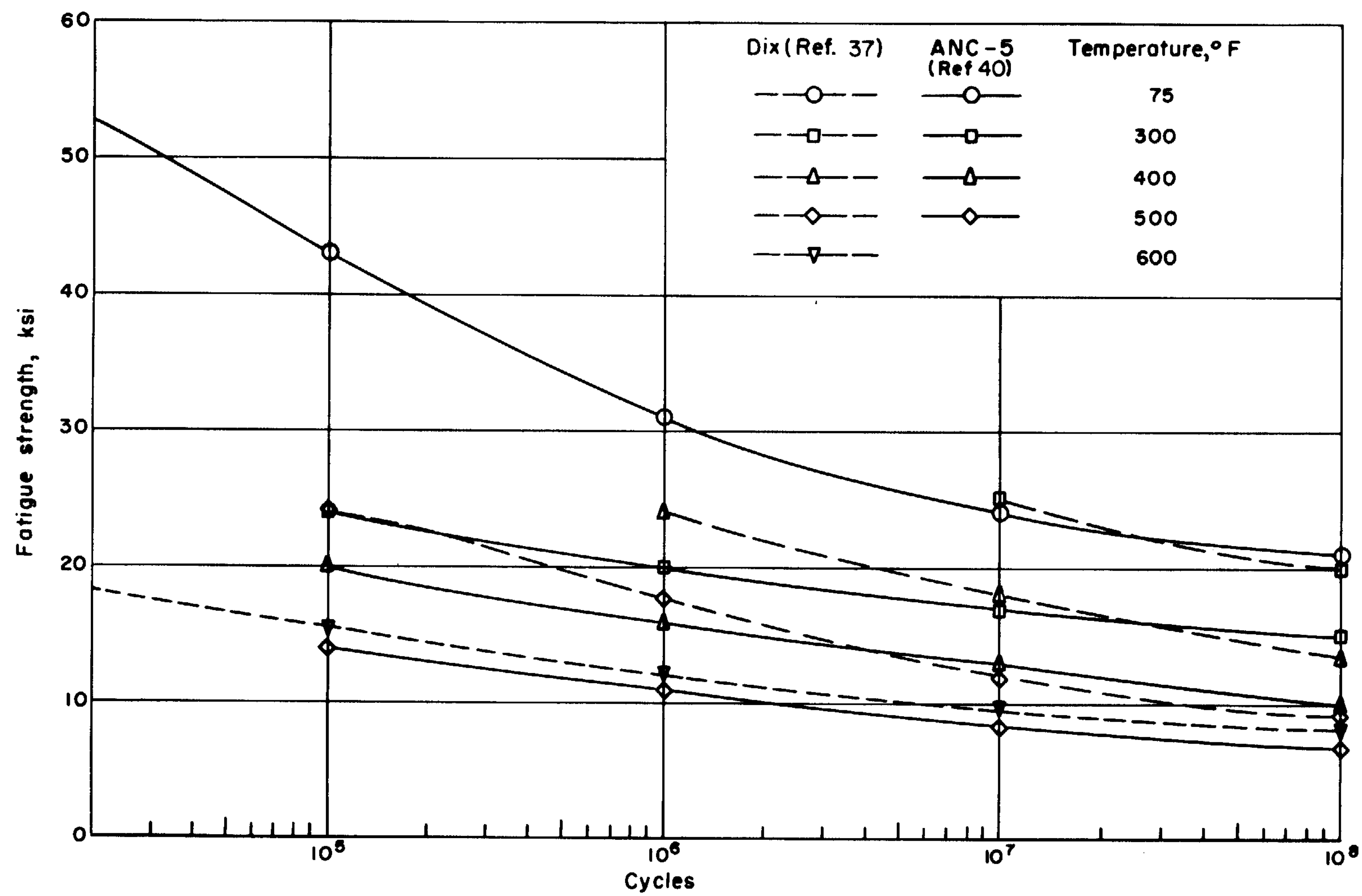


Figure 1.- Effect of prolonged heating on fatigue properties of 2024-T4 aluminum alloy at elevated temperatures.

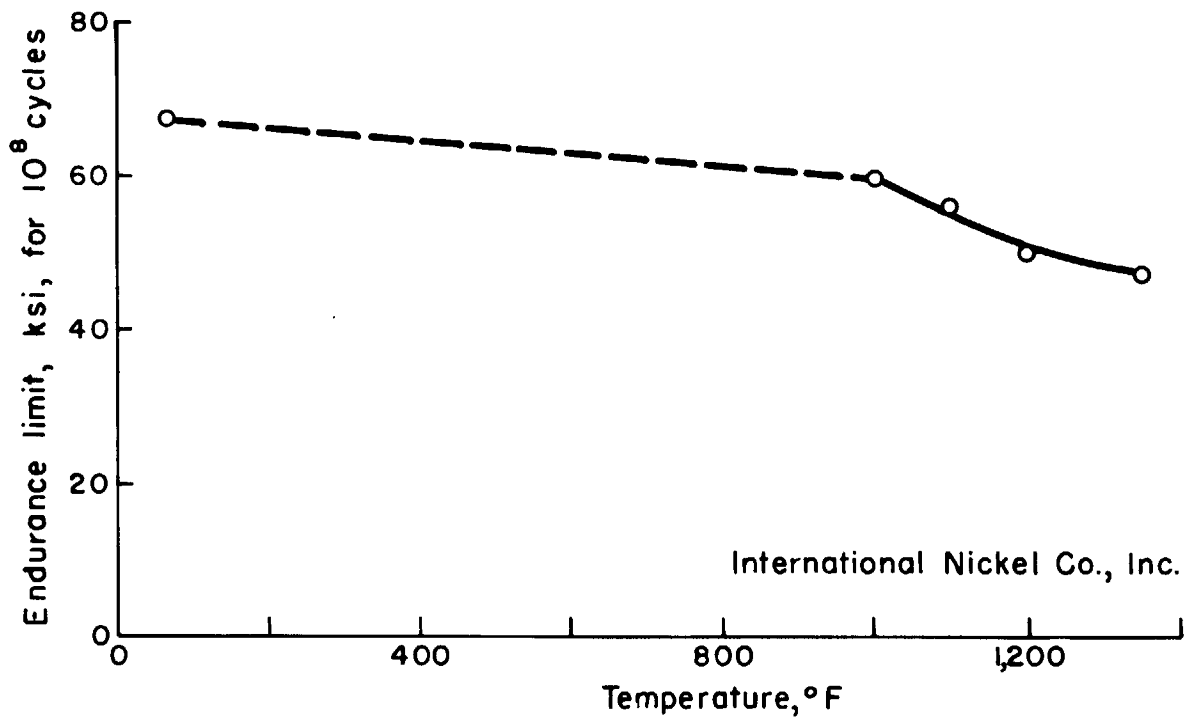


Figure 2.- Elevated-temperature fatigue curve for Incoloy 901-hot-rolled bar stock. Solution treated 2 hours at 2,050° F, water-quenched, aged 24 hours at 1,375° F, air-cooled.

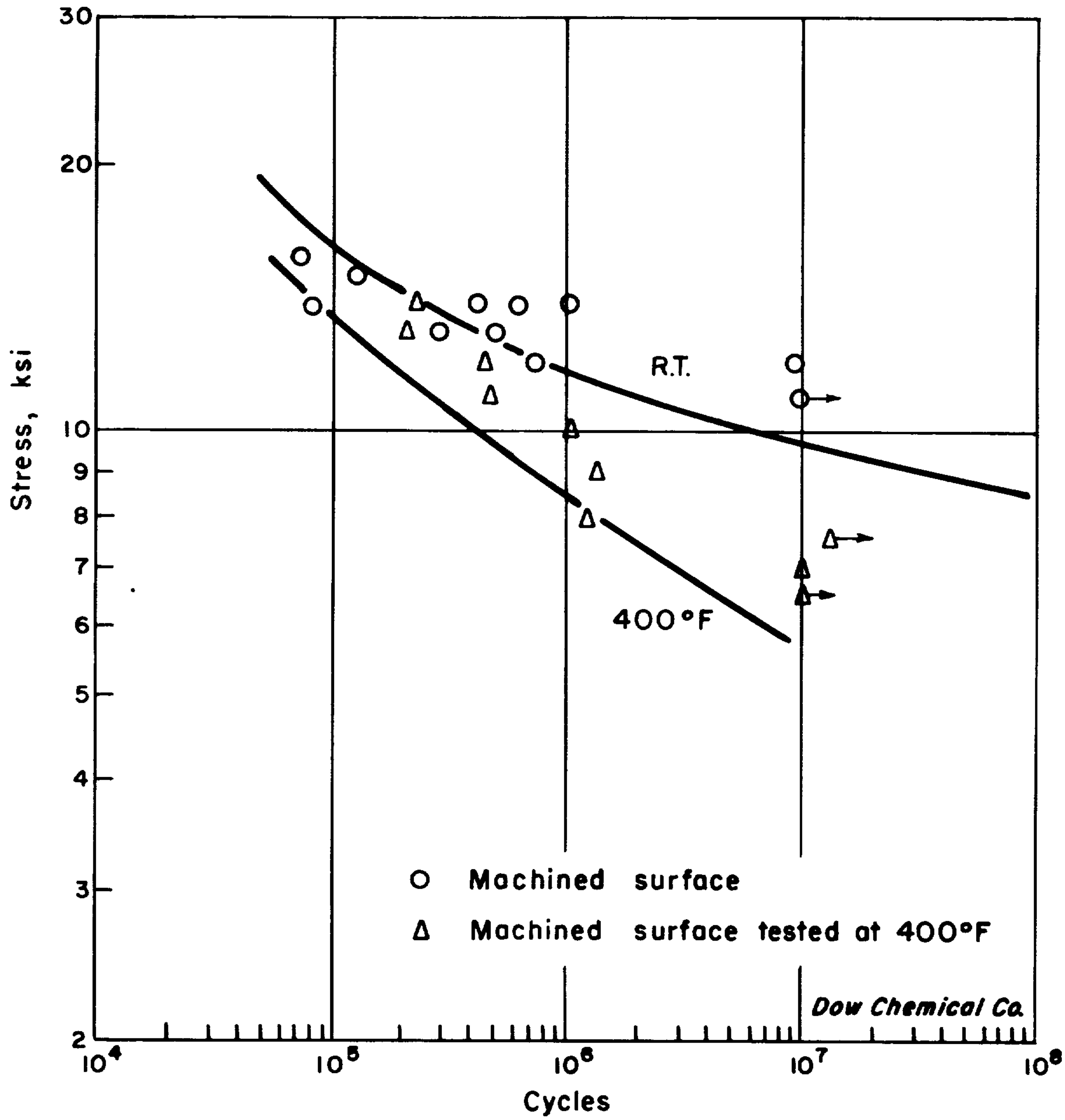


Figure 3.- Approximate median S-N curve for sand cast EZ33A-T5 magnesium alloy obtained with Krouse plate bending fatigue machine. R = -1.

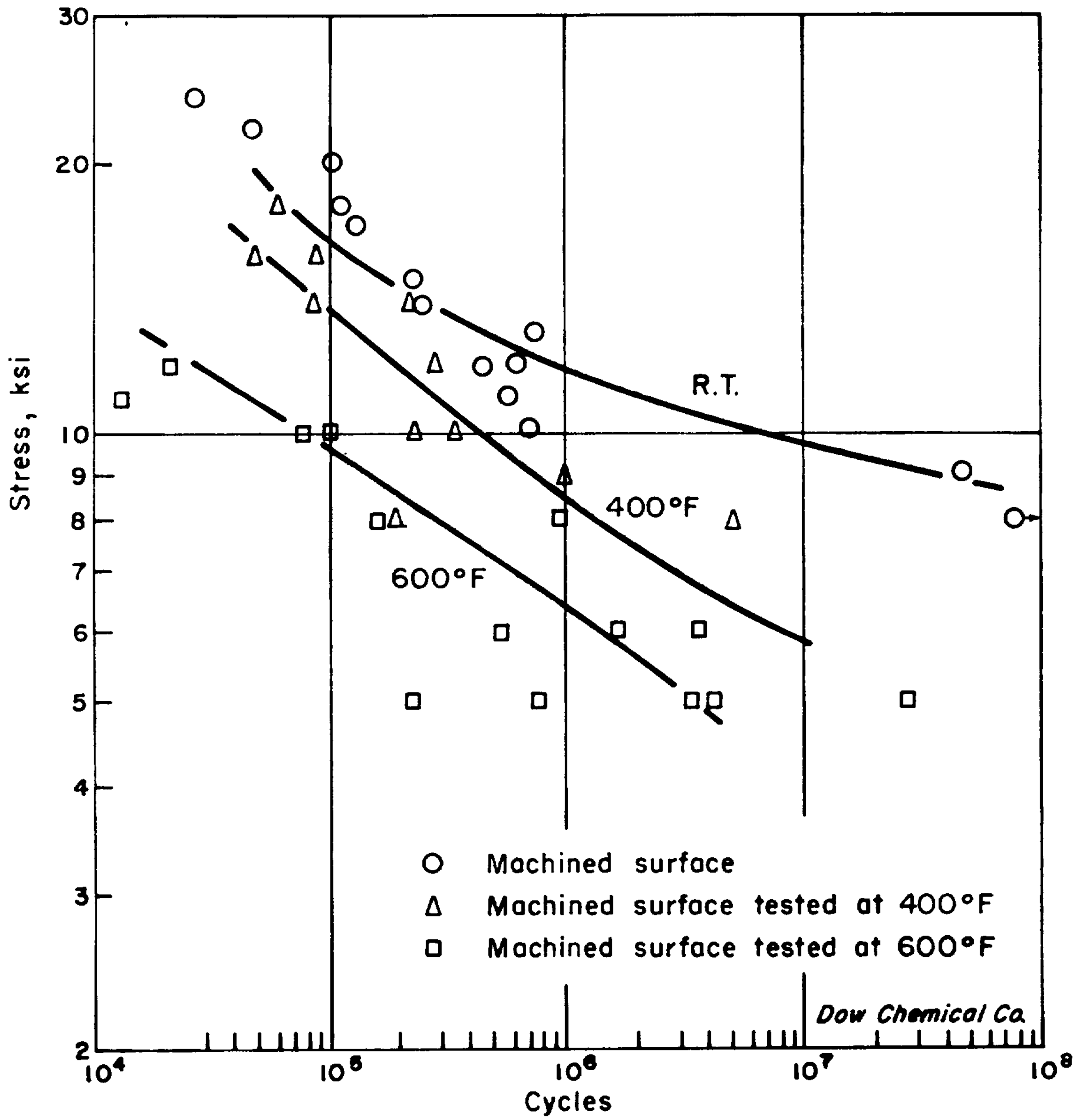


Figure 4.- Approximate median S-N curve for sand cast HK31A-T6 magnesium alloy obtained with Krouse plate bending fatigue machine. R = -1.

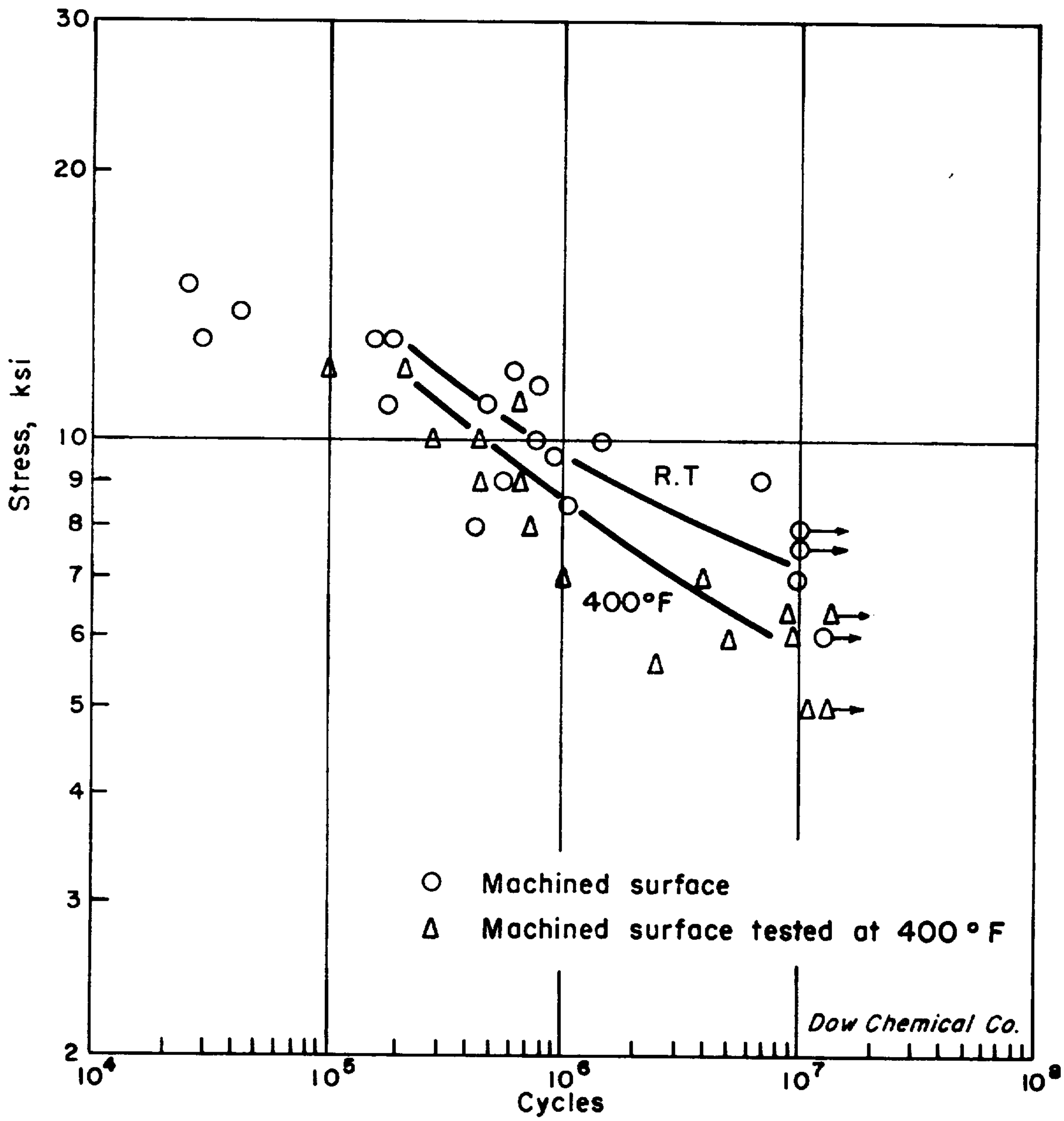
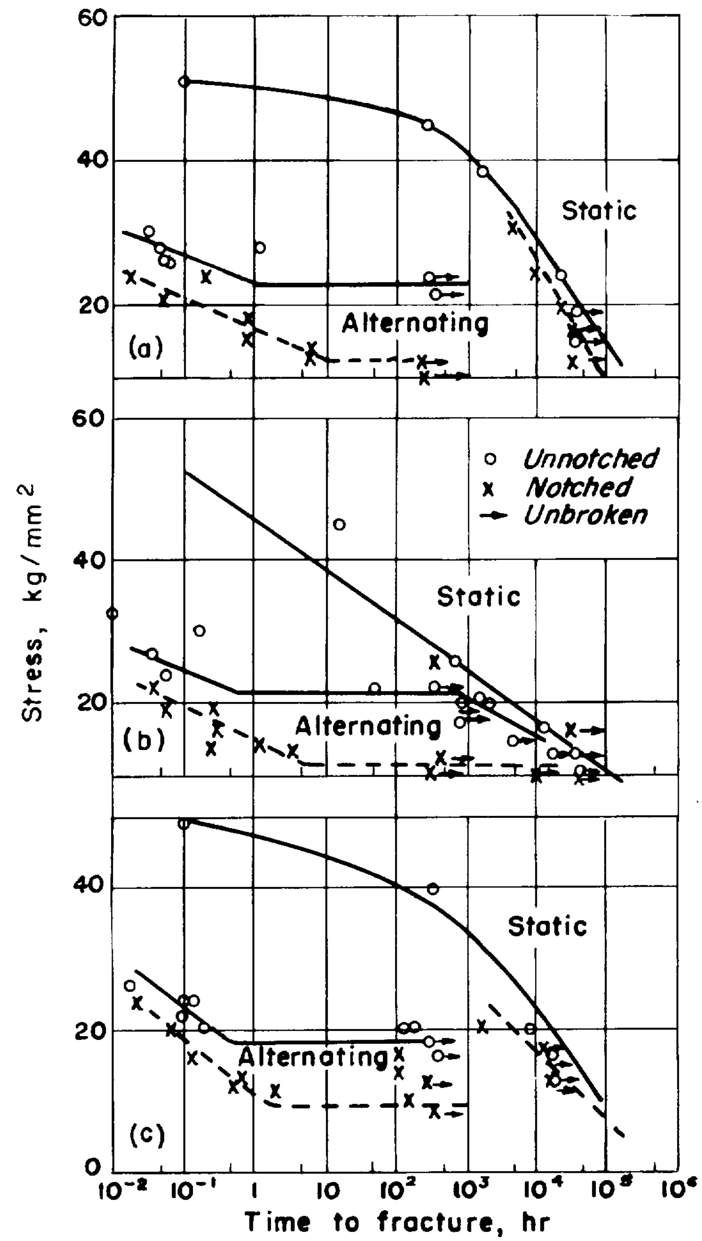
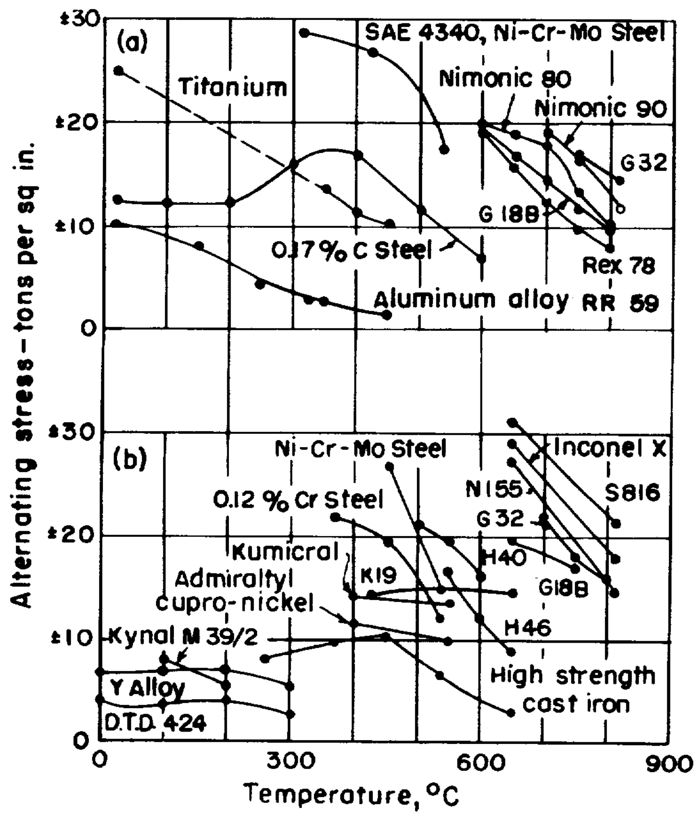


Figure 5.- Approximate median S-N curve for sand cast EK30A-T5, T6 magnesium alloy obtained with Krouse plate bending fatigue machine. R = -1.



(a) 550° C.
(b) 600° C.
(c) 650° C.

Figure 6.- Stress against rupture-time curves for austenitic steel (ref. 64) at various temperatures.



(a) Direct stress.
(b) Bending fatigue tests.

Figure 7.- Influence of temperature on fatigue strength of metals (ref. 98).

NASA MEMO 6-4-59W
National Aeronautics and Space Administration.
AERODYNAMIC HEATING AND FATIGUE.
Wilhelmina D. Kroll, National Bureau of Standards.
June 1959. 30p. diagrs.
(NASA MEMORANDUM 6-4-59W)

A review of the physical conditions under which future airplanes will operate has been made and the necessity for considering fatigue in the design has been established. A survey of the literature shows what phases of elevated-temperature fatigue have been investigated. Other studies that would yield data of particular interest to the designer of aircraft structures are indicated.

Copies obtainable from NASA, Washington

1. Loads and Stresses, Structural - Repeated Dynamic (4.3.7.7.1)
2. Materials, Properties - Fatigue (5.2.5)
3. Materials, Properties - Thermal (5.2.11)

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