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James W. Freeman
Howard R. Voorhees

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James W. Freeman and Howard R. Voorhees
University of Michigan, Ann Arbor, Michigan

ABSTRACT

Design and selection of materials for extreme pressure applications is discussed from the metallurgical viewpoint, with emphasis on high-temperature applications where creep governs design considerations. Major factors covered include properties of materials and their relations to service requirements. Effects of metallurgical factors on properties are reviewed, together with anticipated behavior under complex stresses, stress concentrations, and stresses which vary during service. Applications for the so-called "super-alloys", as related to their properties, are considered.

INTRODUCTION

Selection of the proper alloy for any application requires matching material properties to service requirements at a minimum cost. Invariably some compromises in design and operating conditions are necessary to obtain adequate agreement. Extreme pressures introduce nothing new into basic design principles, but the thick sections needed to keep stresses within acceptable limits intensify many of the usual problems. When temperatures are increased many or all of the usual materials may become so weak that it is impossible to build a practical vessel for high pressures from them. The materials engineer must then turn to special alloys which have been developed for retention of strength at elevated temperature.

Quite exact performance of alloys can be predicted if the design and materials engineers, working together, can correctly anticipate the exact stresses, temperatures and corrosion effects. This is however not a simple matter in extreme pressure applications. The heavy sections introduce complex stresses and stress gradients, and rigidity of these heavy sections intensifys inevitable stress concentrations. Temperature gradients give rise to thermal stresses which complicate stress analysis. Finally, most of the data available for the strength of alloys were determined for static uniaxial tension at constant temperature. In practice pure tensile stresses are rare and the simple tension properties must be adapted to complex biaxial and triaxial loads, stress gradients over the section, varying stresses and varying temperatures.

Most operations at extreme pressures involve use of alloys under conditions where little or no prior experience exists. In moderate-pressure applications a wealth of experience is available on which to base expected performance of materials. Because it is difficult to anticipate service stresses and temperatures exactly, the absence of experience is a real handicap.

The primary requisite of any material is adequate strength. The first step in selection of materials is therefore to check the strengths of available alloys. Basic requirements of design and selection of materials are either to avoid actual fracture or to prevent any part from becoming inoperative due to excessive deformation within the expected service life. At ordinary temperatures this is accomplished by limiting the stress to the yield strength or by using some fraction of the ultimate tensile strength or yield strength which experience has indicated to allow adequately for unpredictable stress concentrations and variation in alloy properties. As is well known, the ASME Unfired Pressure Vessel Code uses one-quarter of the ultimate tensile strength and either 5/8 or 2/3 of the yield strength for this purpose.

At high temperatures a new phonomenon is encountered in addition to reduced strength from temperature alone: continuous plastic deformation or "creep" at constant stress. When a typical alloy is first loaded at elevated temperature, plastic deformation for a given stress level begins at a relatively high rate and declines steadily in rate during an initial "primary" period. Gradually the rate of creep strain levels off for a more or less extended period of "second-stage" or steady-state creep. At still later times the creep accelerates ("third stage") until fracture of the specimen finally occurs. This continued deformation and ultimate fracture under stress at elevated temperatures requires modification of the basic methods for evaluating strength to include time dependency.

HIGH-TEMPERATURE TEST DATA

Tests on high-temperature alloys are set up to obtain data the engineer feels are related to particular service requirements. These are most commonly tests in simple tension under constant load and temperature.

In different applications the amount of creep which can be tolerated varies. Also, expected service time ranges all the way from a few minutes to design lives of 25 to 40 years for central power stations. Published information tends to vary considerably and seldom covers all possible ranges of stress, time, temperature and amount of creep. Unfortunately, the metallurgist has no sure way to establish performance at conditions remote from those tested.

Stress-Rupture Strength

The time until fracture under creep conditions is dependent on the stress level. At constant temperature the relationship between the initial applied stress and fracture time can usually be shown as a straight line, or intersecting straight-line segments, when plotted to logarithmic coordinates. The resulting "stress-rupture time" curves (See Figure 1) are a time-dependent measure of the ultimate strength. On these plots the elongations measured on the fractured specimens are often included as additional information of value.

Common practice is to conduct actual tests out to about 1000 hours and then to extrapolate to 10,000 and 100,000 hours. These extrapolations can be very reliable if a family of curves is established at several temperatures including at least 200° F. above the temperature of interest. Reasonable similarity of slope for the stress-rupture time curves is evidence of reliability at the lower temperature. A number of curves covering the range of useful temperature for an alloy describes the time dependent ultimate strengths quite completely. Rupture strengths are usually presented as the stresses for fracture in 1, 10, 100, 1000, 10,000 and/or 100,000 hours.

Design Data Curves

Rupture strengths have the same limitation as does tensile strength at ordinary temperatures: they do not define the stress-dependency of limited amounts of strain. In many cases only a limited amount of deformation can be tolerated before a part becomes inoperative. At high temperature strain is limited through use of data establishing the relationships between stress and creep as a function of time. A series of different constant-load tests is run and the creep measured. The results are conveniently presented as curves of stress versus log time for total strains of 0.1, 0.2, 0.5 and 1.0 per cent, the strains which seem to most useful to designers (See Figure 2). These total strains are defined as the elastic strain on loading plus any plastic strain on loading plus the creep strain. Together with the stress-rupture time data these curves cover most of the conditions an engineer may encounter and are therefore called "design curves".

Creep Strengths

Direct determination of limited-deformation design curves is usually carried only to about 1000 hours and there is at present no reliable way of extrapolating to longer times. The strength for limited deformations in prolonged time periods is usually estimated from the stresses for second-stage creep rates of 0.0001 and 0.00001 per cent per hour determined from tests of about 1000 hours duration. Three or four tests are conducted in this range of rates and a stress-creep rate curve plotted for interpolation (Figure 3). It is customary to extrapolate these rates as follows:

0.0001%/hr = 0.1%/1000 hours = 1%/10,000 hours,
0.00001%/hr = 0.01%/1000 hours = 0.1%/10,000 hours
= 1%/100,000 hours.

Even assuming that the second-stage creep rate remains constant, it is evident that the total strain is greater than indicated by that rate alone, due to deformation on loading and the higher rates of first-stage creep. Whether or not corrections are made for the added strains prior to the start of second-stage creep, creep strengths are basically a measure of load-carrying ability for limited deformations and prolonged time periods. The two values quoted are those most widely used by engineers. Intermediate values or values for other time periods can be established by similar treatment if sufficient test data are available.

Existing Data

A set of design curves, together with creep data, for one temperature requires from 9,000 to 12,000 hours of testing time, more than a year's use of a test unit. Only when an alloy has well-established potential use, and well-standardized production techniques, are design curves over a temperature range justified. Consequently, most of the data available represent some portion of a complete evaluation. Rupture data are quite commonly available. Creep strengths of considerable reliability are available chiefly for alloys which have been employed in large tonnages for many years, as in the power-boiler and petroleum-refining fields. Data for stress versus time for total deformation are relatively rare.

When test data from several sources and for different lots of a given alloy have been obtained, a range in properties is always found. For a specific treatment this stems from unavoidable variations in production procedures and inherent variables in testing. Often a given alloy will be heat-treated in different ways for different uses, with resultant variation in reported strength properties. For these reasons data compilations are being prepared to provide an indication of expected spread in properties (1). There is growing interest in surveys of this type and in statistical evaluation of alloys produced within commercial specifications.

USE OF HIGH-TEMPERATURE DATA

Rupture, creep, and total-deformation data evaluate alloys in terms of performance under simple static uniaxial tension stresses at constant temperature. One of the main problems in extreme pressure applications is the proper use of such data under complex stress and temperature conditions. Several common problems will be discussed in terms of existing knowledge. Many fundamental questions will be seen to still await answers, and some of the procedures to be suggested are approximate.

Complex Stresses

By complex stressing is meant the simultaneous action on a small element in a structure of stresses in different directions. When any one force is exerted on a body it may act to pull out or push in on the surface, or it may tend to produce sliding ("shearing") parallel to the surface. When the force meets the surface at any angle other than 90° or 0°, both types of action are produced and the force may be resolved into a normal (tensile or compressive) component and a shearing component. Regardless of how many forces act at a point, or in what direction, it is always possible to find three mutually perpendicular directions in which the shear stress is zero so that the only stress in these three directions are pure tension or compression. These three stresses ($S_1 > S_2 > S_3$) include the maximum and minimum normal stresses at the point and are called "principal stresses". By convention, tensile stresses are denoted as positive and compressions as negative stresses.

Pressure inside a cylindrical vessel exerts its major effect as a tension in the circumferential or hoop direction, tending to split the wall along its length. For a thin wall this stress (S) equals the internal pressure (p) multiplied by the ratio of the cylinder diameter (D) to twice the wall thickness (t): $S = pD/2t$. When the ends are closed by movable pistons, the pressure exerts no axial pull so that the intermediate principal stress is zero. The principal stress in the radial direction is zero at the outer surface and equals the pressure stress $-p$ at the inner surface. Under this condition and with a very thin wall only the hoop stress is significant and the effect on the metal is the same as in a sheet stressed by a straight pull along a pair of opposite edges.

If the pistons are replaced by caps fastened to the cylinder ends, an axial pull on the walls is added, equal to half the hoop stress for the particular case of a very thin circular cylinder. Such a stress pattern, corresponding to simultaneous pulling along the length of a sheet and across its width, represents biaxial loading. In thicker vessels the axial stress becomes less important and the compressive stress of the pressure against the inside wall assumes a magnitude of the same order as the axial stress. The most general pattern -- triaxial stressing -- is thus obtained near the bore of a thick cylinder at high pressure. This corresponds in simultaneous action of forces on all six sides of a block.

Theories of Failure Under Complex Stresses

A number of relationships have been proposed to derive from the three principal stresses a single equivalent stress giving the same effect as an equal stress in pure tension. This enables one to use data from pure tension to determine yield, fracture, fatigue, creep and stress-rupture under complex loading. Of the theories put forward from time to time only three combine satisfactory simplicity and reasonable agreement with experimental evidence. In historical order of their appearance, the three theories are:

(1) Maximum Principal Stress: The largest of the principal stresses (S_1) is postulated to be the only one of importance, with failure or creep independent of stresses normal to the direction of S_1.

(2) Maximum Shear Stress: The critical stress combination is taken to be the largest shearing stress present, $(S_1 - S_3)/2$.

(3) Shear-Stress Invariant: The equivalent stress $\bar{S}$ is computed from the separate principal stresses by the relation:

$$\bar{S}^2 = 1/2 \left[(S_1 - S_2)^2 + (S_1 - S_3)^2 + (S_2 - S_3)^2\right] .$$

This theory, generally attributed to von Mises, goes by many names including "Octahedral Shear Stress", "Distortion Energy" and "Maximum Shear Strain Energy".

Results of Complex-Stress Studies

For ductile alloys yielding, fracture and fatigue at room temperature all seem to depend on a shear mechanism with generally-better correlation by the shear-stress invariant theory than by the maximum shear stress. Brittle materials, such as cast iron, follow the criterion of maximum principal stress for fracture and fatigue (2-7).

The technical literature also reports studies (8-11) on a variety of alloys under different patterns of complex stress at temperatures where creep occurs. For these tests the elastic limit, creep behavior, and short-time stress-strain relations (some carried to fracture) were all definitely not a direct function of the largest principal stress. Satisfactory correlation could usually be obtained in terms of either the shear-stress invariant or the maximum shear stress, with slight favor for the former.

Published findings for rupture after creep under combined stress are limited to a series of five tests on a 0.5% Mo steel at 550° C (1021° F) and three test points for commercial-purity copper at 250° C (482° F). (See Ref. 12). In these particular tests the criterion of failure in stress-rupture appeared to be closely that of maximum principal stress. This finding was quite unexpected in view of past observations that the shear-stress invariant theory applied during loading and for both first and second stages of creep. Further studies are required before one may set down a final conclusion as to the general criterion for stress-rupture under complex stresses.

It is tentatively recommended that both creep and stress-rupture properties of ductile alloys under complex stresses be calculated from simple-tension data by use of the shear-stress invariant theory.

Non-Uniform Stress Distributions

Not only are the stresses multiaxial in pattern in a thick pressure vessel, but they are also non-uniformly distributed. In fact, the chief characteristic of extreme-pressure equipment which distinguishes it from most other is the steep stress gradient through the walls.

Stress gradients are even steeper and more localized in the vicinity of notch or a sudden change in cross section. If a notch is introduced into a member submitted to tension perpendicular to the notch, the stress in the direction of the tension will rise sharply near the notch root. Local stresses in other directions will also develop, but of smaller magnitude.

During elevated-temperature service, stress gradients of the nature described tend to level out by creep, with the result that the actual fiber stress at any portion of the vessel wall changes with time, even in service at constant applied pressure and temperature. The higher the temperature, the faster redistribution of stress should occur due to the rapid increase in creep rates for a given stress with temperature.

Notched-Bar Rupture Tests

Response of a heat-resistant alloy to the presence of a stress concentration is being evaluated increasingly by rupture tests on notched specimens. In some cases, notches of varying sharpness may uniformly raise the stress-rupture time curve. (See Figure 4.) For other conditions, notches have been reported to increase rupture life at high stresses and shorten life at lower stresses. Some published data indicate that at still lower stresses the notched specimens may once more have a longer rupture life than smooth. The curves of Figure 5 indicate the latter possibility. For many borderline cases, rupture life of the same alloy may be lowered by some notches and raised by others of different geometry.

Results shown in Figures 4 and 5 were accumulated during studies still in progress at the University of Michigan and supported by the Materials Laboratory, Wright Air Development Center (13). For the S-816 alloy a combination of low yield strength and rapid relaxation by creep at 1350° F makes it virtually impossible to retain a stress concentration. At this same temperature the higher yield point and high resistance to relaxation shorten life for Inconel X-550 under the rather severe stress concentrations studied. This difference in behavior is also evident from the times required for relaxation without elastic follow-up from the yield strength to the 1000-hour rupture stress -- less than one hour for S-816, nearly 100 hours for Inconel X-550.

Vessels to operate at extreme pressures, especially on a commercial scale, are of necessity massive. Non-uniformities of stress arising from a large ratio of wall thickness to diameter are present whatever the scale of equipment size. In addition, a heavy section in a massive structure provides a greater degree of restraint, reducing its ability to flex and adjust to a localized stress concentration. Moreover, a thicker wall offers greater chance for temperature gradients and thermal stresses, but less opportunity for their relief.

The notch-bar rupture test provides a very useful qualitative indication of the ability of an alloy to adjust to concentrated stresses. Whenever extreme service conditions demand use of a new alloy, or even of familiar alloys in an untried application, careful consideration should be given to notch-sensitivity characteristics.

Demonstrated ability of a particular alloy to reduce local high stresses and prolong life in a notched-bar rupture test at the expected service temperature suggests that the same alloy made into a pressure vessel should be able to relax initial high bore stresses. Perhaps of greater importance, such an alloy provides a measure of insurance against disasterous effects of unpredictable stress concentrations and inadvertent operation at conditions more drastic than planned.

Creep strengths and rupture strengths generally rise and fall together. Desire for rapid creep to eliminate initial stress concentrations must be balanced against need for high rupture strength for super-pressure applications. This dilemna serves to illustrate the constant compromises required in successful selection of materials.

All other things being equal, an alloy with proven notch strengthening for a wide range of notch acuities and test conditions is always to be preferred. Should superiority in creep-rupture strength or other property require the use of an alloy at temperatures where a notch lowers the rupture strength, special precautions must be taken in the design to avoid the presence of sudden section changes or other stress raisers, and case must be exercised during operation to minimize thermal stresses and shock loading.

When better data are absent, ductility in the rupture test can be used as a rough measure of resistance to stress raisers. Rapid decrease in ductility with increasing time for rupture is particularly indicative of probable notch sensitivity. There is a range between about 2 and 10 per cent elongation where notch sensitivity may or may not be present. But even two per cent is more than would be required to relieve even the most severe stress concentration. It, therefore, appears that ductility in rupture tests is only qualitative in its prediction of relaxation resistance.

Life of a part under an initial stress gradient at high temperature is intimately connected with relative creep and rupture strengths at service conditions. If an alloy is very resistant to creep the peak stress remains to control the time and point of rupture. On the other hand, for metals with low creep strength, rapid leveling of stress gradients occurs without excessive use of life during the initial period of localized high stresses. Restraint and triaxiality at the point of stress concentration also exert a major influence.

If a metal fiber is free of restraint against elongation the plastic strain of creep results in a change in length. (This is the situation in the usual constant-load creep test.) However under complete restraint against change in overall dimensions the same fiber would only experience a drop in stress level, called "relaxation". All plastic creep strains would now act internally to replace part of the initial elastic strain.

Resistance of alloys to such relaxation of stresses can be measured in a modified form of creep test in which portions of the load are removed as creep occurs, thereby lowering the stress acting and keeping the length of the specimen constant.

Complete relaxation curves showing residual stress as a function of the elapsed time are seldom presented. Instead the residual stress at, say, 100, 1000, and 10,000 hours are reported for a given initial stress. Most of the relaxation data currently available have been accumulated by the ASTM-ASME Joint Committee on Effect of Temperature on Properties of Metals for publication in the near future.

Relaxation data have direct application in design of bolting and some gaskets and cone-joint fittings where the conditions of simple loading and high degree of restraint are fulfilled. For vessel design, relaxation data give useful comparisons between materials in their ability to redistribute localized high stresses and can be used to estimate the rate of change of stress concentrations. A little consideration will show that only stress differences are amenable to relief by relaxation. Assuming the von Mises law to apply, the stress gradient subject to relaxation in a pressure vessel free from extraneous stresses would be the shear-stress invariant at the bore less that at the outer surface.

In triaxial stressing, plastic yielding and creep should lower the largest principal stress component fastest, reducing differences between pairs of principal stresses even faster. When a stress concentration is characterized by a favorable degree of triaxiality it is even possible to lower the effective stress sufficiently to obtain an increase in life above that for the case of uniform stress. The governing factor is the amount of rupture life used up in reaching a sufficiently low effective stress to prolong life. If the alloy has high creep resistance at high stress levels, the rate of relaxation of stress concentrations will be so slow that life will be shortened even though the internal creep strains may reduce the effective stress to quite low a value. On the other hand, a material which creeps readily and has low relaxation strength at high stress levels will allow the concentrated stresses to be reduced before an appreciable amount of rupture life has expired, and life will be prolonged by the lowered effective stress present during the large fraction of total service life. In work performed at the University of Michigan under an Air Force contract, the variable behavior of different alloys in rupture tests of notched bars under axial loading could be satisfactorily explained by such reasoning (13).

In extensive tests with three heat-resistant alloys, it was also established that in the absence of large metallurgical alterations fractions of rupture life are additive; i.e., the portion of life used up by a given period of time at a particular stress is simply the actual time at that stress divided by the rupture life in a test with that same stress throughout. Rupture will occur when the sum of all the fractions of live consumed reaches unity (14). These results have been confirmed for alloys of other types (15).

For materials and temperatures where the addibility of life fractions holds, the actual rupture life to be expected for a vessel under a stress gradient can be calculated, limited only by how closely one can determine the initial stress pattern and follow the changes with time of this pattern at critical points of the vessel.

Effect of Variable Temperature

Pressure equipment is frequently operated batch-wise, with intermittent heating to service temperature for an on-stream period and then cooling before the next cycle. Long-time experience indicates that for metallurgically stable materials under such operation only the period at working temperature need be considered in estimating service life, provided the stress continues to act while the temperature is being brought up or reduced. Almost the same result is to be expected when the stress and temperature rise and fall simultaneously.

If the stress is removed before cooling and not re-applied until after the temperature is brought back up, the result is usually quite different. In this new case, metallurgical changes ("recovery") occur which reduce the strengthening that caused the declining rates of first-stage creep. This results in more creep and earlier fracture than would be anticipated from constant temperature and stress. It is possible for very frequent temperature cycles to keep the metal always in the primary creep period, considerably reducing life.

In advertent overheating in service under stress to excessive temperature, even briefly, can reduce life of a pressure vessel very sharply. This results partly from the much shorter rupture life at higher temperatures where a few minutes' operation can be as harmful as many hours at normal operating conditions. In addition, temperature-induced structural changes can be very damaging. Overheating can also have other deleterious effects. If restraint to expansion is present, thermal shock could easily be the worst damage. Protective oxides may be destroyed, with resultant acceleration of corrosion.

Thermal Stresses and Thermal Shock

In a heavy wall pressure vessel, it is difficult to avoid uneven heating and cooling. The restraint to expansion or contraction imposed by the parts of the vessel which have expanded less (heated to a lower temperature) or contracted less (not cooled as much) results in a localized stress. Restrained expansion can be a source of very high stress. Steels subjected to temperature gradients of 200° to 300° F per inch under complete restraint would develop stresses in excess of the fracture strength. On the other hand, heating without restraint to expansion causes no thermal stress no matter how large the temperature change.

A uniform steady temperature gradient through a vessel wall would be subject to stress redistribution by yielding and creep relaxation at a sufficiently high temperature. Such stresses and their effects would be subject to the principles previously discussed. The important point to recognize is that such temperature gradients can be sources of high stresses.

In many cases high thermal stresses are only temporarily present during rapid rates of heating or cooling before the temperature reaches a final uniform level. Such rapid non-uniform heating or cooling in the presence of a high degree of restraint is commonly called thermal shock. Only rarely does failure occur in one cycle. Repeated heating and cooling induces a fatigue effect, eventually causing cracks or undue warping.

Thermal shock stresses are a function of the temperature gradients and the degree of restraint. Both vary over wide ranges and usually cannot be determined sufficiently well to calculate effects. A further complication is the continual change in stress and temperature as the part heats or cools, so that it is difficult to relate these factors to metal properties.

The usual recourse is to conduct thermal shock tests. The results of such tests are highly empirical and generally cover only one condition of stress and restraint. Specimens are repeatedly subjected to a specific condition of non-uniform heating and cooling until cracks appear. Unless such tests are closely correlated to actual service conditions the results may not predict metal behavior in the proposed service.

The lower the coefficient of expansion, the less the difficulty from thermal stresses. Likewise, the higher the thermal conductivity the less severe will be the temperature gradients. These two factors are the major reasons why thermal stress problems are more severe in austenitic stainless steels than in low alloy ferritic steels. It can also be postulated that low yield strength and high ductility reduce the peak stresses by stress adjustment. Thus, as alloys become more refractory and maintain strengths to higher temperature the more severe the thermal stress problems. If ductility is sacrificed for strength, the problem will be intensified.

When equipment operates intermittently, the period of holding at high temperature may allow recovery from the plastic deformation of thermal shock which occurred during the heating period or during cooling on a preceding cycle. This may allow further plastic flow during succeeding cycles without fracture. It is possible to repeat such processes and finally obtain total deformations much larger than would occur in a tensile test, thus leading to more warpage than can be tolerated.

Thermal stresses can be quite high at any temperature in the temperature range involved in heating and cooling. Thus, it is important that an alloy not be unduly brittle at any temperature in this range. Often thermal shock failures occur at quite low temperatures because the alloy is brittle at those temperatures or became brittle as the result of prior service at higher temperatures.

In addition to the damage arising from the stress present in thermal shock, there is a largely-unknown field involving combined effects of temperature and plastic flow on the properties of the metal afterwards. In many cases there is reason to suspect that loss of strength or embrittlement introduced by the thermal shock may be of more importance than the stress effects themselves.

Fatigue

Under dynamic loading fracture can occur by "fatigue" when the maximum stress is only 40 to 60 per cent of the static ultimate strength. At low temperatures superimposing dynamic stresses on large static stresses can reduce the load carrying ability as is commonly shown by Goodman diagrams. The intermittant strokes of the piston pumps employed for extreme-pressure applications could lower the load-carrying ability below that predicted by calculations based on a steady nominal pressure.

As temperatures are increased the ratio between static ultimate tensile strength and fatigue strength under completely reversed stresses does not change much. However, when temperature is sufficiently high creep makes the ultimate strength time dependent. Temperatures and time periods for rupture are eventually attained for all materials where the rupture strength is less than the fatigue strength. These temperatures become lower as the time for rupture increases.

Fatigue strengths in steels for completely reversed stresses do not reach a fatigue limit at elevated temperatures as they do at ordinary temperatures. The fatigue strength continues to decrease with increasing numbers of cycles of stress, similar to the behavior of non-ferrous metals. Most fatigue strengths at high temperatures are evaluated in terms of the stress for failure in 10^8 cycles.

Combined static and dynamic stress effects at high temperatures can best be appreciated by considering the effects of superimposing alternating stress on steady stresses. The general effect is illustrated by Figure 6. Alternating stresses superimposed on the stresses for rupture in several time periods have less and less effect on the stress for rupture in a given time period as the temperature and time period for rupture increases. At 1500° F the alternating stress has little effect until it approaches the 1500° F fatigue strength. Small superimposed stresses frequently increase the steady stress required for fracture in a given time period. Apparently similar influences occur for limited amounts of creep.

Various materials differ in respect to the temperature and time periods at which superimposed alternating stress ceases to reduce strength. Figure 6 illustrates only the general effect but not the specific effect for all alloys.

Fatigue is very sensitive to stress concentrations. A stress concentration does not deteriorate as much with time as it can when static creep occurs. Increasing temperature, therefore, does not reduce the damaging effect of a notch nearly as much as it does for static loading.

On the other hand, the beneficial effects of residual stresses in offsetting fatigue loading is less helpful at elevated temperatures. Operations frequently used at low temperatures to increase fatigue strength which depend on residual stresses, such as shot-peening surfaces exposed to bending fatigue, lose their advantage due to creep-relaxation removing the residual stresses. Care must be exercised at high temperatures to insure that surface cold work does not greatly reduce strength and thereby make a material more susceptible to fatigue. Also, corrosion problems can intensify fatigue effects.

Corrosion Effects

Chemical reactions of a deleterious nature between the environment and a pressure vessel are difficult to predict. They range from simple air oxidation through reaction with a large variety of chemical compounds which may be introduced into or formed by reactions taking place in pressure vessels. Specific knowledge of probable behavior is generally required for each case. Hydrogen introduced into the metal could cause serious embrittlement or even corrosion effects under certain circumstances. High pressures or high stresses in the metal of the vessel present additional hazards by possible alterations of the corrosion from expected normal behavior.

Each case requires careful analysis of available experience and test data for the expected corrosion effects. It is difficult to devise laboratory corrosion tests which faithfully anticipate service conditions. In extreme-pressure applications considerable caution is needed in applying available corrosion data until experience is obtained. Certainly it is to be anticipated that the higher pressures and high stresses will alter known corrosion characteristics. Unfortunately, relatively little test data or experience is available even under less severe service conditions for most of the high-strength alloys developed only recently.

Corrosion effects may be far more damaging in extreme pressure applications than in less severe types of service. Previous discussion has emphasized the reduction in safety margins when stress concentrations are present. Thus, if corrosion causes pitting or intergranular corrosion the resulting stress concentrations can be very dangerous.

Stress corrosion cracking problems certainly would be expected to increase in extreme pressure applications. Relatively little is known about such reactions where the combination of a critical stress and a corrosive medium can cause rapid and spectacular failures with little or no external evidence of corrosion. Such effects can occur with surprisingly mild corrosive media. For example, it has recently been found that austenitic stainless steel can be peculiarly susceptible to stress-corrosion cracking at temperatures around 600° F where there is a water-steam interface with a slight chloride contamination in the water.

Repeated stressing well within the fatigue limit of an alloy may be perfectly safe. If, however, the stress accelerates corrosion and the corrosion introduces further stress concentrations, the ability of the material to withstand fatigue loads may be drastically reduced.

Other Types of Data

Elongation and reduction of area values in rupture tests are valuable indicators of probable performance of an alloy. Previously, the relations of such values to relaxation characteristics and notched-bar properties as indicators of stress concentration sensitivity was discussed. The usual uncertainties of actual service conditions make it desirable to have a ductile material so that deformation may warn of impending failure. Ductility values are also useful in determining if metal quality is correct.

Impact tests are another useful measure of metal performance. Most alloys have high impact strength at high temperatures. Certainly, low impact strength would be reason to be very suspicious of material for a pressure vessel. Concern is not only over response to rapidly applied stresses but also over the accompanying indication of susceptibility to brittle failure under complex stresses. If impact tests are conducted over a range of temperatures, a temperature is found where the energy absorbed falls off very rapidly. At or below these impact transition temperatures the alloy will be liable to brittle failure under shock loads and is susceptible to brittleness under stress concentrations. Thus, for low temperatures only materials with very low impact transition temperatures, such as 18-8 stainless steel or aluminum are favored for pressure applications. Most steels have transition temperatures not far from room temperature. If a vessel is to be exposed to high stress at low temperature, even though it operates most of the time at higher temperature, materials with low impact strength should be avoided.

Exposure to temperature and stress may embrittle many materials. Consequently tensile and impact data which do not show embrittlement developing at lower temperatures after such exposure are reassuring. It is important to recognize that such changes generally raise transition temperatures. Material with a sufficiently-low transition temperature initially could become brittle at temperatures somewhat above normal as a result of high-temperature service.

Ductility and impact tests, as well as bend tests, have utility as checks on metal quality, though the tests themselves bear little direct relation to design. Results are useful in establishing whether the material has sufficient freedom from flaws and the proper structure to respond correctly to design conditions.

USE OF PROPERTIES IN SELECTING ALLOYS

The preceding section presented the principles of relating the usual strength properties of alloys at high temperatures to the more complex conditions of actual service. Because such strength properties under creep conditions are both temperature and time dependent, it is necessary to establish which ones apply for a given application.

Experience indicates that the measurement of strength used for alloy selection and proportioning of parts should not exceed the yield strength in any case. Likewise, where creep governs strength, the deformation in service should be limited to between 1 and 2 per cent during the design life for pressure vessels. It would seem necessary to avoid actual failure, thus ruling out design to the full rupture strength. Larger deformations than 1 to 2 per cent might allow instability to develop in the highly stressed vessel with consequent unduly rapid increases in applied stress.

For any life up to about 10,000 hours, it would seem necessary to obtain data on stress versus time for total deformation. Long practice indicates that the commonly available stresses for creep rates of 0.0001 per cent per hour (1 per cent per 10,000 hours) and 0.00001 per cent per hour (1 per cent per 100,000 hours) can be used for more prolonged service and meet the requirement of limiting the deformation to 1 to 2 per cent.

In practice it is recommended that both creep and rupture data be considered. The stress for 10,000 hour rupture life ought to be no more than 70 to 80% of that for a creep rate of 0.0001% per hour. The ratio for 0.00001% per hour and the 100,000 hour rupture strength should be no more than 60%. Higher ratios indicate that one or the other strength value is in error, or that failure will occur with very little deformation. The latter is indicative of stress concentration sensitivity. Lower values of the ratio usually indicate that minimum creep rates were not established in the creep tests or that the rupture strength was incorrectly extrapolated. Those experienced in high temperature testing can usually explain such discrepancies in the data so that correct appraisals can be made. Elongation and reduction of area data from the rupture tests provide additional useful information about the characteristics of an alloy.

The next step is to estimate the actual metal temperatures. If the temperature is not constant, the proportions of expected life at various temperatures and stresses should be estimated so that the fraction of life used up at the various conditions can be estimated. It turns out that a relatively small proportion of the total life at a high temperature and stress governs total life due to the far more rapid rate of use of available life with increasing temperature. Situations involving temperature gradients may require somewhat more complex estimates to determine the governing temperature-stress conditions.

The ASME has established allowable stresses as a function of temperature for alloys commonly used for pressure vessels (16). Whenever code requirements must be met, these stresses apply regardless of the expected life. These stresses were established for safe operation including many non-tangible factors. Where creep governs strength, the stresses are based on 100% of the 0.00001% per hour creep strength or 100% of the 100,000 hour rupture strength whichever was lower, using conservative average values for each alloy. This procedure does not allow for expected service life other than that the engineer has the option of using lower stresses where long life requirements make such procedures desirable in his opinion. He does not have the option of using higher stresses for shorter life applications, so long as the code applies, without obtaining special approval by the Code Committee. Furthermore these allowable stresses at temperatures below the point where creep governs do not permit use of the full yield strength. They are furthermore based on minimum tensile and yield strengths permitted under applicable specifications for alloys. No credit is allowed for special heat treatments to enhance properties at either low or high temperatures.

With the criteria of strength, expected service life and temperature conditions fixed, data for available alloys can be surveyed and estimates of the dimensions of the vessel developed for various alloys. This generally will greatly narrow down the possible choices. At the same time, estimates of corrosion effects should be made, probably further narrowing the possibilities.

At this point, it is necessary to evaluate the uncertainties involved. If the service stresses and temperatures and the properties of the alloys are quite accurately known, the principles outlined justify design to the full limit of the properties of the alloys. However, if considerable uncertainty in these values exists, most engineers tend to be conservative. If the major uncertainty involves stress concentration effects, notched-bar rupture data or ductility data in rupture tests indicating notch insensitivity justify ful use of the strength data. If the alloy has known notch senstitivity, the wall must be proportioned using the maximum effective stress initially present at the bore, with no allowance for any stress redistribution by creep.

The usual relaxation test data can be directly applied to bolting, shrink fits, and other applications where performance depends on maintenance of elastic pre-stressing. It is as yet not possible to apply relaxation test results to stress redistribution problems. Simple relaxation correlates qualitatively with stress-concentration sensitivity. However, quanititative relationships have not yet been developed.

Uncertainties in the temperatures of operation probably lead, in practice, to the most conservative design. Strengths fall off so rapidly with temperature increase that engineers must be sure that the strength is adequate for the highest possible temperatures. Analysis of many pressure applications at high temperatures has shown very conservative design stresses due to temperature uncertainties. In design for extreme pressure applications, with the need for efficient use of alloys, it is vital that temperatures not only be known but also accurately and reliably controlled. The choice of the temperatures for which the strength properties will be used must be guided by how well this can be done.

Consideration should also be given to the previously mentioned fatigue, thermal shock, impact and effects of structural changes. Difficult as it may be, thermal stresses should be included in estimates and, if thermal shock is to be expected, how well the material will withstand it. Most of these factors are very indefinite and difficult to include firmly in an analysis. Usually all the needed information is not available. Careful inspection during service to insure freedom from these difficulties is therefore necessary.

In addition to design problems, a number of metallurgical problems must be considered. All alloys have ranges in properties inherent to the normal variations in chemical composition, manufacturing conditions, heat treatments and certain less tangible effects generally classified as "heat-to-heat" variations. Thus, the high temperature strength is not a single fixed value but a range for each specific alloy with a specific treatment. The problem then arises as to which values to use. Usually, the required time and cost of creep-rupture tests prohibit determination of strength values for each heat. The value of such tests is also doubtful unless the test material would be subjected to the same conditions of manufacture as the pressure vessel itself.

Usual practice is to use conservative average values when sufficient data are available. In a critical design such as a vessel for extreme pressures, this can be dangerous. This, again, is a reason why engineers tend to be conservative in the choice of strength criteria. In many cases, parts are fabricated under production conditions and cut up for testing to obtain "typical values". The cost of such procedures, however, generally limits them to proposed high production items. In the absence of such assurance that the expected properties can be produced in a large, heavy walled pressure vessel, it seems necessary to use conservative values.

Quality problems in themselves, as well as inspection problems, increase with section size and lack of experience. The alloy producers and fabricators, therefore, have a far more difficult task in providing material known to be free from defects. This is especially true where only one or at most, a limited number of parts are made, as is liable to be the case for vessels for extreme pressures. In the case of high strength heat-resistant alloys, where there may be little experience with large sized, heavy wall vessels, it may be necessary to carry on development work to obtain the necessary "know-how".

Fabrication problems may become controlling factors. Many quite widely-used alloys which give no problems in ordinary use may become troublesome in larger sizes. For instance, 18-8 Cb (Type 347) stainless steel has been used for many years and enjoyed a good reputation for weldability. Yet, at the present time, welding problems in heavy wall pipe for the newer high temperature steam plants are very serious. The alloy is apparently subject to a hot-shortness just under the melting point which makes it difficult to produce crack-free welds in heavy sections. Secondly, sections of the heat-affected zones adjacent to the welds tend to crack in service. Apparently, these zones are deficient in ductility and ability to withstand thermal stresses as a result of being heated to temperatures in excess of 2000° F during welding. Many of the so-called new "Superalloys", which may have attractive properties for highly loaded pressure vessels, can have weak brittle welds. This is particularly true for alloys which develop high strength through precipitation hardening from titanium plus aluminum additions.

Care must be exercised in considering the possibility of using many alloys to be sure that they can be made and fabricated in the section size needed. There may also be pactical restrictions in production conditions or response to heat-treatment which will result in properties considerably different from those reported in the literature for the usual tests on small-size bar stock. For instance, it might be entirely impractical to hot-cold work a pressure vessel to enhance its properties although the procedure might be routine in bar stock or gas turbine rotor disks. Often it is necessary to limit solution heat treating temperatures to lower temperatures than were used to obtain test values on bar stock in order to obtain fine grained ductile metal structures. It may be impossible to make a large size casting with adequate properties even though the alloy may be very successful as a small casting. This is particularly true for those alloys which are normally investment cast.

PROPERTIES OF ALLOYS

A large number of possible metals and alloys might be used depending on the temperature and stress. Figure 7 has been included as a means of orientation of the possible useful temperature range for the various base metal systems. The criterion of stress for rupture in 1000 hours was used because it was the measure of strength most universally available. The comparison is far from complete but it does indicate the temperature and stress ranges of usefulness for most base alloy systems and types of alloys. Creep strengths would shift the stress levels to lower temperatures or, at a given temperature, to lower stress levels.

The comparison shows the progression of useful temperatures for base alloy systems from magnesium, aluminum, copper, titanium, carbon and low alloy steels, stainless steels, through the so-called Superalloys. Additional materials are shown as a matter of interest. Molybdenum and molybdenum base alloys maintain a very high level of strength to very high temperatures. It is now available in large sizes and a variety of forms from arc-cast ingots. However, it deteriorates very rapidly by oxidation in the temperature range where strengths are of most interest unless protected by an oxidation-resistant coating. Reliable coatings are not yet established although promising techniques are available. There are also many fabrication problems. The cermet data show the strength levels obtained in products made from metal-refractory carbide mixtures. Cermets are highly experimental and suffer from stress-concentration and impact sensitivity. The material designated SAP (Swiss Aluminum Powder) shows the large increase in possible temperature at useful strength levels obtained by preoxidizing pure aluminum powder and then producing billets by powder metallurgy techniques. The material can be forged, rolled or extruded and yet retain high creep resistance. It is still experimental with some shortcomings. The technique is interesting for, if comparable gains in heat resistance could be obtained by a like technique in higher melting point metals, it would result in a major increase in useful temperature ranges. Titanium alloys are included in the comparison in view of their excellent corrosion resistance and high strength. The useful temperature range for titanium now extends to about 700° F with indications that it may eventually be raised to 1000° F. Much has been learned about the metallurgy of titanium. It is, however, a relatively new material with a good deal remaining to be learned about its fabrication and reaction to service conditions, so that its use should be approached on an experimental basis. Titanium is particularly prone to embrittlement by hydrogen and any conditions exposing it to hydrogen should be carefully reviewed before it is used. It is also very expensive.

A number of the superalloys are only available as castings. In some cases, these may be limited to relatively small investment castings.

Most pressure vessels are made of steel. The usual materials range from carbon steel through increasing amounts of chromium up to 12 per cent combined with 0.5 to 1.0 per cent molybdenum. Typical creep data for these materials are included in Table 1. These alloys are usually used in the soft condition, either annealed or normalized and tempered. Carbon steel is usually used as hot-worked. Maximum strengths generally are obtained in the 1.25 per cent Cr - 0.5 per cent Mo steel up to about 1000° F and in the 2-1/4 Cr - 1 Mo up to 1100° F.

A number of medium-carbon low alloy steels can be heat treated to quite high levels of strength in the temperature range up to 1000° to 1100° F. Such steels may have useful characteristics for some pressure vessel applications. The Cr-Mo-V steels maintain strength up to the highest temperatures for this group except for the complex 12 Cr steels. It should be noted that as the temperature and time period increases these steels lose their superiority to the softer annealed conditions or to the soft low-alloy steels of the previous group.

The standard stainless steels represent the next step upward in ability to maintain strength with increasing temperature. Most of these steels have rather low yield strengths and this tends to limit applied stresses.

There are a large number of relatively new alloys which have combinations of attractive properties for high-stress applications at high temperatures. Some of the available strength data are included in Table 1. It should be recognized, as previously discussed, that it may or may not be possible to fabricate pressure vessels from these alloys. To the authors' knowledge, some experience is available with a number of these alloys such as 19-9DL, N-155, and Inconel-X. The newer most refractory alloys, such as M252, Waspaloy, Inco 700, Udimet 500, etc., may have severe size limitations at the present time. They are universally more difficult to machine than are the standard stainless steels. Such alloys as HS 21 and HS 31 (X-40) have mainly been used as relatively small investment castings.

It is to be emphasized that this list of alloys is by no means complete. The ramifications of production condition, heat treatments and properties have not been adequately covered. In those cases where properties are potentially useful, it is strongly recommended that the possible application be reviewed with the alloy producers. This should be done, in any case, for any alloy. Such groups have a background of experience and "know how" which is essential to the success in special applications.

CONCLUSIONS

Principles of using available data to select alloys for vessels for extreme pressure at elevated temperature have been reviewed. When the service stresses and temperatures are accurately known, together with properties of the specific lot of alloy used, performance of the alloy will be in accord with predictions within practical engineering limits.

Some of the properties which may be used to provide safeguards against some unknown stress conditions were discussed.

A short listing of alloy properties is given. This was intended to indicate typical properties of some of the newer alloys with high strength at high temperatures.

Metallurgical variables which are always present require a more thorough study for each application than can be covered in a paper of this type. Direct consultation with the alloy supplier is suggested before a new alloy is selected for use at conditions where no prior experience exists.

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TABLE 1

HIGH-TEMPERATURE PROPERTIES OF SOME REPRESENTATIVE ALLOYS

	Chemical Composition, Percent by Weight												
Alloy	C	Mn	SI	Cr	Ni	Co	Mo	W	Cb	Ti	Al	V	Others
Low carbon steel	0.15max	0.5	0.25max										
1.25Cr, 0.5Mo steel	0.15max	0.4	0.75	1.25			0.5						
2.25Cr, 1 Mo steel	0.15max	0.4	0.3	2.25			0.5						
4140 steel	0.4	0.9	0.3	1			0.2						
Cr-Mo-V steel	0.3	0.5	0.75	1.25			0.5					0.25	
C422	0.2	0.75	0.35	13	0.75		1		1			0.3	
Stainless, type 304	0.08max	0.6	0.6	18	9								
Stainless, type 347	0.08max	1.5	0.5	18	12				0.8				
19-9DL	0.3	1.1	0.6	19	9		1.2	1.2	0.4	0.3			
16-25-6	0.1	1.25	0.7	16	25		6						N 0.15
17-24 CuMo	0.12	0.75	0.5	16	14		2.5		0.45	0.25			Cu 3.0
Croloy 15-15N	0.10	1.5	0.5	15	15		1.5	1.5	1.0				N 0.12
A-286	0.05	1.35	0.95	15.5	26		1.25			2	0.2	0.3	
N-155	0.12	1.6	0.4	20	20	20	3	2	1				N 0.12
S-816	0.40	1.3	0.6	20	20	Bal.	4	4	4				
Inconel X	0.05	0.5	0.4	14.5	Bal.	1.0				2.5	0.8		Fe 7.0
M-252	0.15	1.0	0.65	19	Bal.	10	10			2.5	0.9		
Waspaloy	0.07	0.6	0.6	19.5	Bal.	13.9	3.3			2.8	1.1		Fe 1.1
Inco 700	0.1			15	50	27	3			2.25	3		
Udimet 500	0.08	0.2	0.2	20	Bal.	15	3.5			3	3		
HS31 (X-40)	0.48			25	9.7	55		7.2					

TABLE 1 (continued)

Alloy	Stress (psi) for Minimum Creep Rate of 0.0001%/Hour = 1%/10,000 Hours											
	800°F	850°F	900°F	1000°F	1100°F	1200°F	1300°F	1350°F	1400°F	1500°F	1600°F	1700°F
Low carbon steel	19,000		11,000	5,000	1,700	800						
1.25Cr, 0.5 Mo steel	32,000		26,500	18,000	7,000	4,000						
2.25Cr, 1 Mo steel			40,000	14,000	8,000	4,500						
4140 steel												
Cr-Mo-V steel												
C422												
Stainless, type 304			28,000	20,000	13,000	8,000	5,000		3,000	2,500		
Stainless, type 347				32,000	23,000	16,000	10,000		5,000	1,750		
19-9DL (Annealed)						22,000		12,500		5,000		
19-9DL (Hot-cold worked)						34,000						
16-25-6						22,000	15,000		10,000	6,000		
17-24 CuMo						24,000		16,000		11,000		
Croloy 15-5N						23,200		13,500		9,400		
A-286						28,000						
N-155						29,000		14,000		9,000		
S-816						29,000		20,000		11,000		
Inconel X						63,000		37,000		18,000		
M-252												
Waspaloy												
Inco 700												
Udimet 500												
HS 31 (X-40)												

TABLE 1 (continued)

	Stress (psi) for Minimum Creep Rate of 0.00001%/Hour = 1%/100,000 Hours										
Alloy	800°F	850°F	900°F	1000°F	1100°F	1200°F	1300°F	1350°F	1400°F	1500°F	1600°F	1700°F
Low carbon steel	10,800		6,500	2,500	1,000							
1.25Cr, 0.5 Mo steel	15,000		13,100	7,800	2,800	1,500						
2.25Cr, 1 Mo steel	18,000		14,000	7,800	4,200	2,000						
4140 steel		10,000	7,000	2,400								
Cr-Mo-V steel			44,000	14,000								
C422												
Stainless, type 304			20,000	15,000	7,000	4,000	2,500		1,500	1,000		
Stainless, type 347				27,500	16,500	10,000	5,000		2,000	1,000		
19-9DL(Annealed)						12,000		7,000		2,000		
19-9DL(Hot-cold worked)						15,000						
16-25-6(Annealed)						13,000	9,000		6,000	4,000		
17-24 CuMo						19,000		10,000		6,800		
Croloy 15-15N						13,500		9,000		5,400		
A-286												
N-155						22,000		11,000		6,500		
S-816						14,000		12,000		7,000		
Inconel X						53,000		30,000		13,000		
M-252												
Waspaloy												
Inco 700												
Udimet 500												
HS 31 (X-40)												

TABLE 1 (continued)

Alloy	Stress for Rupture in 1000 Hours (psi)											
	850°F	900°F	1000°F	1050°F	1100°F	1200°F	1300°F	1350°F	1400°F	1500°F	1600°F	1700°F
Low carbon steel	22,000	18,000	11,000		6,000	2,500						
1.25Cr, 0.5 Mo steel		50,000	30,000		16,000	8,000						
2.25Cr, 1 Mo steel			23,000		14,000	8,500	4,000					
4140 steel												
Cr-Mo-V steel			62,000		20,500							
C422			57,000		37,000	17,000						
Stainless, type 304		49,000	36,500		25,000	16,500	10,000		6,000	4,000		
Stainless, type 347			49,000		35,000	23,000	14,000		8,000	4,500		
19-9DL(Annealed)						32,000		12,000		10,000		
19-9DL(Hot-cold worked)						40,000		12,000				
16-25-6(Annealed)						33,000	22,000		12,000	8,000		
16-25-6(Hot-cold worked)						40,000	22,000					
17-24 CuMo				49,000		37,000		20,500		12,000		
Croloy 15-15N						33,000		19,000		9,000		
A-286						47,500		22,500		8,000		
N-155(Annealed)						38,000		25,000		13,000		
N-155(Hot-cold worked)						55,000						
S-816						55,000		30,000		18,000		
Inconel X						67,000		38,000		18,000		
M-252						78,000	54,000		35,000	20,000		
Waspaloy								37,500		20,000		
Inco 700						87,000		59,000		30,000	17,000	8,000
Udimet 500										31,000	14,000	10,000
HS 31 (X-40)									35,000	23,000	16,000	10,000

TABLE 1 (continued)

Alloy	Stress for Rupture in 10,000 Hours (psi)											
	850°F	900°F	1000°F	1050°F	1100°F	1200°F	1300°F	1350°F	1400°F	1500°F	1600°F	1700°F
Low carbon steel	17,000	13,500	7,000		3,500	1,000						
1.25Cr, 0.5 Mo steel		39,000	24,000		11,000	4,000						
2.25Cr, 1 Mo steel			17,500		10,500	5,500	2,000					
4140 steel												
Cr-Mo-V steel			31,000		9,500							
C422			49,000		23,000							
Stainless, type 304		38,000	27,000		17,500	10,500	6,000			2,500		
Stainless, type 347			39,000		27,000	17,500	10,500			2,500		
19-9DL (Annealed)						27,500						
19-9DL (Hot-cold worked)						30,000						
16-25-6 (Annealed)						25,000	14,000		7,500	5,000		
17-24 CuMo				45,000		32,000		16,500		7,600		
Croloy 15-15N						26,500		16,000		6,500		
A-286						31,000						
N-155						26,000						
S-816						42,000		22,000		12,000		
Inconel X						50,000		30,000		12,000		
M-252												
Waspaloy												
Inco 700												
Udimet 500												
HS 31 (X-40)												

TABLE 1 (continued)

Alloy	Stress for Rupture in 100,000 Hours (psi)									
	900°F	1000°F	1100°F	1200°F	1300°F	1350°F	1400°F	1500°F	1600°F	1700°F
Low carbon steel										
1.25Cr, 0.5 Mo steel	30,000	16,000	7,000	2,000						
2.25Cr, 1 Mo steel		14,000	7,500	4,000	1,500					
4140 steel										
Cr-Mo-V steel										
C422										
Stainless, type 304		21,000	13,000	7,000	4,000		2,500	1,750		
Stainless, type 347		32,500	22,000	13,000	7,500		4,000	1,500		
19-9DL (Annealed)				17,000						
16-25-6 (Annealed)				17,500	9,000		5,000			
17-24 CuMo										
Croloy 15-15N				16,500		12,500		4,500		
A-286										
N-155										
S-816				32,000		17,500				
Inconel X										
M-252										
Waspaloy										
Inco 700										
Udimet 500										
HS 31 (X-40)										

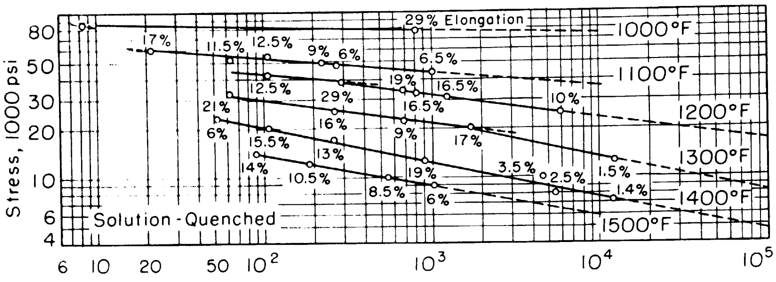

Fig. 1—Stress - Rupture Time Curves for Solution-Treated 16-25-6 Alloy.

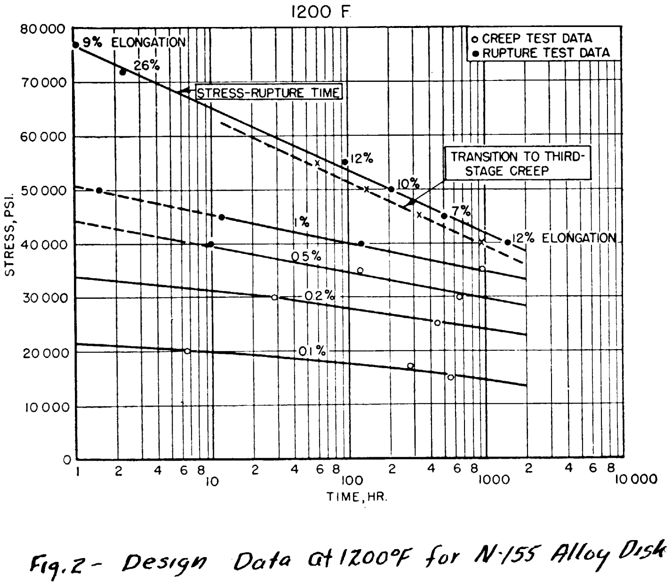

Fig. 2 - Design Data at 1200°F for N-155 Alloy Disk

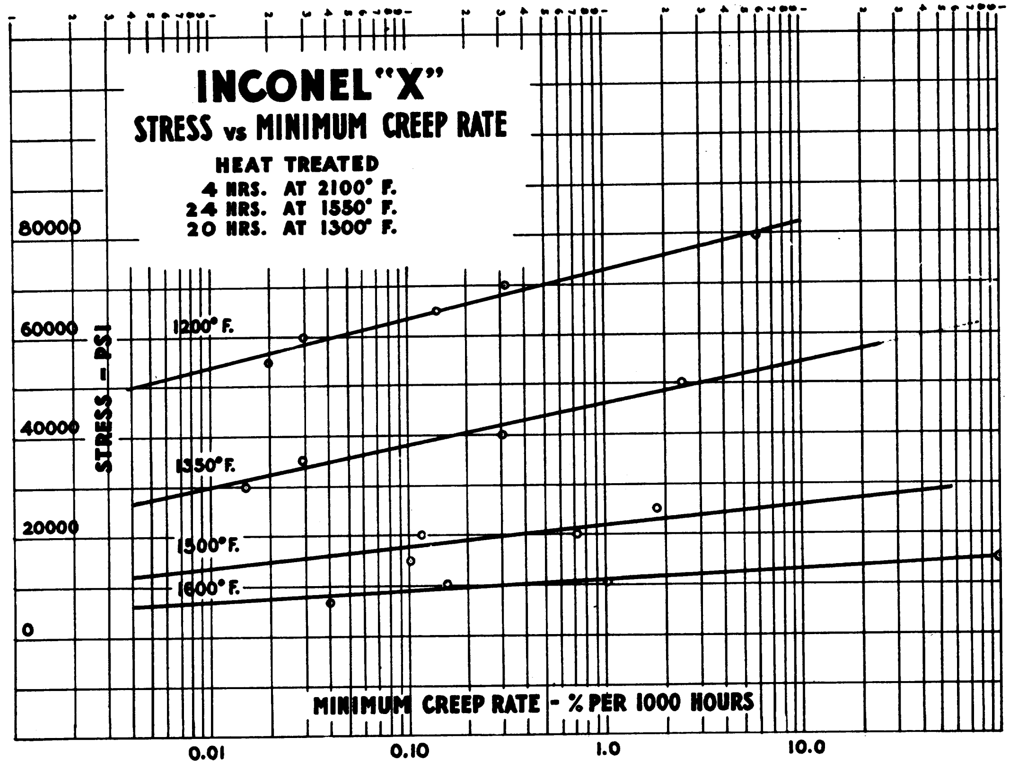

Figure 3. - Typical Stress - Creep Rate Curves

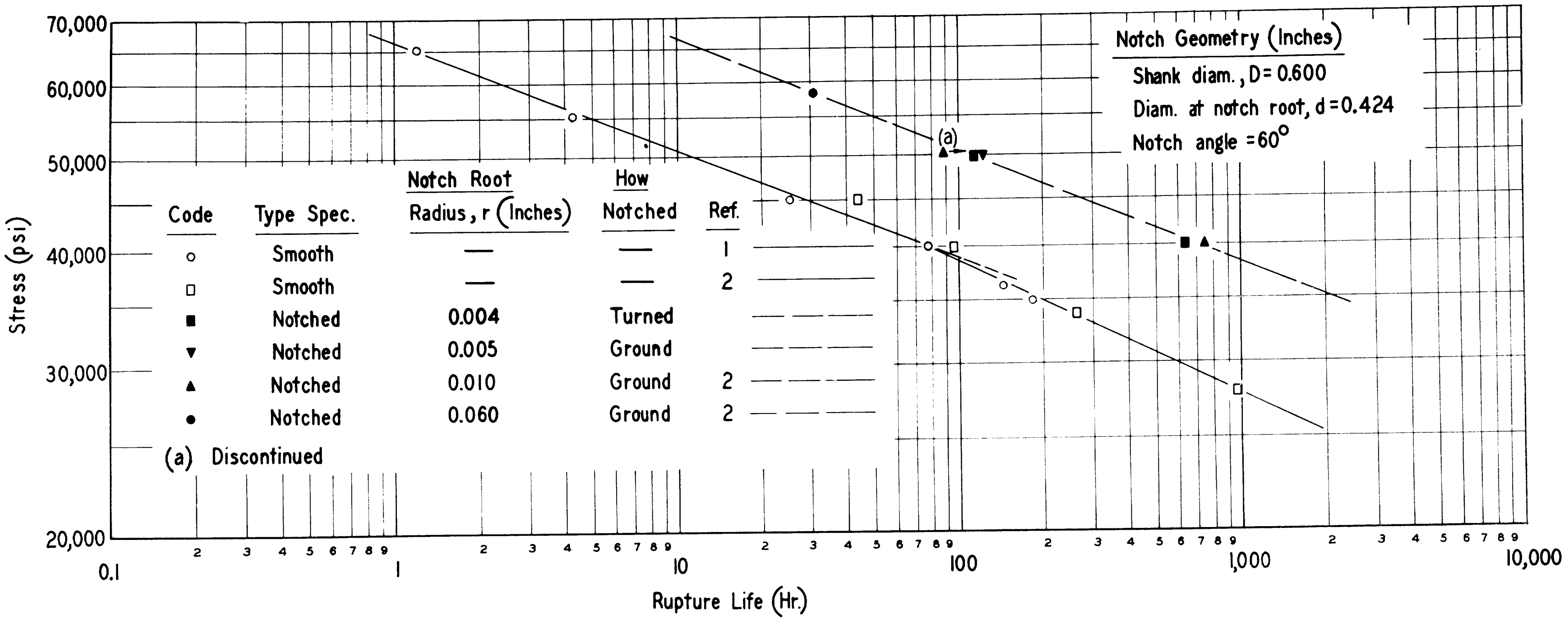

FIG.4 - STRESS VERSUS RUPTURE LIFE AT 1350°F FOR SMOOTH AND NOTCHED BARS OF S-816 WITH CONVENTIONAL HEAT TREATMENT.

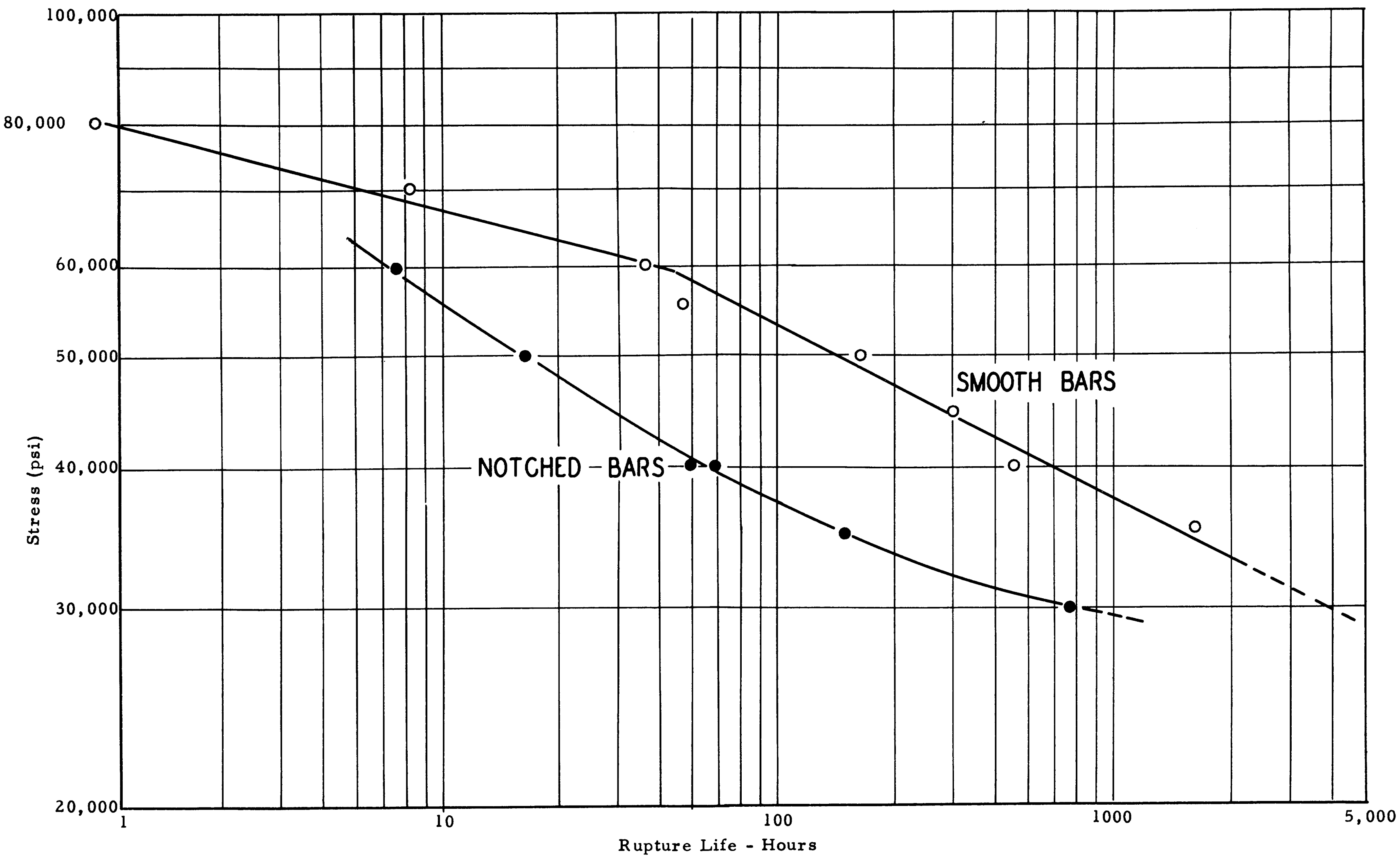

Figure 5.- Stress versus Rupture Life at 1350°F for Smooth and Notched Bars of Inconel X-550

Notch Geometry

Shank Diameter = 0.600 inch
Diameter of Notch = 0.424 inch
Notch Root Radius = 0.005 inch
Notch Angle = 60°

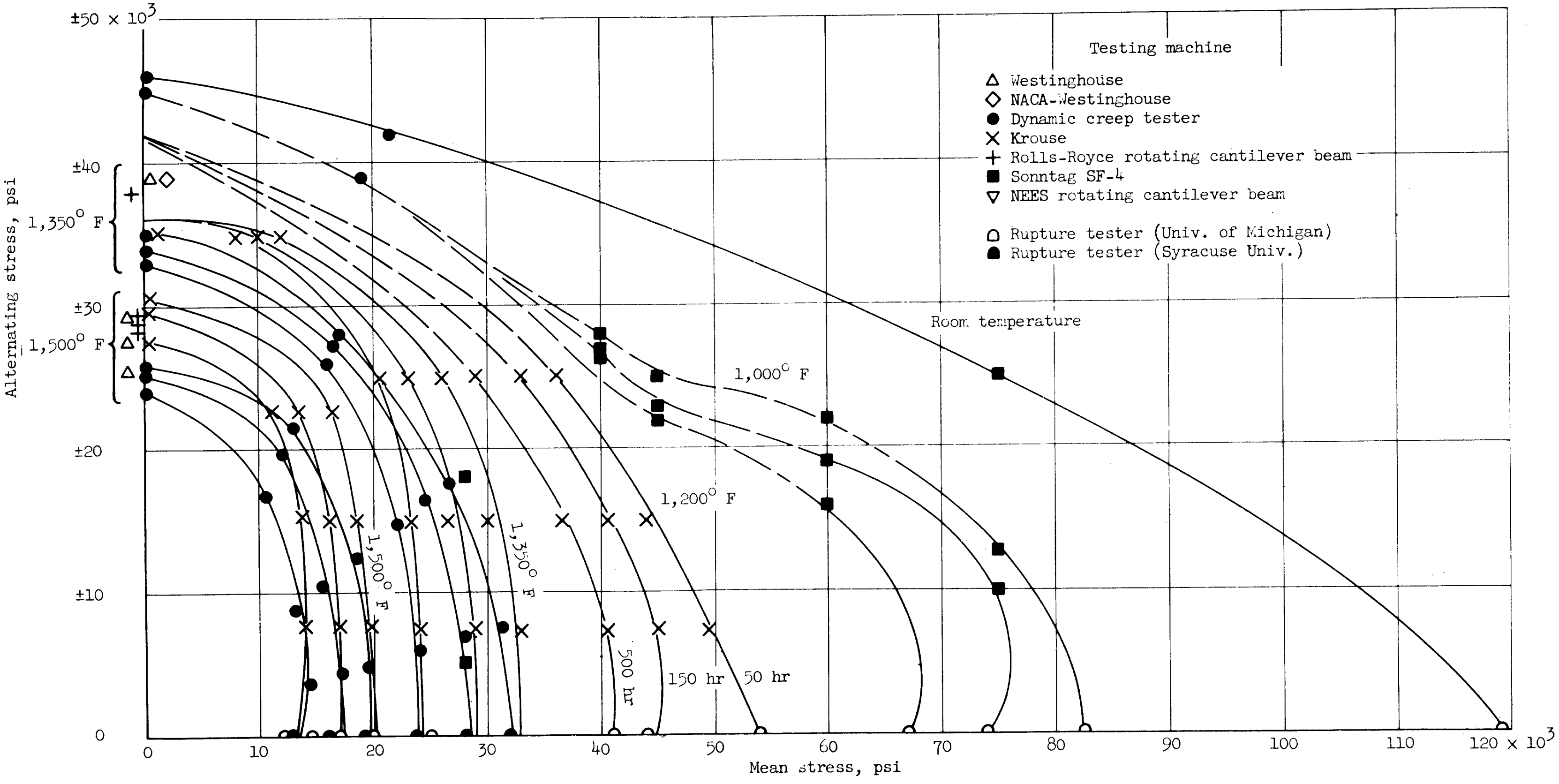

Figure 6.- Curves of alternating stress against mean stress for fracture in 50, 150, and 500 hours at room temperature, 1,000°, 1,200°, 1,350°, and 1,500° F. for N-155 bar stock.

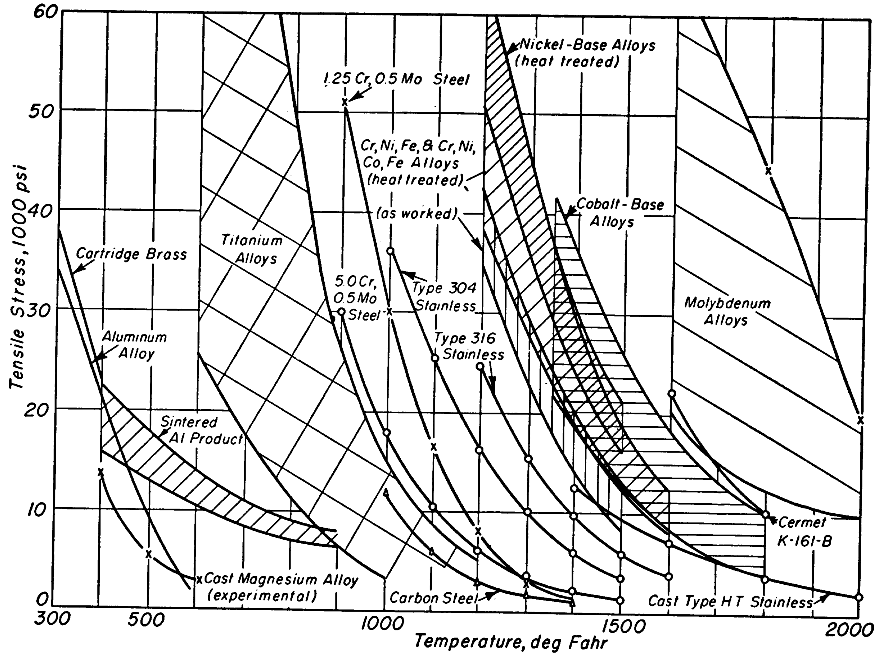

Fig. 7 Stress-Temperature Curves for Rupture in 1000 Hours for Various Commercial and Experimental Alloys