relatively uniform at all temperatures from room temperature to 2100°F. The typical values shown in Figs. 2, 3, and 4 are therefore considered suitable for use as design-allowable strengths.

2 The tensile, yield, and ultimate strengths of N-155 alloy are strain-rate sensitive. Rate effects are noted at critical temperatures which vary with the strain rate used.

3 The tensile elongation and Young's modulus of N-155 alloy are both relatively insensitive to changes in strain rate.

4 The speeds used in conventional room-temperature tensile tests (about 1/2 min to yield, then about 1 1/2 min to fracture) are too slow for determining the realistic short-time tensile strengths at high temperatures due to the major effects of creep.

5 Prior plastic-creep deformation of up to 4 per cent in 900 seconds has no significant effect on the residual tensile strength of annealed N-155 alloy sheet.

6 Creep rates determined at high temperatures and high stresses are extremely rapid. Where such severe temperatures and high, sustained, load levels are encountered in service, the design must be based on creep strength rather than on tensile strength even where comparatively short-time service life is anticipated.

Future Work

The data reported here will be analyzed using time-temperature-parameter methods to determine possible correlations with long-time creep properties. A program to determine the compression strengths and the short-time compression-creep properties of N-155 alloy is also being undertaken. This type of data would be of great value in aircraft and missile design since compression loading very often becomes the governing design criteria in these applications.

Acknowledgments

The author wishes to acknowledge the help received from the many people involved in this work. Particular thanks are extended to A. V. Levy for the many suggestions and critical review of this paper and to C. A. Drury and A. F. Königsfeld who carried out the tests. Thanks are also extended to the Marquardt Corporation for making this research possible and for permission to publish this paper.

References


DISCUSSION

J. R. Kattus

The author has certainly done an excellent and thorough job of evaluating the load-carrying capacity of annealed N-155 alloy sheet under conditions of rapid heating, rapid loading, and short times at temperature. The effects of these conditions on the mechanical properties of N-155 alloy are, in general, quite similar to the effects that we have found in our evaluations of the short-time tensile and creep properties of a large number of other alloys. For example, we have found that the relative effects of tensile strain rate become quite large in all alloys when the temperature is increased above a certain level. This temperature corresponds roughly to the recrystallization temperature of each alloy, strength increasing significantly with increasing strain rate at higher temperatures as shown in Figs. 2 and 3. In contrast to the author's data for N-155, we have found that the tensile...
strength of most alloys also tends to increase, but to a relatively much smaller degree, with increasing strain rate at lower temperatures. In some alloys, however, over certain temperature ranges, strain-rate-sensitive structural changes such as strain aging reduce or completely counterbalance the inherent strengthening effect of increasing strain rate.

The finding that variations in holding time at temperature from 2 to 30 min have no significant effect on the tensile properties of annealed N-155 alloy should not be construed to mean that this is not an important variable in all alloys. The annealed N-155 happens to be a stable material over the entire range of test temperatures. Many other materials, particularly those that are hardened by heat-treatment or by cold work, undergo changes in metallurgical structure at high temperatures. These structural changes are often accompanied by a marked deterioration in mechanical properties. Since the structural changes are dependent upon both time and temperature, a small variation in holding time at certain temperatures can have quite significant effects on strength properties. In some comparative evaluations of cold-worked and annealed N-155 alloy, for example, we have found that the cold-worked material retained a constant relative superiority in strength over the annealed material at temperatures up to 1500°F regardless of variations in holding time from 10 sec to 30 min. At higher temperatures, the recrystallization process in the cold-worked material caused a decrease in strength with increasing holding time, whereas the annealed material was unaffected by variations in holding time. After a 10-sec holding time at 2000°F, for example, the cold-worked material retained the same relative strength advantage that it had had at lower temperature; whereas after a 30-min holding time the strength of the cold-worked material had decreased to a level below that of the annealed material. The length of time that the structural material in a particular application is to be held at elevated temperature as well as the temperature level and the strain rate can have an important bearing on the choice of a material for that application.

D. M. Lorimer and M. Aarnes

For designs at elevated temperature it is apparent that, in order to reduce weight, materials have to be used past the 0.2 per cent yield strength. Bennett’s paper tends to point out that the yield strength at elevated temperatures is affected by strain rate. Below a certain strain rate at a given temperature the material creeps during test. A boundary should be selected in terms of stress, strain, time, and temperature below which the conventional methods of strength checking analysis will be used and above which the creep deformation has to be considered.

The influence of strain rate can be shown by examining Fig. 5 and considering 1800°F data only. If loading was purely elastic to a given strain, Young’s modulus E and the secant modulus E_s would be equal. The variance of E_s from E is a measure of creep during loading. Selecting 2 mils/in. strain we have

\[
\frac{E_s}{E} = \frac{\sigma_s}{\sigma} = \frac{22,500}{0.002} = 11.25 \times 10^4 \quad (\varepsilon = 0.01\ \text{in/in/sec})
\]

\[
\frac{E_s}{E} = \frac{17,000}{0.002} = 8.5 \times 10^4 \quad (\varepsilon = 0.001\ \text{in/in/sec})
\]

\[
\frac{E_s}{E} = \frac{12,900}{0.002} = 6.45 \times 10^4 \quad (\varepsilon = 0.0001\ \text{in/in/sec})
\]

From Fig. 4, we have E at 1800°F as 13 x 10^6, so:

\[
\frac{E_s}{E} = \frac{11.25 \times 10^4}{13 \times 10^6} \times 100 = 8.5\%
\]

so that for:

\[
\varepsilon = 0.01\ \text{in/in/sec appr. 13.5 per cent of the strain is creep}
\]

\[
\varepsilon = 0.001\ \text{in/in/sec appr. 34.7 per cent of the strain is creep}
\]

\[
\varepsilon = 0.0001\ \text{in/in/sec appr. 50.4 per cent of the strain is creep}
\]

Since the annealed N-155 alloy is quite stable for the holding times used in these tests, it is of no consequence that a 15-min hold was used for the tensile test and a 60-sec hold for the creep test. However, if this is regular practice for all materials, an awkward variable will be present in comparing tensile and creep tests on alloys with unstable microstructure. The greater strength of a heat-treated or cold-worked alloy can be used to advantage in a short-time application and is in many missile parts. Therefore, it would seem logical that no hold time at all should be specified in either test. Resistance heating of the specimen brings them quite uniformly up to test temperature, regardless of the heating rate. For those situations where, for example, a missile is carried in a supersonic airstream and heated for a while before firing, a special holding time simulation had better be prescribed rather than attempt to make it into a universal standardized test.

To carry the discussion of service simulation further, one might ask if the elevated-temperature tensile test above the creep point has any direct application at all. A service condition consisting of a single loading application at a certain strain rate and no holding time would be required. There are very few examples of such service conditions to be found. In nearly every case the load must be sustained for some time interval, even though it is only a few seconds. The author has been careful to point out repeatedly that creep test data should be used if there is any chance that the load may remain even for a second or two at high temperature and stress. It would seem, therefore, that the efforts expended on elevated-temperature tensile testing should instead be on short-time creep tests down to temperatures and stresses that will result in practically no measurable plastic

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D. M. Lorimer* and M. Aarnes

* Boeing Airplane Company, Seattle, Wash.

Warren K. Smith

The author has reported on a well planned and interesting investigation of short-time high-temperature properties of an important alloy. It is gratifying to the writer, after having shared similar misgivings about the use made of high-temperature data, to see these timely remarks and cautions directed to the design engineer.

Since the annealed N-155 alloy is quite stable for the holding times used in these tests, it is of no consequence that a 15-min hold was used for the tensile test and a 60-sec hold for the creep test. However, if this is regular practice for all materials, an awkward variable will be present in comparing tensile and creep tests on alloys with unstable microstructure. The greater strength of a heat-treated or cold-worked alloy can be used to advantage in a short-time application and is in many missile parts. Therefore, it would seem logical that no hold time at all should be specified in either test. Resistance heating of the specimen brings them quite uniformly up to test temperature, regardless of the heating rate. For those situations where, for example, a missile is carried in a supersonic airstream and heated for a while before firing, a special holding time simulation had better be prescribed rather than attempt to make it into a universal standardized test.

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deformation within some reasonable time limit. Below this temperature level, the "transition temperature" in this paper, a tensile test is proper. The writer believes it would be easier to determine this transition temperature by short-time creep tests than by doing both high and low strain-rate tensile tests in the majority of laboratories.

Author's Closure

A number of important aspects related to the short time mechanical behavior of materials were stressed in the discussions. This will help greatly in creating a better understanding of the problems involved in testing of materials and those encountered in using the test data in design.

Regarding the comments on hold time at temperature made by Mr. Kattus and Mr. Smith, it was most certainly not the author's intent to create any impression that this variable is unimportant. Longer hold-times can result in much higher or much lower measured mechanical properties depending on the particular material and test temperatures involved. Furthermore, a hold time of "zero" or any other single time interval is not going to be universally acceptable either. The designer and the materials engineer must continue to analyze each design jointly. The final configurations of the high-temperature components must be based on materials data determined at critical temperatures and times which closely simulate the conditions encountered in service.

Elevated temperature testing is expensive and time consuming; however, there are no alternatives at present. The activity in the high-temperature testing field is increasing constantly and more and more data are becoming available from many different laboratories. In this regard, it is strongly urged that greater care be taken in accurately defining the conditions under which the test data were obtained. This supplementary information must be known before an intelligent appraisal of any reported data can be made.

Mr. Smith questions the relative value of tensile tests carried out at temperatures above the "creep point." The author agrees that, in the majority of cases, creep type data are much more useful for actual design purposes. Where ultrashort-time transient loads which are much higher than the steady-state loads are encountered, however, rapid strain rate tensile data could be used to advantage. Thus it is essential that both creep and tensile data for each high-temperature material are available to the design engineer.

Lorimer and Aarnes raised some objections to the use of electrical resistance heating in the determination of mechanical properties. For the rapid heating rates and high temperatures required, resistance is the only practical method available today. A limited amount of "rapid rate" data generated on equipment using standard furnaces, radiant heaters, hot flowing fluids, etc., have been reported in the literature. It is obvious that in each case difficulties were encountered either in obtaining the higher test temperatures or in adapting suitable strain measuring systems to the equipment. The data that have been obtained are therefore sketchy. In any case, wherever a direct comparison with our resistance heating data has been possible, the agreement is excellent. In addition to the spot checks on N-155 alloy sheet data, comparisons have also been obtained on 2024 aluminum, HM21 magnesium, 4130 low alloy steel, 6Al-4V titanium, 17-7 stainless steel, and Rene 41 nickel base alloy. For the purpose of mechanical property determinations therefore, it is immaterial which method of heating is used. Comparable properties will be obtained provided that both the heating rate and hold time at temperature in each case are equivalent.