Development of a Framework for Presentation and Design Analysis of Creep Rupture Data using the CES Materials Selection Software

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Abstract

This paper describes the incorporation of creep-rupture data, generated on many alloys at the National Institute for Materials Science (NIMS) in Japan, into the Cambridge Engineering Software (CES) materials selector. The software allows several stages of selection based on both graphical and analytical comparisons of materials attributes and processing options, but is currently lacking in specialized high temperature data. The new framework is set up to allow direct comparisons of rupture lives and creep rates at selected conditions for potential alloys of choice. Each alloy record is accessed through a selection hierarchy which codifies the data quality, and includes other mechanical and physical properties. Alloys ranging from ferritic steels to cast nickel-based superalloys are included, with data quality codes ranging from multi-heat long term tests to accelerated tests of a single heat. By providing sigma limits for all data sets, and superimposing normal design criteria such as 67% of the mean stress for rupture, selection may be made on the basis of statistical variability as well as absolute strength comparisons. Materials selection indices may additionally be presented in terms of creep and rupture behavior relative to physical properties such as density and thermal expansion coefficient. The database will be accessible using the CES Web capability.

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Introduction

Creep-rupture resistance is the primary property critical for the design of high temperature equipment. It may be specified in terms of a stress for a limiting creep strain in a specific time or the stress for rupture in a specific time. Because designs for gas turbines, steam turbines and boilers have design lives between 50,000 and 100,000 hours, this usually requires significant data extrapolation. The extrapolation may be done from curve fits to isothermal data or by using optimized time/temperature parameters [1]. The latter approach is especially useful for interpolation and for constructing design curves at temperatures different from those for which test results are available.

There are now many open sources of excellent high temperature materials data that provide the opportunity to develop a generally accessible basis for optimization of selection and design for high temperature applications. Ideally, the database should be amenable to representation in different formats for comparison, be web accessible, and have other critical properties incorporated in the software. For materials selection, this should enable searching on property combinations with specified limits on chemistry or processing options.

The most extensive generally available data has been published by the National Institute for Materials Science (NIMS) in Japan [2]. This database includes about fifty alloys tested for times up to 100,000 hours. Since there is normally a significant scatter in data, stemming from both alloy and test variability, it is appropriate to rate the data source quality to allow incorporation of data from different sources as we build a global alloy database. Thus, because the NIMS data covers very long times on a number of heats for each alloy, it merits an A rating. Similarly, a B rating might be assigned to100,000 hour data on one heat, a C rating for data to 10,000 hours on one heat, and a D rating for a short time parametric study or estimate based on stress relaxation testing [3]. There have been a few programs to study variability among different test laboratories, among different heating methods and even different humidity levels. However, these have generally been of short test duration so all that can really be concluded is that the statistical variations and calculated sigma values in the NIMS data are likely to be optimistic since they were limited to one test laboratory using standardized procedures. It should also be noted that the factors contributing to data scatter in the creep-rupture test may not be directly related to the factors contributing to service failure probabilities. Because of these uncertainties, design codes usually require a general safety factor of two-thirds on stress. Since data scatter bands are alloy and process sensitive, rupture data may also be presented with three sigma limits on life.

The creep-rupture database is being setup using the Cambridge Engineering Software (CES), available from Granta Design [4]. The software currently contains several thousand records of materials in which each record contains a systematic and generally complete set of attributes used in materials selection for room temperature applications. There are currently no high temperature creep-rupture data but the structure of the software and the power of the comparative materials selection tools make this an excellent foundation for the creep-rupture database. The NIMS data are fitted with an optimized Larson-Miller, Manson-Haferd, Manson-Succop or Orr-Sherby-Dorn parameter [1]. Polynomial equations could then be set up for rupture life in terms of stress and temperature for the range covered, with the standard error of estimate in terms of logarithmic rupture times (SEE or sigma) and also the coefficient of determination (COD). Minimum creep rates were calculated from linear regression between rupture time and minimum creep rate (Monkman-Grant relation [1]). Provision was also made to estimate times to specific creep strains using linear regression between rupture stress and creep stress in the same time (Goldhoff-Gill correlation [5]). To maximize functionality of the data the parametric equations were converted to high resolution gridded functional data which could then be used to show different relationships among the variables within the CES software.

To establish the framework, four comprehensive databases have so far been incorporated in the CES software. The methodology is described in some detail for one of these.

Hierarchical Alloy Description

The following hierarchy for alloy selection was established:
<u>Alloy Group</u> (carbon steel, low alloy steel, high alloy steel, iron-based superalloy, nickel-based superalloy)
<u>Processing route</u> (cast, wrought, powder)
<u>Chemistry</u>
<u>Heat treatment</u> (annealed, normalized, quenched and tempered, solutioned and aged)
<u>Product form</u> (tube, plate, bar, forging, casting)
<u>Specification</u> (ASTM, STB, ASME, SUS, NCF, AMS, AISI)
<u>Application</u> (discs, blades, pressure vessels, rotors, welds, furnaces)

To develop the database format, NIMS data for four alloys were analyzed:
Low alloy steel, 0.5%Mo, annealed tube, STBA 12 used for boilers and heat exchangers.
Low alloy steel, 1Cr-1Mo-0.25V, normalized and tempered forging, ASTM A470-65 used for steam turbine rotors.
Nickel-based superalloy forging, IN700, used in gas turbine blades.
Nickel-based superalloy casting, IN713C, used in gas turbine blades.

A record for each alloy was prepared using the standard CES format to allow inclusion of other relevant physical and mechanical properties.

NIMS Database

Stress-rupture results for nine heats of 1Cr-1Mo-0.25V rotor forgings are reproduced in figure 1. The

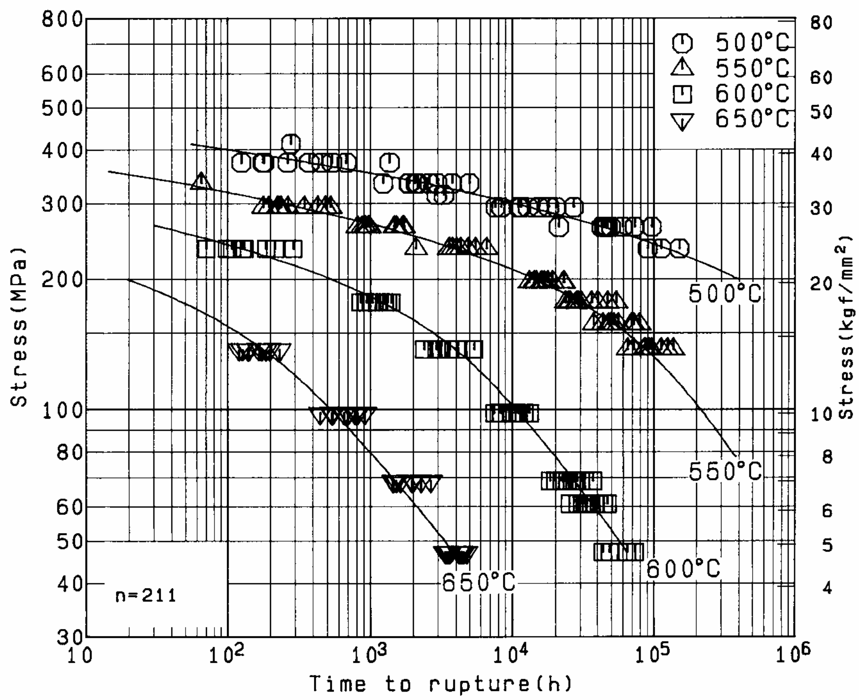

Figure 1 Stress vs. time to rupture at 500, 550, 600 and 650C for 1Cr-1Mo-0.25V steel forgings

data scatter can be largely attributed to chemistry and processing variation, since the tests were all conducted at NIMS [2]. Although this provides a measure of statistical scatter for this alloy it does not include all sources of scatter for stress-rupture data as discussed previously. The curves are based on a Manson-Haferd parameter [1] analysis for test results between 450C and 675C as illustrated in figure 2. The regression coefficients of these curves are given in the polynomial:

$$\text{Log}t_R=17.14452+[(T+273.15)-370][-0.3272606+0.664421\log S-0.5409043(\log S)^2+0.194511(\log S)^3-0.02625728(\log S)^4] \quad (1)$$

Coefficient of Determination (COD)=0.976

Where t_R=rupture time in hours
S=stress in MPa
T=temperature in Celsius
Standard error of estimate (SEE) or sigma for logarithmic rupture times=0.145
Based on 238 data points.

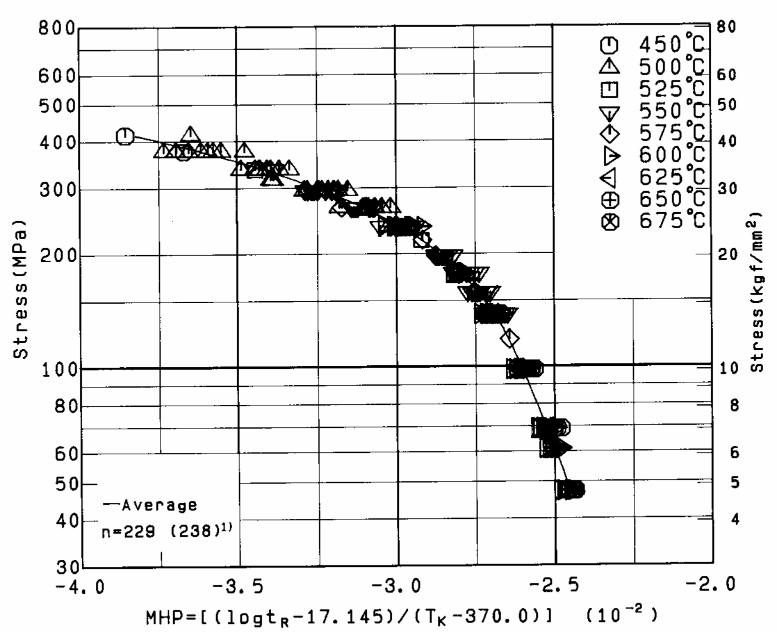

Figure 2 Master rupture curve in terms of the Manson-Haferd parameter for 1Cr-1Mo-0.25V steel forgings

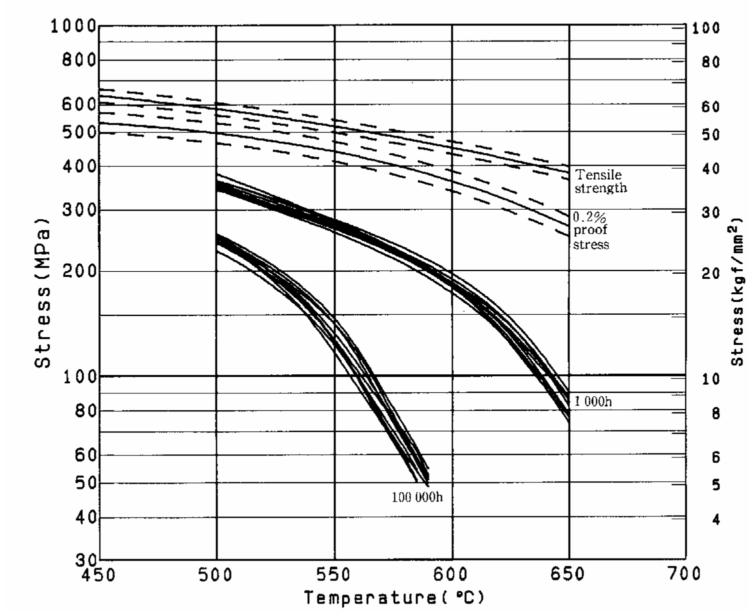

Figure 3 Temperature dependence of tensile strength and creep rupture strength for 1Cr-1Mo-0.25V steel forgings

Figure 3 shows the range of tensile and creep strengths for the heats as a function of test temperature. For tensile strength and 0.2% proof stress the broken curves are the upper and lower 95% prediction intervals (PI), which is approximately plus or minus two sigma.

To develop minimum creep rate curves in terms of stress the Monkman-Grant correlation with rupture life was used. Figure 4 shows the optimized plot for all test data based on the regression equation:

$$\log t_R = 0.54205 - 0.96872 \log(mcr) \tag{2}$$

where mcr=minimum creep rate (%/hr.)

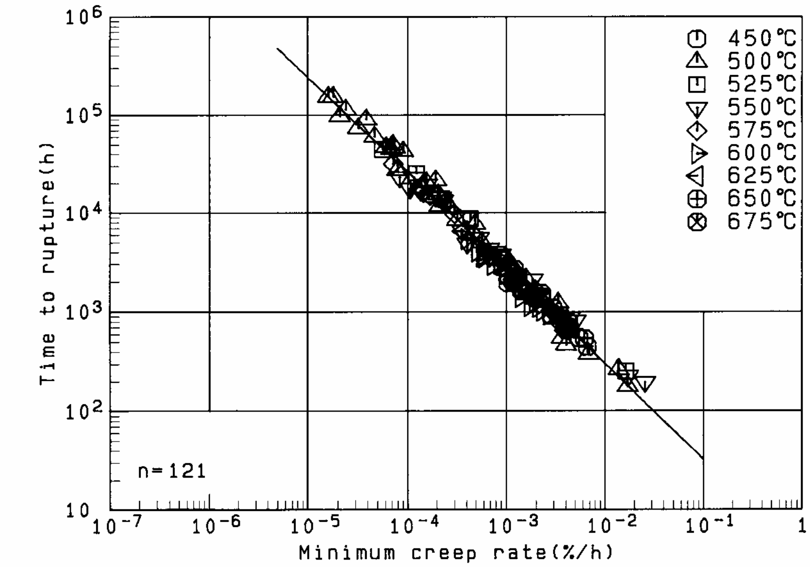

Figure 4 Time to rupture vs. minimum creep rate for all Cr-Mo-V forgings

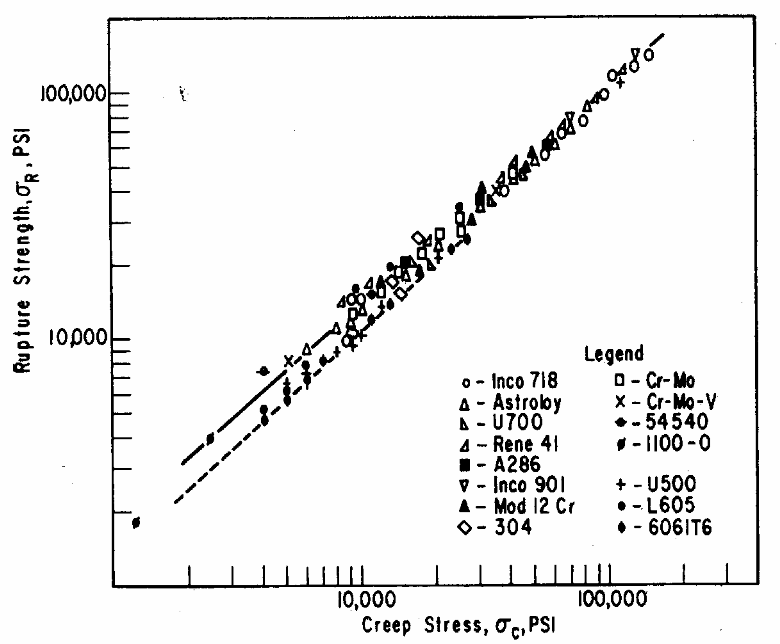

Figure 5 Creep strength, rupture strength correlation for 1% strain

To produce curves of times to specific creep strains as a function of stress, the Goldhoff-Gill [5] correlation between stress for creep and stress for rupture in the same time may be used. Figure 5 shows the correlation for 1% creep strain for a variety of alloys. This approach factors out both time and temperature from the correlation. Later work showed that predictability was improved by using curves customized for each alloy class. Thus, the optimized correlation for a low alloy steel was:

$$\log S_R = 0.3687 + 0.7901(\log S_{1\%}) \quad (3)$$

COD=0.9981.

Note in this case, consistent with figure 5, S=stress in ksi.

Software Construction

Two techniques were developed to build the schema to hold creep rupture data. The first involved using the parametric equations as math functional data. The equations that relate rupture time to temperature and stress are polynomials with different orders which can be entered directly into CES allowing the user to plot rupture time vs. temperature or stress. The CES interpolation also allows the calculation of rupture time at a specified temperature or stress. However, the math functional approach cannot readily be used to plot stress vs. temperature or stress vs. time. To do this in CES the parametric equation would have to be rearranged in terms of stress and then entered into the database as a separate attribute. For the higher order polynomials this is not mathematically possible. The same problems occur when trying to equate the Monkman-Grant relationship to the creep rupture model to obtain a plot of stress vs. minimum creep rate. Thus, this approach limits the functionality of the database.

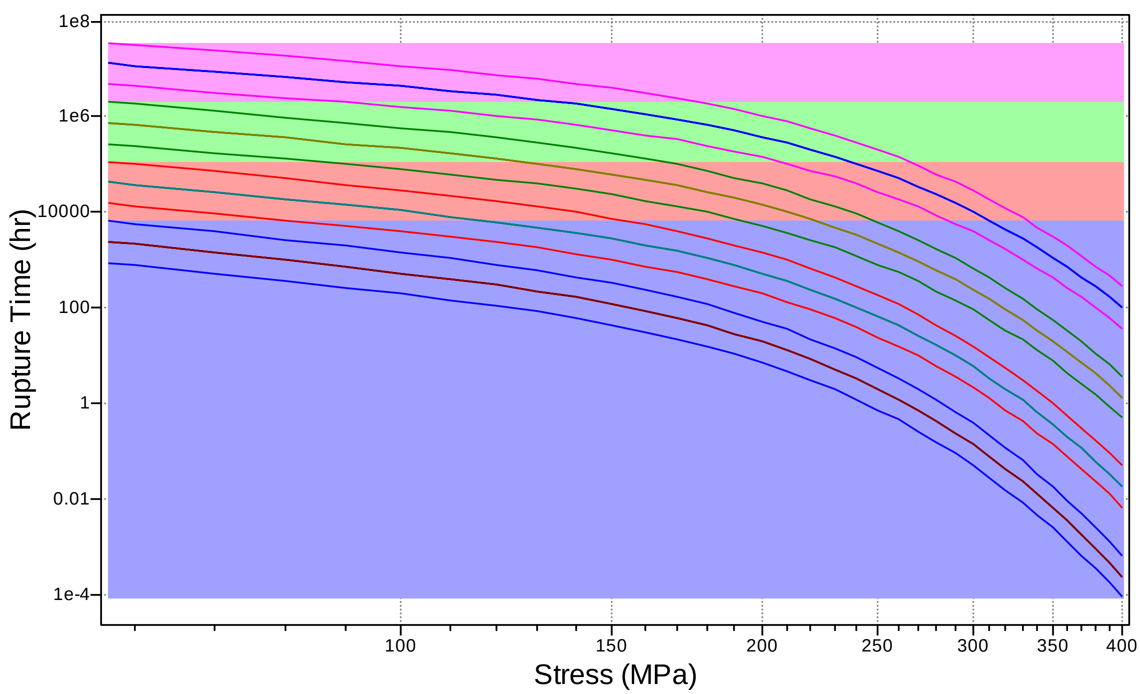

Figure 6 CES rupture curves for Cr-Mo-V steel at 500, 550, 600 and 650C with 3 sigma ranges

The second approach was to convert the equations into gridded data. A matrix of temperature vs. stress was set up and populated with calculated values of times to rupture. When entered into CES, the user can plot time to rupture at any value of stress and temperature between the limits of the grid. CES can only perform linear interpolation between the grid points. However, the errors generated are minimized if the grid is of a high enough resolution. This approach makes it possible to add a grid of time vs. temperature, populated with stresses. These values of stress are calculated using iterative numerical methods allowing the user to plot stress vs. temperature or time. In a similar way, a matrix of temperature vs. minimum creep rates can be populated with stress values, allowing the user to plot stress vs. minimum creep rate at a specified temperature. This approach has been selected for the software because of its major advantage in terms of functionality.

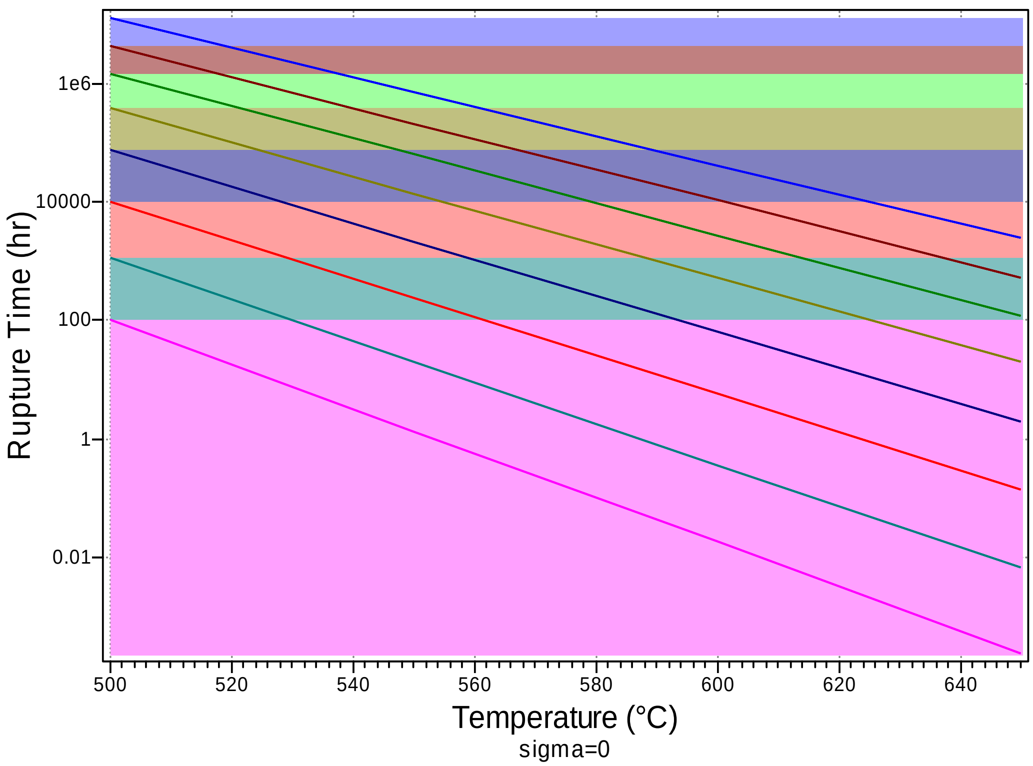

Figure 7 CES plot of rupture life vs. temperature in 50MPa intervals from 50 to 400MPa

Figure 6 is a CES screen copy of rupture time vs. stress at four temperatures for the low alloy steel. Each curve is plotted with three sigma limits. Figure 7 is a CES plot of rupture time vs. temperature. Note that the individual stress lines converge to a low temperature, which is a characteristic of the Manson-Haferd parameter. This type of response may be used to accelerate testing at design stresses by raising the test temperature. Design lives are then obtained by extrapolating down to operating temperatures.

Figure 8 is a CES example plotting minimum creep rate against stress at the four temperatures. The 500C curve is plotted with a six sigma scatterband. This may be compared with the design curve of figure 9 which plots two-thirds of the stress vs. minimum creep rate. Relative to the statistical band the design curve is very conservative at high stresses but much less so at low stresses. For example at 350 MPa the design stress is about twelve sigma below the mean curve, at 250MPa the design curve is at the six sigma limit, but at 90MPa the design curve is barely two sigma below the mean. Although, as discussed previously, the statistical ranges were established principally for alloy variability in the creep rupture test rather than component life variability, this is nevertheless a cause for concern.

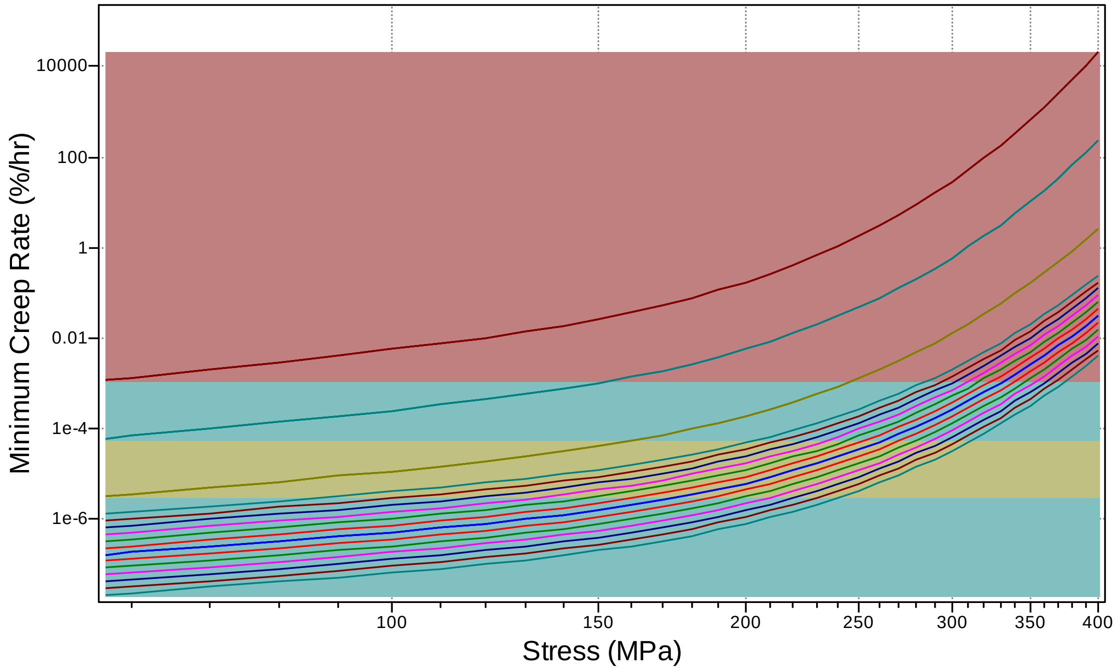

Figure 8 CES plot of minimum creep rate vs. stress at 500, 550, 600 and 650C. Six sigma range shown at 500C

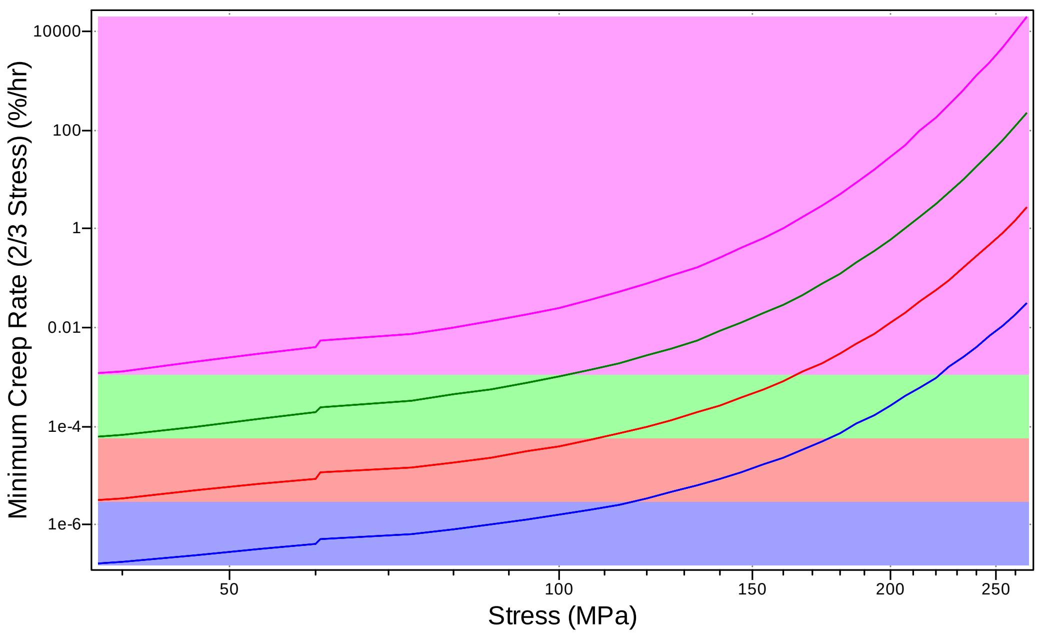

Figure 9 CES design plot of two thirds the stress for a given creep rate at 500, 550, 600 and 650C

The other significant decision that had to be made was the range of data to be shown in the analysis. For the example alloy, the stress range covered was 200 to 400MPa at the lowest temperature, 500C, and 45 to 200 MPa at the highest temperature, 650C. To use the power of the parametric fit, the grids were constructed over the total stress range of 45 to 400MPa. Although the low stress extrapolation is the principal justification for the parametric approach, the high stress extrapolation at high temperatures may lead to failure times of no practical interest.

Future Developments

The next step will involve the inclusion of all the remaining published NIMS data within the CES framework. The functionality will be maximized using the gridded data approach to allow crossplotting of the variables as desired. It will also be possible to plot data from different alloys on the same graph for direct comparison and to superimpose the two-thirds stress design curves on the statistical scatterbands. The times to 0.5% or times to 1% creep strain will be estimated from the creep and rupture data using the correlations discussed earlier, which can be constructed for most of the NIMS data. The flexibility and functionality will be similar to that already available for minimum creep rate.

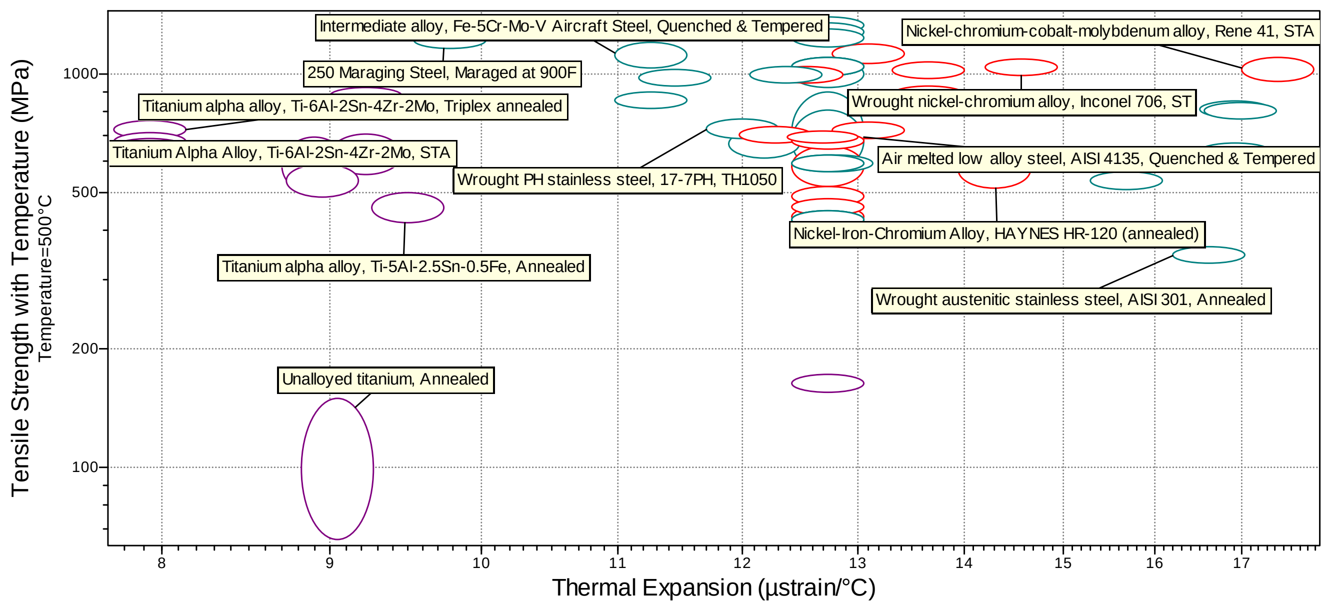

Figure 10 An example plot from the current CES software of tensile strength at 500C vs. thermal expansion coefficient

Finally, measures of creep-rupture strength such as the stress for rupture in a given time may be used in combination with other properties to allow alloy selection for a specific application. A graph stage, limit stage or tree stage may then be constructed in terms of mechanical, thermal or electrical properties or composition. As an example, the closest mechanical property to creep-rupture strength currently in the CES software is tensile strength at temperature. Figure 10 is a plot of the tensile strength at 500C as a function of the thermal property, expansion coefficient. The ranges of each attribute are shown as bubbles. All the bubbles can be readily identified, and a few are shown in the figure.

Although a great deal of effort is required to set up the database and allow users to add data and modify the tools, this is judged to be a worthwhile task. It is always essential, however, to keep in mind the approximations that are inherent in any data management procedure. This is particularly true for creep-rupture data. It is hoped that the software will encourage big picture thinking with a healthy dose of caution.

References

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