MECHANICAL PROPERTY CORRELATIONS FOR 2 1/4 CR-1 MO STEEL IN SUPPORT OF NUCLEAR REACTOR SYSTEMS DESIGN*

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SUMMARY

In recent years, 2½ Cr-1 Mo steel has gained worldwide importance as a structural material for use in nuclear systems, particularly in steam generator systems, where it finds extensive use as an evaporator and superheater material. This importance is reflected in the large number of research programs being carried out in an effort to generate mechanical properties data for this material. However, these data can be useful for design purposes only if they are presented in a systematic and coherent manner. Further, the design of nuclear systems involving use of any material (particularly at elevated temperatures, where creep effects are important) requires a good understanding of the mechanical properties of that material. In recognition of the above needs, Oak Ridge National Laboratory has embarked upon an extensive program of generation, collection, analysis, and presentation of mechanical properties data for 2½ Cr-1 Mo steel tested in air, in primarily the annealed condition. The findings of this program will be described, including methods of analysis, evaluation of possible sources of error, and a discussion of the assumptions associated with some of the results.

The behavior of 2½ Cr-1 Mo steel as determined from conventional tensile tests has been investigated at test temperatures ranging from room temperature to 600°C at several strain rates. Mathematical models have been developed for each property based on data collected from various sources. Where appropriate, tolerance limits have been determined.

Trends in data indicate several interesting phenomena. For instance, the temperature dependence of 0.2% offset yield strength and ultimate tensile strength and the effect of strain rate on various tensile properties give an indication of strain aging effects.

A creep equation valid over the temperature range of 371 to 593°C and corresponding isochronous stress-strain curves have been developed. In addition, models have been developed for minimum creep rate, time to the onset of tertiary creep, and time to rupture as functions of stress, temperature, and tensile strength.

Fatigue curves for cyclic life as a function of strain range and of stress range have been developed, including design safety factors. Effects such as temperature and type of anneal have been examined. Strain aging effects are again indicated.

The variation of Charpy impact energy with temperature, including ductile-brittle transition, have also been examined. Pronounced heat treatment effects and lot-to-lot variations have been noted.

This effort comprises the most thorough attempt at a comprehensive determination of the mechanical properties of 2½ Cr-1 Mo steel made to date. The development of mathematical representations of mechanical behavior, accompanied by corresponding statistical confidence limits, represents a significant advance in the understanding of the properties of this material, an understanding which is vital in the design of nuclear systems.

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1. Introduction

The exacting and stringent requirements in the design of elevated-temperature nuclear reactor systems call for both an extensive understanding of advanced design methods and a thorough knowledge of the mechanical behavior of the construction materials. In recent years, 2 1/4 Cr-1 Mo steel has gained worldwide importance as a structural material for use in nuclear systems, for example in steam generator systems, where it finds extensive use in evaporators and superheaters. As a result, the long- and short-term mechanical behavior of this material must be well characterized, and many research programs have been or are being carried out to generate these needed mechanical properties data. However, these data can be useful for design only if they are presented systematically and coherently. To satisfy these needs, an extensive program of generation, collection, analysis, and presentation of mechanical properties data for 2 1/4 Cr-1 Mo steel has been carried out.

1.1 Methods of Analysis

Tensile, creep, fatigue, and impact properties were analyzed, and then mathematical models were developed for the various properties and (where appropriate) tolerance limits were calculated.

The central tolerance limits used exclusively in this paper specify with a confidence level of 0.95 the bounds within which 90% of the observed values are expected to fall. Each limit may be interpreted separately to mean that at this confidence level 95% of the observations are expected to fall above the lower or below the upper limit. The tolerance limits are simultaneous in all levels of the independent variables; that is, they may be calculated repeatedly for different levels of the independent variables, without affecting the level of confidence. Calculation of tolerance limits is discussed in greater detail by Leiberman and Miller [1].

1.2 Data Used

To arrive at a measure of both the general trends in mechanical properties and their variations, the largest and widest possible data base was needed. Data used in the various analyses came from a wide range of sources in the literature (such as references [2-4]), data privately supplied by other laboratories [5-7], and data obtained at Oak Ridge National Laboratory (ORNL) [8-9]. Data employed resulted from tests conducted in air on annealed or isothermally annealed material [10]. Since the data came from various sources, various annealing treatments were used. Typical such treatments for the material used were as follows:

Anneal — Austenitize at 927°C for 1 hr; furnace cool at 28°C/hr to 450°C; air cool to room temperature.

Isothermal Anneal — Austenitize at 927°C for 1 hr; furnace cool at 83°C/hr to 704°C; hold 2 hr, furnace cool at 333°C/hr to room temperature.

Only data for material meeting certain restrictions were included in the analysis. These restrictions were: room-temperature ultimate tensile strength ≥ 414 MPa (60 ksi); room-temperature 0.2% offset yield strength ≥ 207 MPa (30 ksi); 0.07–0.15 wt % C; 2.0–2.5 wt % Cr; and 0.9–1.1 wt % Mo. Various product forms have been included, such as plate, bar, rod, tube, and pipe.

2. Tensile Properties

Results from short-term tensile tests provide data that are not only directly applicable for use in setting design stress intensity limits [11] but also give general insights into the flow and failure characteristics of a material. Various tensile strength and ductility properties of 2 1/4 Cr-1 Mo steel are discussed below. Actual stress-strain behavior of this material has been described by Klueh and Hebble [12].

2.1 Strength Criteria

Figures 1 and 2 show the collected data for 0.2% offset yield strength and ultimate tensile strength as functions of temperature, including expected values with upper and lower tolerance limits. Yield strength (434 data points) and ultimate tensile strength (457 data points) were both described by third-degree polynomials in temperature.

Both properties are, of course, functions of factors other than temperature (chemical composition, metallurgical structure, strain rate, etc.). Indeed, the data used were obtained at a variety of strain rates (10^{-4} – 10^{-1} /min) over a range of compositions, etc. However, the intent here was to determine general trends, and therefore it was deemed acceptable to express the models in terms of temperature only. Certain qualitative insights can be gained, however, from a further look at the data. The maximum in ultimate tensile strength in the region of 300–450°C gives indications of dynamic strain aging effects [13]. Also, in this temperature regime, lower strain rates tend to give higher values of ultimate tensile strength and decreased ductility, especially for single lots of material [8].

2.2 Ductility Criteria

Total elongation, uniform elongation, and reduction of area exhibit minima in the range 300–450°C, again indicating strain aging effects. Figure 3 shows total elongation data obtained from tensile tests using specimens with 2-in. (51-mm) gage lengths.

3. Creep Properties

Since 2 1/4 Cr-1 Mo steel is often used at service temperatures approaching 600°C, successful design requires the consideration of possible creep effects. Indeed, the material does creep above about 375°C. Therefore, the constant-load, uniaxial creep properties in the region 375–600°C were studied in some detail.

3.1 Creep Equation

As a first and important step, available isothermal strain-time (constant-load) curves were collected to formulate a model for creep strain as a function of time, temperature, and applied stress. Analysis was limited to curves displaying classical three-stage creep behavior. Unfortunately, only a few such curves with precise strain measurements for annealed material were obtainable. The final data set used consisted of three multitest sets of creep curves from references [5,6,8], containing a total of 37 tests with creep times reaching 5000 hr. Many tests were omitted because the curves showed tertiary creep almost as soon as they began, especially at high stresses.

After consideration of several standard forms of creep equations [14] a model of the following form was formulated:

$$\epsilon_{\text{total}} = \epsilon_c + \epsilon_L, \quad (1a)$$

$$\epsilon_c = \frac{t}{A + Bt} + \dot{\epsilon}_m t, \quad (1b)$$

where ϵ_L = instantaneous time-independent strain upon application of load,

ϵ_c = creep strain,

t = time (hr),

$\dot{\epsilon}_m$ = minimum creep rate (%/hr),

$$\log_{10} \dot{\epsilon}_m = -30.04 + 1.516 \times 10^{-2}T + 2.001 \times 10^{-3}T (\log_{10}\sigma)^2,$$

$$\log_{10} A = 12.26 - 3.348 \times 10^{-6}T^2 + 9.353 \times 10^{-4}\sigma^2 - 1.167 \times 10^{-4}T\sigma,$$

$$\log_{10} B = -52.19 + 8.682 \times 10^{-2}T - 3.308 \times 10^{-5}T^2 - 1.152(\log_{10}\sigma)^2,$$

σ = stress in ksi or in MPa/6.89, and

T = temperature in °R or in $(^{\circ}\text{C} + 32) \times 5/9 + 460$.

This model was selected on the basis of (1) fit of data; (2) simplicity, e.g. small number of coefficients, ease of differentiation, etc.; (3) ease of estimating coefficients; and (4) specific term for minimum creep rate. Figure 4 shows isochronous stress-strain curves constructed for values of ϵ_{total} obtained by use of ϵ_c calculated from Eq. (1) and ϵ_L obtained from short-term tensile curves in ASME Code Case 1592 [15]. Comparison of such curves with corresponding curves from Code Case 1592 show that the code case curves, constructed for intentional conservatism, are indeed slightly more conservative than the present isochronous stress-strain curves in that they predict slightly higher strains at most combinations of stress, temperature, and time.

Equation (1b) is valid from 371 to 593°C at stresses ranging from 7 to 450 MPa, unless otherwise limited (e.g. by ultimate tensile strength). Time limits are given by the time to tertiary creep, as described below.

Minimum creep rate could also be estimated as a function of temperature and stress by use of all available minimum creep rate data, since these data are fairly numerous. Various models to describe the minimum creep rate behavior of 2 1/4 Cr-1 Mo steel are currently being investigated. Preliminary results show, however, that the data can be well described by most models only if room-temperature ultimate tensile strength is included as an additional independent variable. (This problem was not encountered in the development of Eq. (1) since all materials used to develop that equation were of similar strength.) Development of an advanced minimum creep rate model is still in the preliminary stages, but initial analysis by a Larson-Miller parameter [16] of the form $P(\sigma) = T(C + \log \dot{\epsilon}_m)$ with T in K, $\dot{\epsilon}_m$ in %/hr, and σ in ksi yielded a least squares optimized value of -17.76 for C .

3.2 Time to Tertiary Creep

The above creep equation contains a linear second-stage creep term, which, of course, continues in a straight line to infinite times and strains. Clearly, then the equation is valid only up to the onset of tertiary creep. Therefore, it is necessary to estimate times at which the onset of tertiary creep will occur in order to establish bounds on the creep equation. Data used to do so were determined by 0.2% strain offsets from the linear secondary creep lines from 155 tests [5,6,8] in the range 454-677°C. Times ranged from 10.2 to 13,000 hr. Practical design, however, concerns temperatures as low as about 375°C and times as long as 100,000 hr or more. Thus, it was necessary to extrapolate any model developed in both temperature and time. Several parametric methods, including the minimum commitment method [17] were attempted. However, these methods predicted unreasonable times when extrapolation to 371°C was attempted (see Table I). Therefore, best results were obtained from a model of the form:

$$\log_{10} t_3 = b_0 + b_1 \log_{10} \sigma + b_2 T + b_3 (10)^{(T \log_{10} \sigma) / 1000}, \quad (2)$$

where t_3 = time to tertiary creep (hr),

σ = stress (MPa or ksi),

T = temperature (K or °R),

constant (standard deviations):	MPa and °K	ksi and °R
b_0	$12.05(\pm 5.4)$	$18.94(\pm 1.7)$
b_1	$-0.465(\pm 1.6)$	$-3.15(\pm 0.57)$
b_2	$-0.00759(\pm 0.0037)$	$-0.00805(\pm 0.00083)$
b_3	$-0.0389(\pm 0.017)$	$-0.00370(\pm 0.0024)$

It is felt that extrapolations in time with this model are conservative at least up to 50,000 hr in the range 371–593°C. Figure 5 shows the original time to tertiary creep data as a function of applied stress, with several isothermals calculated from the above model.

3.3 Rupture Life

A large number of rupture life data for 2 1/4 Cr-1 Mo steel were available, however, the temperature range was limited. The data set used in the present study included 599 tests at temperatures ranging from 500 to 600°C and stresses from 34 to 345 MPa with rupture times reaching 50,000 hr. Since so many data were available, some test results at higher temperatures were omitted to avoid biasing the lower temperature data, while data at temperatures below 500°C were not available. It has been suggested [4] that portions of individual isothermals for annealed 2 1/4 Cr-1 Mo steel can be adequately described by straight-line fits of log stress vs log time to rupture. However, in the present investigation, several other requirements were placed on the model. These included:

1. The model must express rupture time as a continuous function of stress and temperature, not merely as individual isothermals.
2. The model must predict reasonable values in the range 371 to 500°C, although no data were available in this range.
3. The model must be simple, but must well describe the data and include tolerance limits as measures of uncertainty.

Standard parametric methods were again applied, but these methods failed to meet requirement (2), as in the case of time to tertiary creep. Consideration of several algebraic models led to the choice of the following model:

$$\log_{10} t_p = b_0 + b_1 \sigma + b_2 T + b_3 \sigma^2 T, \quad (3)$$

where t_p = time to rupture (hr),

σ = stress (MPa or ksi),

T = temperature (K or °R),

constant (standard deviations):	MPa and °K	ksi and °R
b_0	$25.92(\pm 0.62)$	$25.92(\pm 0.62)$
b_1	$-0.02999(\pm 0.0012)$	$-0.2067(\pm 0.0083)$
b_2	$-0.02350(\pm 0.00067)$	$-0.01306(\pm 0.00037)$
b_3	$4.021 \times 10^{-8}(\pm 3.8 \times 10^{-9})$	$1.061 \times 10^{-6}(\pm 1 \times 10^{-7})$

This model was fit to all the data (i.e., all temperatures) simultaneously, and the constants were obtained by the method of least squares. Stress-rupture isothermals calculated from this model are shown in Fig. 6, along with corresponding lower tolerance limits.

Although by convention, Fig. 6 is plotted in terms of $\log \sigma$ vs $\log t_p$, it must be realized that

t_r is the dependent and σ the independent variable, and that the actual analysis was conducted accordingly. For instance, as shown, the tolerance limits apply to time at a given stress, not vice versa.

It should be noted that the present model predicts lower 10^5 -hr rupture strengths from 538 to 593°C than those given in reference [4]. This difference can be attributed to several factors: (1) In reference [4], individual isothermals were fitted, while here all temperatures were treated simultaneously in order to express rupture life as a continuous function of temperature. (2) The two results are based on an analysis of two different data sets. The data used here include results from more sources and data for isothermally annealed material. Also, the present study did not include data for normalized-and-tempered material and for castings, while reference [4] included some of both. In any event, the spread in the tolerance limits in this region indicates a large degree of uncertainty, and both results are well within these tolerance limits.

Also, since the models of rupture life and time to tertiary creep are of different form, and since they were determined from widely different data bases, the relationship between the two models is not necessarily a realistic one. For instance, in high-stress regions, some predicted times to tertiary creep are greater than predicted rupture lives. Possible solutions to this problem include expressing both properties in terms of the same model, or expressing time to tertiary creep in terms of the better known rupture life. Indeed, for 2 1/4 Cr-1 Mo, such a relationship has been reported [18], with

$$t_3 = t_r^{1.05/3} \quad (4)$$

Other investigators [19] have reported t_3 approximately equal to $0.4 t_r$.

3.4 Creep Ductility

Values of rupture elongation and reduction of area in creep show too much scatter to permit meaningful direct analysis. Some indirect estimates of creep ductility can be made, however. For instance, the strain predicted by Eq. (1) at a time equal to the corresponding time to tertiary creep from Eq. (3) provides an estimate of the creep strain to tertiary creep (although the time is actually a 0.2% offset value, so that this approach is not strictly valid).

4. Fatigue Properties

The fully reversed, strain-controlled, continuous cycling fatigue properties of annealed and isothermally annealed 2 1/4 Cr-1 Mo steel have been reported [20]. Average curves of strain range versus cycles to failure at various temperatures are shown in Fig. 7, with corresponding data. Some load-controlled data were used in very high-cycle regions, where behavior is essentially elastic, with values of load range converted to strain range using Young's Modulus. The room temperature to 427°C (800°F) curve was constructed using 427°C data only, and is felt to be conservative for lower temperatures. The crossovers in the room temperature, 316, 371, and 427°C data are again possibly due to strain aging effects. The curves are valid for strain rates $\geq 4 \times 10^{-3}$ /sec.

The data show a relatively small dependence of cyclic life on temperature at a strain rate of 4×10^{-3} /sec. However, recent tests at ORNL and elsewhere [21] have shown that the fatigue lifetime of this material depends on strain rate at temperatures as low as 370°C because of strain aging and at higher temperatures because of creep effects (creep-fatigue interaction.)

5. Impact Properties

The variation of Charpy V-notch impact energy with temperature for annealed and isothermally annealed 2 1/4 Cr-1 Mo was found to be descriptibly by a model of the form

$$E = A\{1 - \exp[-B(T - C)^2]\} \quad (5)$$

valid at $T > C$, where

E = energy absorbed to fracture,

T = temperature, K or °R, and

A, B, C = empirical constants.

In this model, the energy is zero at temperature equal to C , rises sigmoidally, and levels off at an upper-shelf energy equal to A . However, lot-to-lot and heat treatment (cooling rate, etc.) variations are so great that it was necessary to estimate the constants in the above model for each separate combination of lot and heat treatment (9 combinations were used). Values of A ranged from 82 to 227J, of B from 2.2×10^{-5} to 6.29×10^{-4} , and of C from 183 to 277K.

Note that, if one defines the ductile-brittle transition temperature (DBTT) as the temperature corresponding to a given energy, the DBTT can be calculated from the above model. Results of such calculations for an energy of 30J (42 ft-lb), for instance, give a DBTT of $-7C \pm 11^\circ C$, while an energy of 10J (14 ft-lb) gives a DBTT of $-23 \pm 10^\circ C$ for plate material.

6. Conclusions

A large collection of mechanical properties data for annealed and isothermally annealed 2 1/4 Cr-1 Mo steel has been used to develop analytical descriptions of several mechanical properties of this material. Specific conclusions were as follows:

1. The 0.2% yield strength, ultimate tensile strength, and short-term tensile ductility may be adequately described by third-degree polynomials in temperature. Corresponding central tolerance limits were also developed. Trends in the data indicate strain aging effects.

2. A creep equation of the form $\epsilon_c = t/(A + Bt) + \dot{\epsilon}_{mt}$ was developed to provide a mathematical model for creep strain as a function of stress, temperature, and time. Rupture life and time to tertiary creep were described by mathematical models expressed as functions of temperature and stress, while minimum creep rate requires the inclusion of room-temperature ultimate tensile strength as an additional independent variable to achieve adequate correlation.

3. Strain- and load-controlled continuous cycling fatigue data from recent test programs and from the literature were used to construct curves of strain range versus cycles to failure from 10^2 to 10^8 cycles.

4. A mathematical model describing Charpy V-notch impact energy as a function of test temperature was developed. This model allows direct estimates of the ductile-brittle transition temperature.

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Table I: Comparison of Various Methods for Prediction of Time-to-Tertiary Creep From 371 to 482°C

Temperature (°F) (°C)	Stress		Time to Tertiary Creep (hr)				
	(ksi)	(MPa)	Proposed Model	MS	OSD	LM	MCM
700 371	10	69	2,500,000	4,300,000	60,000,000	84,000,000	1,800,000,000,000,000
700 371	20	138	240,000	230,000	3,200,000	1,800,000	800,000,000,000,000
700 371	30	207	57,000	42,000	490,000	200,000	440,000,000,000,000
700 371	40	276	19,000	13,000	120,000	46,000	270,000,000,000,000
800 427	10	69	380,000	560,000	2,100,000	2,600,000	350,000,000
800 427	20	138	34,000	31,000	110,000	78,000	47,000,000
800 427	30	207	7,500	5,500	17,000	10,000	11,000,000
800 427	40	276	2,300	1,700	4,400	2,600	3,300,000
900 482	10	69	57,000	76,000	130,000	150,000	160,000
900 482	20	138	4,700	4,200	6,700	5,600	12,000
900 482	30	207	920	750	1,000	850	1,800
900 482	40	276	240	240	260	240	390
Residual Sum of Squares			24.48	24.58	24.56	24.71	23.85
Number of unknown constants in model			4	5	5	5	indeterminate

Fig. 1. 0.2% Offset Yield Strength as a Function of Temperature.

Fig. 2. Ultimate Tensile Strength as a Function of Temperature.

Fig. 3. Total Elongation [% in 2 in.(51 mm)] as a Function of Temperature.

Fig. 4. Isochronous Stress-Strain Curves Calculated from the Derived Equation and Code Case 1592 Hot Tensile Curves.

Fig. 5. Time to Tertiary Creep Isothermals Showing Experimental Data and Calculated Curves.

Fig. 6. Expected Value and Lower Central Tolerance Limit Isothermals for Rupture Life, Including Data at 593°C (1100°F).

Fig. 7. Average-Fatigue Curves from Room Temperature to 593°C (1100°F), Including Experimental Data.