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ISOCHRONOUS STRESS VERSUS STRAIN CURVES FOR NORMALIZED-AND-TEMPERED 2 1/4 Cr-1 Mo STEEL*

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ABSTRACT

Tensile and creep data were collected for normalized-and-tempered 2 1/4Cr - 1Mo steel and used to construct isochronous stress versus strain curves to 100,000 h for temperatures to 566°C (1050°F). A plasticity equation was selected that normalized the flow curves to the yield strength, and a creep equation was formulated that included a parabolic primary creep term and a linear term. Due to the early initialtion of tertiary creep in the normalized-and-tempered steel, the isochronous curves were limited to 1 % total strain.

INTRODUCTION

The construction of isochronous stress versus strain curves for pressure boundary materials was introduced in connection with the development of design methods and failure criteria for high-temperature nuclear components (Smith, 1972). Curves for several classes of materials were included in ASME Boiler and Pressure Vessel Code Sect. III, Subsection NH which deals with the design of Class 1 nuclear components that operate in the creep range. Recently, there has been interest in writing simple rules for Sect. VIII, Div. 2 that would provide design criteria for heavy-wall vessels that experience short-time excursions to temperatures in the creep range. As part of this exercise, isochronous stress versus strain curves are needed to help in the estimation of stress redistributions after temperature excursions. Normalized-and-tempered 2 1/4Cr-1Mo steel plate, say (SA-387 Grade 22 Class 2) or its forging equivalent (SA-336 F22), is one of the candidate alloys for examination. This steel is used to construct process vessels that operate in the temperature range of 427 to 482°C (800 to 900°F) but could experience local temperature excursions to above 538°C (1000°F).

Isochronous stress versus strain curves to 482°C (900°F) for normalized-and-tempered 2 1/4Cr-1Mo steel were produced by Swindeman, Booker, and McAfee (1983). In their analysis, tensile and stress-rupture data were gathered from compilations produced from U.S., British, German, French, and Japanese sources. Lot-centered data-fitting methods were used to establish average and minimum strength values. Tensile data from forty-three lots of materials were processed, and a polynomial in temperature was used to correlate yield strength against temperature. The shape of the tensile curve was anchored to observations for a single lot, but a model was constructed to allow the curve to be normalized for any 0.2% off-set yield strength. Stress-rupture data from fifty-three lots were included in the analysis, and a polynomial in absolute temperature and log stress was used to correlate the log rupture life with stress and temperature. The longest rupture time was 85,000 hours and the highest temperature was 600°C (1112°F). For creep evaluation, four lots were found that included minimum creep rates (mcr), while only one lot was available for examining the shape of the creep curve. The creep law was based on a combination of a rational polynomial for primary creep and a linear term that captured secondary creep contribution. The minimum creep rate was correlated with the rupture life through the Monkman-Grant relationship. The two material coefficients in the rational polynomial were correlated against the minimum creep rate and implicitly with the rupture life. Thus, the rupture life model, which was based on a large number of data, was used to determine the isochronous stress versus strain curves for times to 300,000 hours.

An attempt was made to extend the above model to higher temperatures, but it was found that the primary creep model predicted excessively large strains at high temperatures and low strains. To resolve the issue, additional creep data were collected and used to develop an improved model suitable for the construction of curves at temperatures above 482°C (900°F).

SELECTION OF MATERIALS

Creep data were found for the fourteen lots of steel listed in Table 1. Product forms included pipes, plates, and forgings. The thermal-mechanical processing, tensile properties, and microstructures were examined to determine if the steels would fit into the normalized-and-tempered class. Three criteria were set for acceptance: (1) The minimum mechanical properties for Grade 22 Class 2 must be met [310 MPa (45 ksi) yield strength and 515 to 690 MPa (75 to 100 ksi) ultimate strength)]; (2) Tempering temperature must be at least 677°C (1250°F); and (3) Proeutectoid ferrite in the microstructure must be less than 20%. The first ten lots were from heats examined by Leyda and Prager (1986) to determine the effect of heat treatment and microstructure on creep and stress-rupture of Grade 22 Class 2 material. Six heats were included and four of the heats were tested in both the normalized-and-tempered and quenched-and-tempered conditions. All lots met the minimum mechanical properties but the microstructures differed significantly. Three lots contained more than 20% ferrite, and data from these lots were not used in the creep analysis. One lot, originally bainitic was tempered to conditions that produced spherodite. Data from this lot were not used. One lot was tempered at 662°C (1225°F) and data were not included. One lot (heat 20017) evaluated by Klueh (1977) exhibited exceptionally high strength, but data were retained for analysis since the material was incorporated into the analysis performed earlier by Swindeman, Booker, and McAfee (1983).

Table 1. Materials considered for the creep analysis

Lot	Heat	Thick (mm)	Cooling	Temper Temp. (°C)	Yield (MPa)	Ultimate (MPa)	Micro-Structure	Used for Analysis?
1	C3928	191	AC	677	414	607	B+35%F	No
2	B2099	178	AC	693/730	386	517	S	No
3	A6542	57	AC	682	448	593	B	Yes
4	A6542	57	WQ	682	476	607	M	Yes
5	C2682	76	WQ	627/710	490	600	M	Yes
6	C2682	76	AC	627	310	614	B+65%F	No
7	C2672	76	WQ	627/716	483	600	M	Yes
8	C2672	76	OC	627/677	379	572	B+45%F	No
9	A1803	83	WQ	621/710	496	614	M	Yes
10	A1803	83	AC	710	476	607	B+5%F	Yes
11	A6660	150	AC	662/690	448	558	B	Yes
12	A6660	150	AC	662	545	655	B	No
13	C3443	330	WQ	690	414	558	B+10%F	Yes
14	20017	25	AC	704	558	669	B	Yes
15		25	AC	704	414	531	B+20%F	No
16	646363	457	WQ	649/693	476	593	B	No

Notes: AC=air cooled; WQ=accelerated cooling; B=bainite; M=martensite; F=ferrite S=spherodite

THE SHORT-TIME STRESS VERSUS STRAIN CURVE

The tensile behavior of Grade 22 Class 2 steel was examined in some detail by Klueh and Oakes (1976). The yield strength and ultimate strength data for a single lot (heat 20017) were reported for a broad range of temperatures and strain rates. This heat was quite strong, relative to other heats and lots of steel, and a material more typical of thick-section sizes was sought. Data for stress versus strain to 1% strain were available for two other lots identified in Table 1. Of these, lot 11 (heat A6660) was judged to be the most representative of Grade 22 Class 2 material, and the tensile curves for this material were used to formulate the plasticity model. In contrast to the observations of Bynum, Ellis, and Roberts (1976), no yield point phenomenon was observed at room temperature. The tensile curves tended to be parallel, with lower flow stresses for higher temperatures. Above 482°C (900°F) strain rate effects became important and the rate of hardening decreased with increasing temperature, especially for strains above 1%. A typical set of curves is provided in Fig. 1 for room temperature, 427°C (800°F) and 538°C (1000°F). A simple power law was selected to correlate inelastic strain (e_p) with stress (S), and the stress was normalized to the 0.2% yield stress (Sy) to produce the following relationship:

$$e_p = C\,(S/Sy)^m \qquad (1)$$

where the coefficient C has the value 0.00189 and m has the value 14.53.

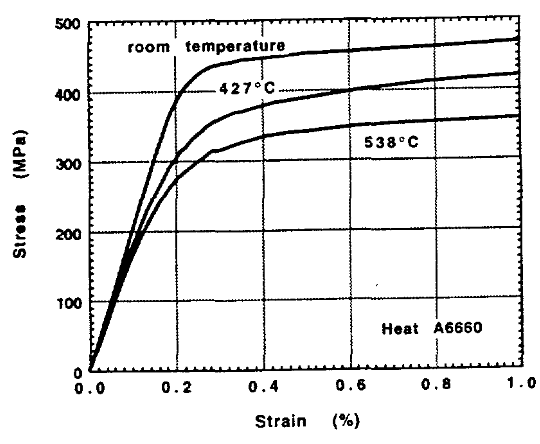

Fig. 1. Typical tensile curves for heat A6660

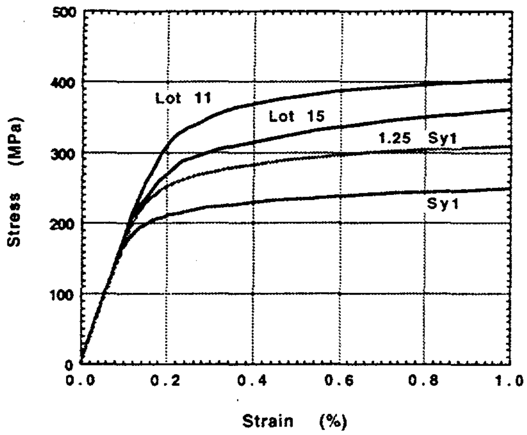

Fig. 2. Comparison of constructed tensile curves based on SY1 and 1.25SY1 with experimental curves at 482°C (900°F).

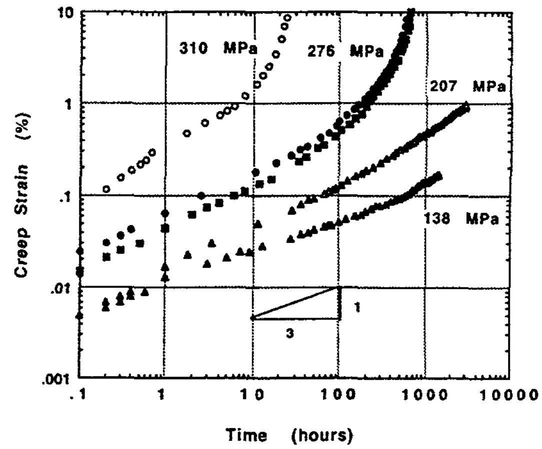

Fig. 3. Log strain versus log time creep curves for heat A6660 at 482°C (900°F).

The elastic strain was added to the plastic strain to construct the zero time isochronous curve. The normalization of stress permitted the use of average or minimum strength properties for the construction of the zero time isochronous curves. Fig. 2 compares curves for 482°C (900°F) based on (a) the minimum strength (S_{Y1}) from Table Y1 in ASME Section II Part D, (b) the "average" value based on 1.25 S_{Y1}, and (c) the curves for two lots: Lot 11 and Lot 15.

CREEP

Typical creep curves for lot 11 (heat A6660) were plotted on log-log paper to examine the general features of the primary stage, and examples are shown in Fig. 3. For most temperatures and stresses it appeared that the strain in the primary creep stage could be represented as log strain proportional to one third log time. By adding a linear term to a primary creep term, a simple two-term creep equation was formulated to represent creep (e_c) in the first and second stages:

$$e_c = A\,t^{1/3} + mcr\,t \qquad (2)$$

where t is time, A is the primary creep coefficient, and mcr is the minimum creep rate. The temperature and stress dependencies of the mcr were estimated by use of Larson Miller analysis incorporating a lot-centering technique [Sjodahl (1978), Booker and Booker (1980), Manson, S. S., and Muralidharan, (1984)]. The Larson Miller parameter (LMP) for the mcr data was written as:

$$LMP = T\,(C - \log mcr) \qquad (3)$$

where T is Kelvins and C is the Larson Miller constant determined by a least squares procedure. For analysis purposes, the stress dependency of the LMP was chosen to be a cubic polynomial in log stress:

$$LMP = a_0 + a_1 \log S + a_2 (\log S)^2 + a_3 (\log S)^3 \qquad (4)$$

where a_i are the coefficients determined in least squares analysis. The optimized LMP constant was found to be near 23.8, and the values for the nine lots ranged from 23.1 to 24.47. In Fig. 4 the log stress versus LMP correlation is shown for nine lots of steel for C of 23.8. The nature of the polynomial in log stress produced curvature in the master curve. Upon extrapolation to higher values of the LMP, there was a tendency for the master curve to bend upward. The deviation was not judged to be significant in the construction of the isochronous curves for most temperatures and times, since the stresses at which upward curvature was observed were low and the primary creep component was dominating. At very long times and high temperatures, however, there was a risk that the linear component of creep would be greater than estimated with eq. (4). To address this issue, a supplementary

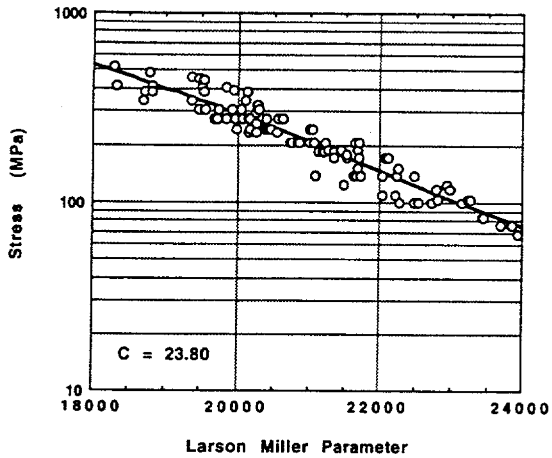

Fig. 4. Correlation of minimum creep rate data with the Larson Miller Parameter for nine lots of steel.

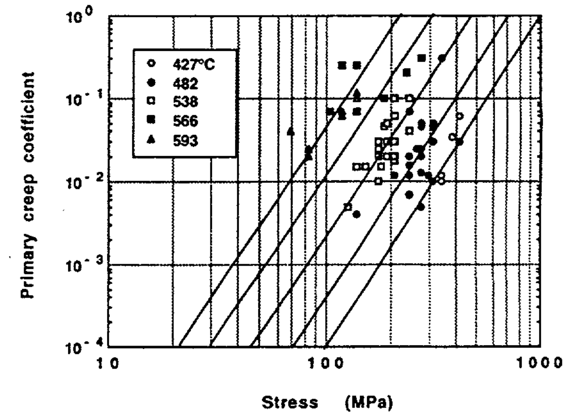

Fig. 5. Log primary creep coefficient versus log stress for eight lots of steel.

analysis was performed in which the near-linear region of the master curve in Fig. 4 was represented by a well-behaved stress function:

$$LMP = B - p \log S \quad (5)$$

where B and n are materials parameters whose values are 30838 and 6688, respectively. This stress function could be extrapolated with no problems.

The primary creep coefficients were estimated by a very simple procedure. From eq. (3) the mcr at one hour was subtracted from e_c and the result was a direct measure of A. The A values were plotted against stress on a log-log scale as shown in Fig. 5. Considerable scatter was observed, but a simple power law representation was selected for the stress dependency with A as a function of temperature f(T):

$$A = f(T)\, S^4 \quad (6)$$

where f(T) was determined from the intercept of each isothermal curve when S was unity. An equation to represent f(T) was not necessary, since only isothermal curves were needed. The values of f(T) listed in Table 2 were used for the construction of the creep equation.

Table 2. Parameter values for the isochronous curves

Temperature		Modulus		1.25 Y1			ac
(°C)	(°F)	(GPa)	(10^6ksi)	(MPa)	(ksi)	(MPa units)	(ksi units)
371	700	187	27.1	307	44.50	3.10E-14	7.00E-11
399	750	183	26.6	302	43.75	1.11E-13	2.50E-10
427	800	181	26.3	296	42.87	3.54E-13	8.00E-10
454	850	159	23.0	288	41.70	1.11E-12	2.50E-09
482	900	177	25.6	280	40.62	4.42E-12	1.00E-08
510	950	173	25.1	268	38.90	1.11E-11	2.50E-08
538	1000	170	24.6	256	37.12	3.54E-11	8.00E-08
566	1050	167	24.2	238	34.50	1.11E-10	2.50E-07
593	1100	163	23.7	221	32.00	3.54E-10	8.00E-07

CALCULATED CREEP CURVES

Calculated creep curves for 482°C (900°F) are plotted in Fig. 6. These log strain versus log time curves were compared to typical data plotted in Fig.3, and it was confirmed that the general behavior features were captured by the creep law given by eq. (2) for creep strains to 1%. The calculated creep curve for 276 MPa (40 ksi) at 482°C (900°F) is plotted in Fig. 7 along with creep curves for ten lots of steel. The solid symbols represent lots that were used in the analysis.

The open symbols represent lots that were not used. The calculated curve captures the general trend of the data to approximately 1% creep. Tertiary creep started at very low strains and became increasingly significant beyond 1 % creep.

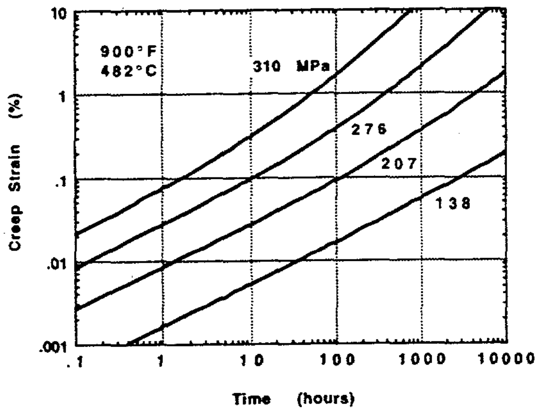

Fig. 6. Calculated creep curves for 482°C (900°F)

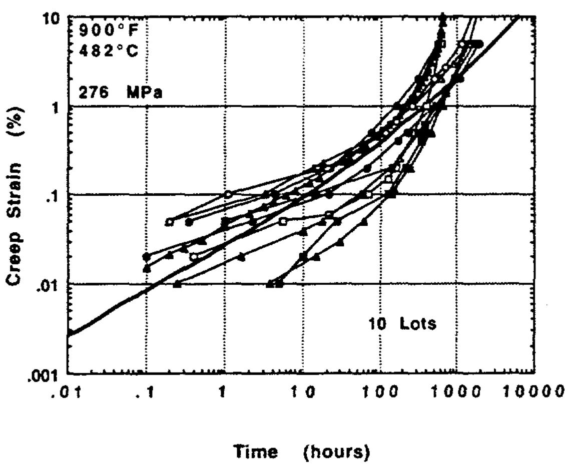

Fig. 7. Comparison of calculated and measured creep curves for 276 MPa at 482°C (900°F)

CALCULATED ISOCHRONOUS CURVES

Creep strains calculated from eq. (2) were added to the zero time curve to construct isochronous curves over the range 482 to 566°C (900 to 1050°F). It was found that the use of eq. (5) instead of eq. (4) did not significantly change the isochronous curves at low stress and long times, so eq. (4) was retained for all stress levels. A comparison of data to the isochronous curve for 1000 hours and 482°F (900°F) is provided in Fig. 8. The ASME BPV Code stress units are provided on the abscissa. Curves for 482, 510, 538, and 566°C are provided in Figs. 9a through Fig. 9d, respectively.

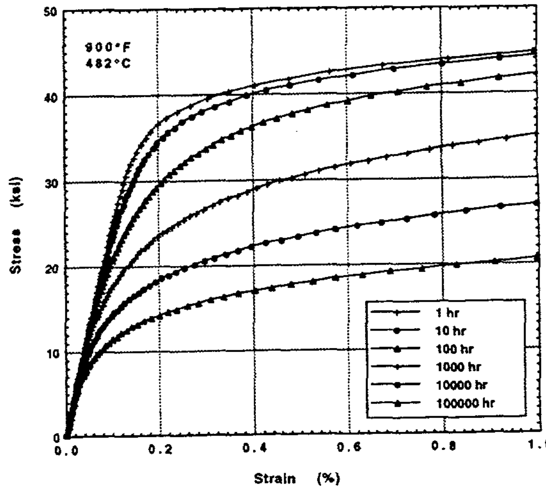

Fig. 8a. Isochronous curves for 482°C (900°F)

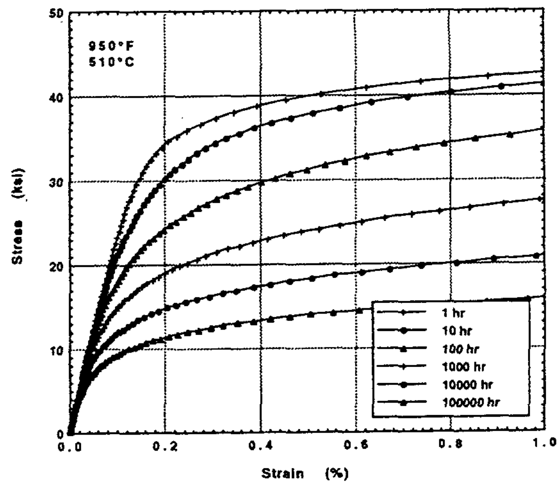

Fig. 8b. Isochronous curves for 510°C (950°F)

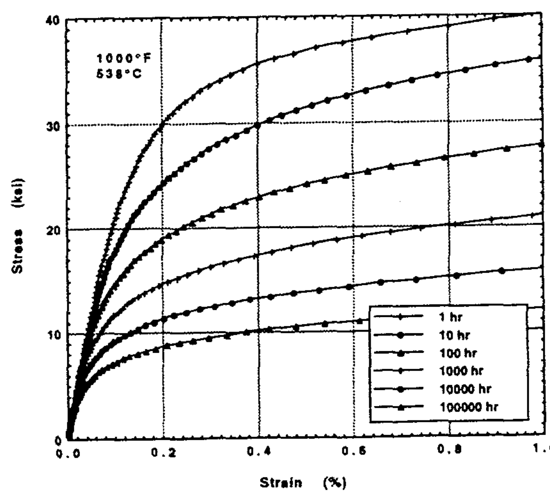

Fig. 8c. Isochronous curves for 538°C (1000°F)

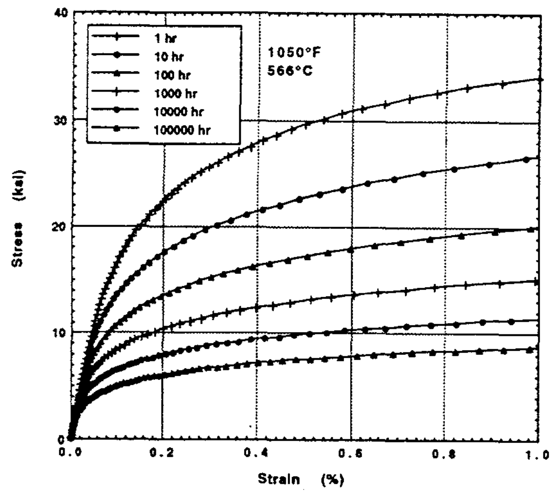

Fig. 8d. Isochronous curves for 566°C (1050°F).

DISCUSSION

The chrome-moly steels are highly sensitive to thermal-mechanical processing, and there exists a considerable overlap in the tensile and creep-rupture properties of the annealed, normalized-and-tempered, and quenched-and-tempered (enhanced strength) grades. All grades exhibit dynamic strain-aging effects under tensile loading (Klueh and Oakes, 1976). All exhibit complex creep behavior (Klueh and Booker, 1978). Just like other grades and classes, the normalized-and-tempered 2 1/4Cr-1Mo steel exhibits a first stage of creep that may be decelerating (classical), linear, negative, or accelerating (tertiary). Such variability makes it difficult to formulate a creep law that will be representative of a broad range of compositions, cooling rates, tempering parameters, stresses, and temperatures. The power-law primary creep formulation used here is simple and representative of the available data over a small range of strains. It is important to recognize, however, that tertiary creep starts at very low strains in this material, and a more realistic creep equation would include a tertiary creep term. Changes in the size, distribution, morphology, and elemental constituents of the various carbides are often identified as the reasons for the changing characteristics of the creep curves and the "early" initiation of tertiary creep. In their evaluation of normalized-and-tempered 2 1/4Cr-1Mo steel, Swindeman, Booker, and McAfee (1983) examined the tertiary creep and found that consideration of the effect on the isochronous stress versus strain curves was not needed for strains below 2%, but their database was not as large as the database used in the current analysis.

An interesting aspect of the analysis is the comparison of isochronous curves for the normalized-and-tempered steel with the curves provided for annealed steel in ASME Section III Subsection NH. The analysis suggests that the normalized-and-tempered steel is more creep-resistent than the annealed material to at least 566°C (1050°F). This does not mean that the normalized-and-tempered steel has a higher rupture strength or design allowable stress at 566°C (1050°F) or above. In fact, the strength of normalized-and-tempered steel relative to annealed steel has been investigated by Klueh and Booker (1978) and Bynum, Ellis, and Roberts (1976). They both observed that the annealed material was stronger at higher temperatures. Some of the lots of steel that were not used in the development of the creep law exhibited equal or even better strength than the lots that were included in the analysis, so there appears to be a need for a more detailed study of the facors that influence primary creep of the low alloy steels.

CONCLUSIONS

The tensile yield curves for NT 2 1/4Cr-1Mo steel may be constructed from a simple plasticity equation that is normalized to the yield strength. This normalization permits curves to be constructed for minimum strength based on ASME Sect. II-D Table Y1 or a multiple of the minimum strength.

Creep curves to one percent strain may be represented by a parabolic primary creep term in combination with a linear creep term based on the minimum creep rate. Creep data for nine lots of steel to 1000 hours exhibit reasonably good agreement with the calculated curves.

Tertiary creep occurs at low strains and limits the applicability of the model for the construction of isochronous stress versus strain curves to 1% strain.

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REFERENCES

Booker, M. K., and Booker, B. L. P., 1980, "New Methods for Analysis of Materials Strength Data for the ASME Boiler and Pressure Vessel Code," pp. 31-64 in *Use of Computers in Managing Materials Property Data*, MPC-14, American Society of Mechanical Engineers, New York, NY.

Bynum, J. E., Ellis, F. V., and Roberts, B. W., 1976, "Tensile and Creep Properties for an Annealed Versus Normalized and Tempered 2-1/4 Cr- 1Mo Steel Plate," pp. 1 to 28 in *Chrome Moly Steel in 1976*, MPC-4, American Society of Mechanical Engineers, New York, NY.

Chao, B. L., Odette, G. R., and Lucas, G. E., 1988, *Kinetics and Mechanisms of Hydrogen Attack in 2.25Cr-1Mo Steel*, ORNL/Sub/82-22276/01, Oak Ridge National Laboratory, Oak Ridge, TN, August.

Handrock, J. L., Marriott, D. L., and Stubbins, J. F., 1987, "Development of a Uniaxial Constitutive Model for a Strain Induced Softening Materials," pp. 83 to 89 in *Thermal Stress, Materials Deformation, and Thermo-Mechanical Fatigue*, PVP Vol. 123, American Society of Mechanical Engineers, New York, NY.

Klueh, R. L., and Oakes, R. E., Jr., 1977, "Strain Rate Effects on the Tensile Properties of a Bainitic (Normalized and Tempered) 2 1/4Cr-1Mo Steel," *J. Eng. Mater. Technol.*, Vol. 99, p. 353.

Klueh, R. L., 1977, "Creep and Rupture Behavior of a Bainitic (Normalized and Tempered) 2 1/4Cr-1Mo Steel," *Int. J. Press. Ves. & Piping*, Vol. 8, p. 165.

Klueh, R. L., and Booker, M. K., 1982, "Heat Treatment of 2 1/4Cr-1Mo Steel for Breeder Reactor Steam Generators," *Nucl. Tech. Vol. 57, p. 114.*

Leyda, W. E., and Prager, M., 1986, "The Effect of Heat Treatment and Resulting Microstructures on the Creep and Stress-Rupture Properties of 2.25Cr-1Mo Gr 22 Class 2 Material," paper presented at the 1988 Pressure Vessels and Piping Conference, Pittsburgh, PA.

Manson, S. S., and Muralidharan, U., 1984, "Analysis of Creep Rupture Data for Five Multiheat Alloys by the Minimum Commitment Method Using Double Heat Term Centering Technique," pp. 1 to 46 in *Progress in Analysis of Fatigue and Stress Rupture*, MPC-23, American Society of Mechanical Engineers, New York, NY.

Sjodahl, L. H., 1978, "A Comprehensive Method of Rupture Data Analysis with Simplified Models," pp. 501 to 515 in *Characterization of Materials for Service at Elevated Temperatures,* MPC-7, American Society of Mechanical Engineers, New York, NY.

Smith, G. V., 1971, *Supplemental Report on the Elevated-Temperature Properties of Chromium-Molybdenum Steels (An Evaluation of 2 1/4 Cr- 1 Mo Steel)*, Data Series Publication DS 6S2, American Society for Testing and Materials, Philadelphia, PA.

Smith, G. V., editor 1972, *The Generation of Isochronous Stress-Strain Curves*, American Society of Mechanical Engineers, New York, NY.

Swindeman, R. W., Booker, M. K., and McAfee, W. J., 1983, *Design Methodology and Materials Data Base for Solvent Refined Coal Dissolver Vessels*, ORNL/TM-8577, Oak Ridge National Laboratory, Oak Ridge, TN, August.