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HIGH STRAIN RATE TENSILE PROPERTIES OF ANNEALED 2 1/4 Cr-1 Mo STEEL*

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ABSTRACT

The high strain rate tensile properties of annealed 2 1/4 Cr-1 Mo steel were determined and the tensile behavior from 25 to 566°C and strain rates of 2.67×10^{-6} to 144/sec were described. Above 0.1/sec at 25°C, both the yield stress and the ultimate tensile strength increased rapidly with increasing strain rate. As the temperature was increased, a dynamic strain aging peak appeared in the ultimate tensile strength-temperature curves. The peak height was a maximum at about 350°C and 2.67×10^{-6} /sec. With increasing strain rate, a peak of decreased height occurred at progressively higher temperatures. The major effect of strain rate on ductility occurred at elevated temperatures, where a decrease in strain rate caused an increase in total elongation and reduction in area.

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INTRODUCTION

The steam generator of the Clinch River Breeder Reactor Plant (CRBRP) — the demonstration liquid metal fast breeder reactor (LMFBR) — is to be constructed of annealed 2 1/4 Cr-1 Mo steel. As part of the safety analysis for the steam generator, high strain rate elevated temperature tensile properties are required. Such data, over the strain rate and temperature ranges of interest have not previously been collected.

In the present work, we have determined the tensile properties over the strain rate range 0.16 to 144/sec and the temperature range 25 to 566°C. Previously, the tensile properties were reported¹ over the same temperature range and a strain rate range 2.67×10^{-6} to 6.67×10^{-3} /sec. In the present paper, these results are combined with the high strain rate results to represent the variation of the tensile properties with strain rate over eight orders of magnitude.

EXPERIMENTAL PROCEDURE

The 2 1/4 Cr-1 Mo steel tested was from a heat of commercial material obtained from Babcock & Wilcox (B&W heat 20017); the chemical composition is given in Table 1. The steel was in the form of a 1-in.-thick plate, and sections of this plate were put in the annealed condition by heating for 1 hr at 927°C (1700°F) and then furnace cooling to 250°C in 27 hr. In this "annealed" condition, the microstructure consisted of a proeutectoid ferrite-pearlite structure; the pearlite was quite fine, and the platelets were resolved only at a magnification greater than 750X. The ferrite grain size was estimated as ASTM No. 5-6. Figure 1 shows the microstructure.

Table 1. Chemical Composition of 1-in. Plate of Annealed
2 1/4 Cr-1 Mo Steel

Analysis	Chemical Composition, wt %							
	C	Mn	Si	Cr	Mo	Ni	S	P
Vendor	0.11	0.55	0.29	2.13	0.90		0.014	0.011
ORNL	0.135	0.57	0.37	2.2	0.92	0.16	0.016	0.012

For the low strain rates from 2.67×10^{-6} to $6.67 \times 10^{-3}/\text{sec}$, tests were made on a 44 kN-capacity (10,000 lb) Instron universal testing machine. Two types of data were taken: (1) conventional load-crosshead displacement data were obtained; (2) for the first 5% strain, data were obtained from an extensometer attached to the center 25.4 mm (1 in.) length of the gage section. The 0.2% offset yield stress was obtained from the more exact extensometer data.

For strain rates between 0.16 and 144/sec, the tests were performed on an MTS electrohydraulic servo-controlled testing machine. On this machine, force was measured with a high response quartz piezoelectric load washer. The piston displacement signal came from a LVDT built into the linear actuator, and the LVDT signal was used as the feedback signal. For tests at strain rates of 0.16 and 1.6/sec, conventional extensometers were used for strain measurements.

The force, piston displacement, and extensometer signals (for the 0.16 and 1.6/sec tests) were recorded on a multichannel digital transient recorder with internal memory. With this recorder, data sampling rates to 5 micro-seconds per sample were possible. Playback from memory after the test was then made twice at reduced speeds compatible with X-Y recorder response time. One playback displayed load vs crosshead displacement covering the entire test to failure. The ultimate tensile strength and fracture strength were determined from this record. A second playback was made to display the expanded crosshead displacement signal during the initial loading portion of the test; the 0.2% offset yield stress was determined from this record. When the expanded crosshead displacement signal for the low strain rate tests was compared with the yield stress determined by conventional extensometry, agreement was quite good. Hence, the expanded crosshead displacement signal was used for yield stress determination at higher test speeds, where the extensometer system lacked response time.

For all tests, specimens taken longitudinal to the rolling direction were used; these specimens had a 6.35-mm-diam by 31.75-mm-long reduced section (0.25 X 1.25 in.). Both machines were operated at a constant crosshead velocity, and the strain rate values given throughout this report are engineering values based on the crosshead velocity and the initial specimen gage length.

RESULTS AND DISCUSSION

The results previously reported¹ for the low strain rate tests (2.67×10^{-6} to 6.67×10^{-3} /sec) are shown in Table 2. In Table 3 the tests over the strain rate range 0.16 to 144/sec are given. Figures 2 to 5 show the three-dimensional representations of the 0.2% yield stress, ultimate tensile strength, total elongation, and reduction in area over the entire strain rate range of 2.67×10^{-6} to 144/sec and from 25 to 566°C. To better show the behavior of the yield stress and ultimate tensile strength, Figs. 6(a) through 6(f) show the results as a function of strain rate at 25, 204, 371, 454, 510, and 566°C, respectively, and Fig. 7 shows the results as a function of temperature at strain rates of 2.67×10^{-6} [Fig. 7(a)] and 6.67×10^{-3} [Fig. 7(b)] 0.16/sec [Fig. 7(c)], and 144/sec [Fig. (d)]. In addition to the yield stress and ultimate tensile strength, Figs. 6 and 7 also show the stress at strains of 2 and 5%.

Except at room temperature, Figs. 2 and 6 show that the yield stress was little affected by strain rate. At room temperature [Fig. 6(a)], there was little effect up to about 0.1/sec, after which it increased rapidly with increasing strain rate. The only other effect of strain rate was an apparent local maximum in the yield stress in the strain rate range 0.01 to 10/sec at temperatures greater than 204°C. The maximum peak height occurs at 371°C [Fig. 6(c)]. This is verified by examination of the yield stress-temperature representations in Figs. 7(b) and 7(c), where a peak is observed in the vicinity of 371°C. Figure 7 also shows the effect of strain rate on the peak, as no

Table 2. Engineering Tensile Properties of Annealed 2 1/4 Cr-1 Mo Steel at Low Strain Rates

Temperature °C (°F)	Strength, MPa (ksi)			Elongation, %		Reduction in Area (%)
	0.2% Yield	Ultimate Tensile	Fracture	Uniform	Total	
<u>Strain Rate - 6.67 X 10⁻³/sec</u>						
25 (77)	260 (37.7)	527 (76.4)	309 (44.8)	12.0	28.2	69.9
204 (400)	219 (31.7)	443 (64.2)	282 (40.9)	11.8	24.6	70.9
371 (700)	228 (33.0)	499 (72.4)	359 (52.0)	9.0	19.0	57.4
454 (850)	216 (31.3)	468 (67.9)	287 (41.6)	10.2	22.9	64.2
510 (950)	208 (30.2)	428 (62.1)	217 (31.6)	8.5	24.7	70.9
538 (1000)	211 (30.6)	424 (61.5)	204 (29.6)	8.5	23.3	72.5
566 (1050)	196 (28.4)	367 (53.2)	148 (21.4)	9.1	28.3	80.3
593 (1100)	201 (29.1)	354 (51.3)	138 (20.0)	7.6	27.8	81.7
<u>Strain Rate - 6.67 X 10⁻⁴/sec</u>						
25 (77)	258 (37.4)	525 (76.1)	316 (48.8)	12.8	28.3	67.3
93 (200)	235 (34.3)	469 (68.3)	284 (41.7)	12.6	28.6	73.4
204 (400)	221 (32.0)	450 (65.2)	294 (42.6)	11.0	23.7	66.2
316 (600)	226 (32.7)	483 (69.8)	334 (48.6)	9.2	19.8	66.8
371 (700)	227 (32.9)	514 (74.5)	352 (51.0)	9.5	20.1	56.9
454 (850)	230 (33.3)	499 (72.4)	310 (44.9)	8.7	21.0	61.5
510 (950)	224 (32.5)	459 (66.5)	231 (33.5)	8.9	23.6	69.2
538 (1000)	217 (31.5)	423 (61.3)	119 (17.3)	8.4	26.3	73.9
566 (1050)	208 (30.2)	374 (54.3)	63 (9.1)	7.7	25.9	79.3
593 (1100)	203 (29.5)	328 (47.5)	35 (5.1)	6.8	36.5	84.7
<u>Strain Rate - 6.67 X 10⁻⁵/sec</u>						
25 (77)	254 (36.8)	514 (74.5)	309 (44.8)	13.3	28.7	69.5
204 (400)	237 (34.3)	474 (68.8)	315 (45.7)	10.9	22.9	66.0
371 (700)	229 (33.2)	516 (74.8)	343 (49.8)	10.4	21.3	58.6
454 (850)	221 (32.1)	494 (71.7)	281 (40.7)	8.7	21.8	64.5
510 (950)	215 (31.2)	416 (60.3)	210 (30.5)	7.4	29.4	76.2
538 (1000)	203 (29.5)	354 (51.3)	212 (30.8)	7.4	36.4	82.6
566 (1050)	203 (29.5)	333 (48.3)	49 (7.1)	6.8	37.0	84.0
593 (1100)	185 (26.8)	250 (36.2)	17 (2.5)	5.8	37.2	89.0
<u>Strain Rate - 2.67 X 10⁻⁶/sec</u>						
25 (77)	242 (35.2)	490 (71.0)	295 (42.8)	12.9	28.0	68.6
204 (400)	233 (33.8)	491 (71.2)	342 (49.6)	9.7	21.0	63.9
371 (700)	230 (33.3)	563 (81.7)	357 (51.7)	10.1	20.6	60.5
454 (850)	226 (32.8)	501 (72.6)	210 (30.5)	9.5	23.8	67.2
510 (950)	206 (29.9)	351 (50.9)	99 (14.4)	6.2	35.8	83.8
538 (1000)	190 (27.5)	268 (38.9)	64 (9.3)	4.6	30.6	86.6
566 (1050)	174 (25.3)	209 (30.3)	41 (5.9)	3.7	56.7	88.4
593 (1100)	145 (21.0)	165 (24.0)	34 (4.9)	3.6	59.0	86.2

Table 3. Engineering Tensile Properties of Annealed 2 1/4 Cr-1 Mo Steel
at High Strain Rates

Strain Rate (sec ⁻¹)	Strength, MPa (ksi)			Elongation, %		Reduction in Area (%)
	0.2% Yield	Ultimate Tensile	Fracture	Uniform	Total	
<u>25°C (77°F)</u>						
0.16	317 (46.0)	528 (76.6)	260 (38)	10.6	28.6	68
0.16	324 (47.0)	545 (79.0)	280 (40)	10.2	27.6	68
1.6	328 (47.6)	565 (82.0)	310 (45)	10.5	30.0	67
1.6	330 (47.9)	553 (80.2)	330 (48)	10.5	30.0	67
16		607 (88.0)	340 (49)	12.3	29.8	68
16		610 (88.4)	340 (50)	11.1	30.2	67
16	387 (56.2)	601 (87.2)	330 (48)	13.8	31.5	67
144	496 (72.0)	689 (100)	410 (60)	11.9	32.2	71
144	490 (71.0)	717 (104)	410 (60)	15.4	31.0	69
<u>204°C (400°F)</u>						
0.16	237 (34.3)	460 (66.8)	300 (44)	11.5	24.3	68
1.6	259 (37.6)	470 (68.2)	290 (42)	11.5	24.9	70
16	244 (35.4)	490 (71.2)	290 (42)	11.9	27.3	72
144	262 (38.0)	508 (73.6)	280 (41)	12.4	27.4	72
<u>371°C (700°F)</u>						
0.16	258 (37.4)	469 (68.0)	340 (50)	8.2	17.8	58
1.6	244 (35.4)	454 (65.4)	320 (47)	9.4	19.3	65
16	210 (30.4)	441 (64.0)	300 (44)	9.4	19.0	62
144	226 (32.8)	439 (63.6)	270 (39)	11.5	23.4	71
<u>454°C (850°F)</u>						
0.16	234 (34.0)	473 (68.6)	260 (38)		20.9	59
0.16	221 (32.0)	466 (67.6)	300 (44)	9.4	21.3	61
1.6	248 (36.0)	451 (65.4)	320 (47)	9.7	19.2	62
16	204 (29.8)	430 (62.4)	290 (42)	9.6	19.8	65
16	222 (32.2)	439 (63.6)	300 (43)	7.3	17.0	63
144	221 (32.0)	434 (63.0)	290 (42)	9.0	19.3	70
144	234 (34.0)	473 (68.6)	320 (46)	10.0	20.1	66
<u>510°C (950°F)</u>						
0.16	228 (33.0)	439 (63.6)	230 (33)	10.3	22.8	71
0.16	212 (30.8)	443 (64.2)	230 (34)		22.7	68
1.6	237 (34.3)	473 (68.6)	300 (44)	9.8	21.2	61
1.6	234 (34.0)	462 (67.0)	300 (44)	9.5	21.9	62
16	211 (30.6)	439 (63.6)	300 (44)	8.2	18.1	63
16	207 (30.0)	456 (66.2)	320 (47)	9.3	19.0	60
144	221 (32.0)	483 (70.0)	330 (48)	9.7	18.1	65

Table 3. (Continued)

Strain Rate (sec ⁻¹)	Strength, MPa (ksi)			Elongation, %		Reduction in Area (%)
	0.2% Yield	Ultimate Tensile	Fracture	Uniform	Total	
<u>566°C (1050°F)</u>						
0.16	218 (31.6)	382 (55.4)	180 (26)		25.2	78
0.16	210 (30.4)	403 (58.4)	180 (26)	8.0	22.6	76
1.6	237 (34.3)	416 (60.4)	210 (30)	10.0	24.1	73
1.6	236 (34.2)	437 (63.4)	210 (31)	10.2	24.5	72
16	221 (32.0)	434 (63.0)	270 (39)	8.9	22.6	68
16	211 (30.6)	455 (66.0)	290 (42)	10.1	21.0	62
144	210 (30.4)	473 (68.6)	340 (49)	10.9	20.0	61
144	232 (33.6)	496 (72.0)	340 (50)	9.5	19.0	58

peak is observed at 2.67×10^{-6} and 144/sec, only at the two intermediate strain rates. On the three dimensional representation, a "hump" appears quite prominent.

Figure 3 shows that the effect of strain rate and temperature on the ultimate tensile strength involves a complicated topography of "ridges and valleys" that are more easily visualized with the aid of Figs. 6 and 7. As with yield stress, the room temperature behavior showed considerable strain rate effect: at strain rates above 0.16/sec, there was a large increase in tensile strength with increasing strain rate; at lower strain rates, the rate of increase was much less rapid. At 204°C, Fig. 6(b), and increase in strain rate from 2.67×10^{-6} /sec caused the ultimate tensile strength to first decrease, then increase (a minimum occurred at about 10^{-2} /sec). At 371 and 454°C, Figs. 6(c) and 6(d), the ultimate tensile strength rather continuously decreased with increasing strain rate; the rate of decrease was greatest at 371°C. Finally, at 510 and 566°C the tensile strength increased with increasing strain rate, the larger rate of increase occurring at 566°C.

In the ultimate tensile strength-temperature relationships shown in Fig. 7, dynamic strain-aging peaks are observed. The maximum peak height occurred at 2.67×10^{-6} /sec at about 350°C. As the strain rate increased, a decreased peak occurred at higher and higher temperatures. At the highest strain rate, 144/sec, the peak occurred near 566°C, Fig. 7(d).

Dynamic strain aging is the result of interactions of solutes (e.g., carbon and nitrogen) with dislocations. The increase in the temperature of the peak strength with increasing strain rate is a reflection of the increased diffusion rate of the solutes with increased temperature (i.e., at the highest temperatures for the high strain rate, the solutes that led to dislocation locking can diffuse rapidly enough to enhance the strength).

Strain rate effects on fracture stress (not shown graphically) were qualitatively similar to the ultimate tensile strength, though the magnitude of the effects were not as great. With the exception of a slight increase at the highest rate (144/sec), at 25°C fracture stress changed little with strain rate. At 204 and 371°C there was a slight decrease with increasing strain rate. For seven orders of magnitude at 454°C, there was no strain rate effect, then a slight decrease at the lowest strain rate (2.67×10^{-6} /sec). Finally, at 510 and 566°C the most significant changes occur: when the strain rate was increased from 2.67×10^{-6} to 144/sec, the fracture strength changed from 99 to 330 MPa at 510°C and 41 to 340 MPa at 566°C.

The effect of strain rate on total elongation, Fig. 4, reflected the effect of strain rate on tensile strength. That is, a relatively high strength was accompanied by a relatively low total elongation. From 2.67×10^{-6} to 1.6/sec, the specimens tested at 371°C had the lowest elongation, followed by those tested at 454°C, a reflection of the maximum strain-aging peak at low strain rate (Fig. 7). Only at 510 and 566°C did the total elongation show significant change over the eight orders of magnitude in strain rate. At these temperatures, the elongation increased with decreasing strain rate: from 18 to 37% at 510°C and 20 to 56% at 566°C. The behavior of the reduction in area, Fig. 5, paralleled that for the total elongation.

Uniform elongation (not shown graphically) showed relatively little effect of strain rate. Only at the lowest strain rate, 2.67×10^{-6} /sec, and the two highest temperatures, 510 and 566°C, was there a noticeable change: the uniform elongation decreased with decreasing strain rate.

The general trends in properties discussed above are well-illustrated by examining the selected engineering stress-strain curves shown in Fig. 8. Curves are shown for strain rates of 2.67×10^{-6} , 6.67×10^{-3} , 0.16, and 144/sec at 25 [Fig. 8(a)], 371 [Fig. 8(b)], and 566°C [Fig. 8(d)]. The large

increase in strength properties above 0.16/sec at 25°C (Fig. 6) is rather obvious when the upward displacement of the 144/sec curve is noted in Fig. 8(a). The relationship of strain rate and the strain-aging peak in the ultimate tensile strength-temperature curves of Fig. 6 is evident in Figs. 8(b) and 8(c). At 371°C, the curves for the lowest strain rates have the highest stress-strain curves. In line with the shift of the peak to higher strain rates at the higher temperatures, Fig. 8(c) shows that at 566°C the trend reverses to again make the curves at the highest strain rates have the highest stress-strain curve. Figure 8(c) also displays the increased total elongation and decreased uniform elongation with decreased strain rate that occurred at elevated temperatures (Fig. 4). Since all the stress-strain curves have similar shapes, especially when just the portion of the curve up to the ultimate tensile strength is considered, we expect that the plastic behavior of the high strain rate tests can be represented analytically by using the Voce equation,² as was done previously for the low strain rate tests.

At room temperature, a yield point, with its accompanying Luder's strain at the lower yield was observed at strain rates of 1.6, 16, and 144/sec. This gives rise to the merging of the yield stress and the stress for 2% strain curves in Fig. 6(a); that is, the Luder's strain exceeds 2%. At 6.67×10^{-3} and 0.16/sec, an inflection point was noted in the stress-strain curves in the strain ranges at which a yield point would be expected. Above 25°C, a yield point was only noted at 144/sec and was quite distinct for all tests conducted at that strain rate up to 454°C.

In all cases, visual examination of the fractured specimens indicated that a ductile cup-cone type of failure occurred. Likewise, metallography revealed that the failures were of a ductile transgranular mode. There was no evidence of any intergranular failure.

In addition to exhibiting a strain-aging peak in the ultimate tensile strength-temperature curve, dynamic strain aging also manifests itself in serrated stress-strain curves (the Portevin-LeChatelier effect). Manjoine³ seems to have first called attention to the fact that discontinuous yielding should occur "when the stress versus strain-rate curve has a negative slope." According to Manjoine,³ "this means that the material can yield more rapidly at a lower stress, as it does; to keep the average rate constant, the material will be stretched much more slowly during another part of the cycle; this causes the load to build up again and the cycle is repeated." Other investigators^{4,5} have placed this on a more quantitative basis by proposing that serrated flow coincides with a negative strain rate sensitivity, r , which is defined as

$$r = \left(\frac{\partial \log \sigma}{\partial \log \dot{\epsilon}} \right)_{\epsilon, T}$$

where σ is stress, $\dot{\epsilon}$ strain rate, ϵ strain and T the temperature.

According to this criterion, we would expect serrated stress-strain curves whenever a negative slope exists for the curves in Fig. 6 (ref. 3), where the yield stress, stress for 2 and 5% strain, and ultimate tensile strength are shown as a function of $\log \dot{\epsilon}$ (Fig. 6 shows stress as a function of $\log \dot{\epsilon}$; nevertheless, a negative slope in Fig. 6 corresponds to a negative r , although Lubahn and Felgar⁶ have pointed out that the strain-rate sensitivity determined from such data may grossly underestimate r). Considering the errors inherent in the measurements (approx ± 3 ksi¹), we would expect little or no serrated yielding for the low strain rate tests (2.67×10^{-6} to 6.67×10^{-3}). Indeed, this was the case. The only instances where serrated yielding was definitely observed was at 204 and 371°C at the two lowest strain rates. At

the high strain rates, it was very difficult to detect serrated yielding because of "noise" in the system. In some instances, however, especially at 454 and 510°C, it was possible to verify serrations as predicted from Fig. 6. Since dynamic strain aging can affect properties other than tensile⁷ (e.g., fatigue), the curves of Fig. 6 are presented for the information they may give other investigators.

Von Karmen^{8,9} showed that when a material, such as our tensile specimen, is subjected to an impact load, a stress wave will propagate through the specimen. If the impact velocity exceeds the wave velocity, fracture will occur at the impacted end. It can be easily shown that this critical velocity for 2 1/4 Cr-1 Mo steel is very much greater than the 457 cm/sec maximum impact velocity used for these tests. However, it is also possible for the amplitude of the stress wave to be of sufficient magnitude to alter the test material's characteristics.¹⁰ We have also examined this possibility by making calculations using the longitudinal wave velocity for 2 1/4 Cr-1 Mo steel and concluded that the initial wave passage through the specimen should not have affected the test results.

Since it is known that up to 90% of the work during metal deformation appears as heat,¹¹ the possibility exists that adiabatic heating during the high speed deformation may affect the results. Such heating should have little or no effect on yield stress, which occurs prior to significant deformation. Adiabatic heating effects can be divided into two parts: that occurring during uniform deformation where heat is generated in the entire volume of the gage section, and that occurring from maximum load to fracture where deformation, and thus heating, is confined to the necked region. Hence, the fracture stress, total elongation, and reduction in area should be much more affected than the ultimate tensile strength and uniform elongation.

The worst case for the present tests is at 25°C and 144/sec. Under the assumption that all the work goes into adiabatic heating, a temperature rise of 28°C was estimated to occur during deformation to maximum load. From maximum load to fracture, about the same amount of work is performed, but on about an eighth of the volume (the necked region), giving rise to a possible 200°C temperature increase in the necked region. At elevated temperatures, the effect will be much less pronounced. From these results it appears that the ultimate tensile strength and uniform elongation should be only slightly affected by adiabatic heating. Although adiabatic heating could significantly affect the fracture stress and ductility measurements, we were unable to delineate such an effect.

SUMMARY AND CONCLUSIONS

The tensile properties of annealed 2 1/4 Cr-1 Mo steel have been studied over the temperature range 25 to 566°C and the strain rate range 2.67×10^{-6} to 144/sec. The following observations and conclusions were made:

1. Except at 25°C, the 0.2% yield stress was little affected by strain rate. Above about 0.1/sec at 25°C, there was a large increase in yield stress with increasing strain rate. The only other effect was a minor peak at intermediate temperatures and strain rates.
2. At 25°C, the effect of strain rate on ultimate tensile stress was similar to the effect on yield strength: there was a large increase above 0.1/sec, though the ultimate tensile strength also showed a smaller rate of increase at lower strain rates. The ultimate tensile strength-temperature relationship exhibited a dynamic strain-aging peak, which was a maximum at about 350°C and 2.67×10^{-6} /sec. In this temperature range, the ultimate tensile strength increased with decreasing strain rate. A strain aging peak

occurred at each strain rate, but as the strain rate was increased, the peak height decreased and occurred at progressively higher temperatures. At the highest temperatures, 510 and 566°C, the ultimate tensile strength increased with increasing strain rate.

3. Except at 510 and 566°C, ductility was little affected by strain rate. At these temperatures, the total elongation and the reduction in area increased with decreasing strain rate, while the uniform elongation decreased with decreasing strain rate.

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Fig. 1

Tensile Yield Stress vs Temperature & Strain Rate
 2½ Cr - 1 Mo Steel, Annealed

Fig 2

Fig 3

Elongation at Failure vs Temperature & Strain Rate
 2½Cr-1Mo Steel, Annealed

Fig 4

Reduction in Area vs Temperature & Strain Rate
 2½ Cr-1 Mo Steel, Annealed

Fig 5

(a)

(b)

(c)

Fig. 6

(d)

(e)

(f)

Fig. 6 (Continued)

(a)

(b)

Fig. 7

(c)

(d)

Fig. 7 (Continued)

(३)

(b)

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Fig. 8