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Effects of Tempering Treatment on Tensile, Hardness, and Charpy Impact Properties of Modified 9 Cr-1 Mo Steel

V. K. Sikka
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EFFECTS OF TEMPERING TREATMENT ON TENSILE, HARDNESS, AND CHARPY IMPACT PROPERTIES OF MODIFIED 9 Cr-1 Mo STEEL

V. K. Sikka, R. E. McDonald, G. C. Bodine, and W. J. Stelzman

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EFFECTS OF TEMPERING TREATMENT ON TENSILE, HARDNESS, AND CHARPY IMPACT PROPERTIES OF MODIFIED 9 Cr-1 Mo STEEL*

V. K. Sikka, R. E. McDonald, G. C. Bodine,† and W. J. Stelzman

ABSTRACT

We investigated the effects of tempering temperature and time on the tensile properties and hardness of modified 9 Cr-1 Mo steel at room temperature and on its Charpy impact energy at room temperature and at 204°C. Effects of postweld heat treatment on room-temperature tensile properties were also investigated, and tensile data at elevated temperatures were obtained for selected tempering conditions.

The room-temperature tensile properties (strength and ductility), hardness, and Charpy impact energy were fitted to a Holloman-Jaffe (HJ) parameter with an optimized constant of 22.3. This parameter allows the trade-off of tempering temperature and time to obtain the desirable properties. The same parameter was also suitable for obtaining the effects of postweld heat treatment on tensile properties. The effects of specimen size and full-size tubular specimens on tensile properties are presented. The yield and ultimate tensile strengths were plotted as functions of hardness. Optical and scanning electron micrographs showed similar microstructures in specimens subjected to tempering conditions producing the same value of the HJ parameter.

INTRODUCTION

Modified 9 Cr-1 Mo steel, currently in the approval process for inclusion in ASTM specifications A 387 for plate and A 213 for tube as grade 91 (see Table 1), offers significantly improved elevated-temperature strength properties over those of 2 1/4 Cr-1 Mo (grade T22) and the standard 9 Cr-1 Mo (grade T9) (refs. 1 and 2). The alloy also has higher creep strength than does type 304 stainless steel for temperatures up to 600°C (refs. 1 and 2).

*Work performed under DOE/BTR AF 15 40 10 3, Task OR-1.7, Advanced Alloy Technology.

†Combustion Engineering, Inc., Chattanooga, Tenn.

Table 1. Recommended specifications for modified 9 Cr-1 Mo steel

(For inclusion in ASTM specifications; the alloy is being designated as grade 91 by the plate and tube subcommittee of ASTM)

Element	Range (wt %)
C	0.08–0.12
Mn	0.30–0.60
P	<0.020
S	<0.010
Si	0.20–0.50
Cr	8.00–9.50
Mo	0.85–1.05
Ni	<0.40
V	0.18–0.25
Nb	0.06–0.10
N	0.030–0.070
Al	<0.04

The alloy is recommended for use in the normalized and tempered condition. The normalizing treatment transforms ferrite to austenite and dissolves carbides. The normalizing temperature for this alloy should be at least 1040°C to permit dissolution of niobium and vanadium carbides.[3] Both these elements improve the elevated-temperature creep properties of the material. The normalizing time at 1040°C is 1 h for a plate thickness of 25 mm and is increased 30 min for each additional 25-mm thickness.

Air cooling from the austenitizing temperature produces martensite with a hardness of about that of Rockwell C 40. This martensite requires tempering to obtain the optimum combination of strength and toughness. Hammond followed the change in room-temperature hardness of martensite as a function of tempering temperature for a fixed tempering time of 1 h (ref. 4). However, for the commercial use of this alloy, a combination

of tempering and postweld heat treating (PWHT) temperature and time must be known to meet the room-temperature specified minimum tensile properties for the alloy. For certain applications, the alloy must meet the specified yield and ultimate tensile strength values without exceeding a certain hardness value. Thus, a knowledge of the relationship between yield and ultimate tensile strength and hardness is required for a range of tempering temperatures and times.

The purpose of this study was to conduct tensile tests at room temperature and at elevated temperatures on material tempered for a variety of temperature and time combinations and PWHT for various times at a given temperature. Room-temperature tensile and hardness data were analyzed in terms of a time-temperature parameter, and the results were compared with the specified minimum tensile properties for the alloy. Room-temperature tensile properties were also plotted as a function of room-temperature hardness to ascertain if the tensile properties could be met without exceeding the hardness requirements.

MATERIALS AND TEST METHODS

Tempering and PWHT were studied for three commercial heats of the alloy. All heats were melted by CarTech,* and their chemical analyses are listed in Table 2. All three were argon-oxygen-decarburized (AOD) melted, and heats 30394 and 30176 were later electroslag remelted (ESR). In fact, heat 30394 has the same composition as 30383 and differs only in melting practice. Plates of 25-mm thickness from heats 30176 and 30394 and of 51-mm thickness from heat 30383 were normalized at 1040°C for 1 h, following which all plates were air cooled to room temperature (RT). One plate from each heat was tempered at the nominal temperature of 760°C for 1 h and once again air cooled to room temperature. Additionally, plates from heats 30176 and 30394 were tempered at 732, 746, 774, 788, and 816°C for 15 min to 16 h. Transverse specimens were machined from all normalized and tempered plates. Almost all specimens were 6.35 mm (0.25 in.)

*CarTech, Reading, Pa.

Table 2. Chemical analysis of commercial heats

Element	Content for each heat[a] (wt %)				
	30383		30394		30176 Plate
	Plate	Tube[b]	Plate	Tube[c]	
C	0.083	0.075	0.084	0.094	0.081
Mn	0.46	0.46	0.46	0.45	0.37
P	0.010	0.009	0.010	0.014	0.010
S	0.004	0.004	0.003	0.004	0.003
Si	0.41	0.40	0.40	0.37	0.11
Ni	0.09	0.08	0.09	0.09	0.09
Cr	8.46	8.17	8.57	8.11	8.61
Mo	1.02	0.99	1.02	1.03	0.89
V	0.198	0.195	0.198	0.200	0.209
Nb	0.072	0.064	0.073	0.072	0.072
Ti	0.005	0.005	0.005	0.002	0.004
Co	0.055	0.055	0.055	0.056	0.010
Cu	0.03	0.03	0.04	0.04	0.04
Al	0.002	0.003	0.014	0.024	0.007
B	<0.001		<0.001		<0.09
W	0.05		0.05		<0.01
As	<0.001		<0.001		0.001
Sn	<0.001		<0.001		<0.001
Zr	<0.001		<0.001		<0.001
N	0.051	0.050	0.053	0.053	0.055

[a]All chemical analysis was carried out at Combustion Engineering, Inc., Chattanooga, Tenn.

[b]Hot extruded.

[c]Hot rotary pierced.

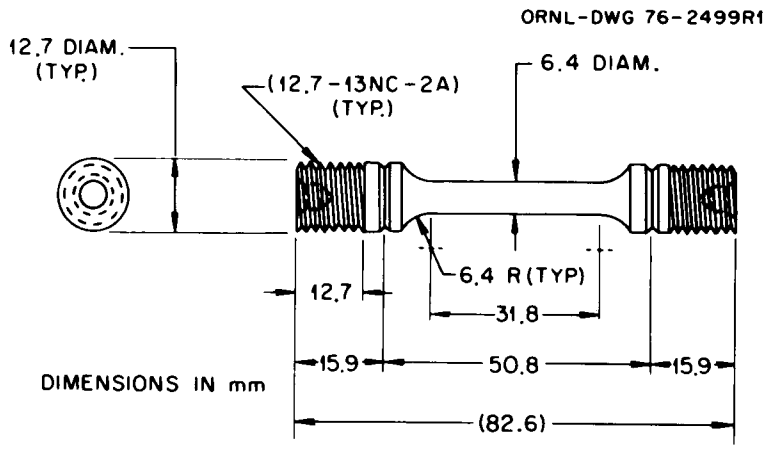


Fig. 1. One type of tensile specimen used for testing modified 9 Cr-1 Mo steel.

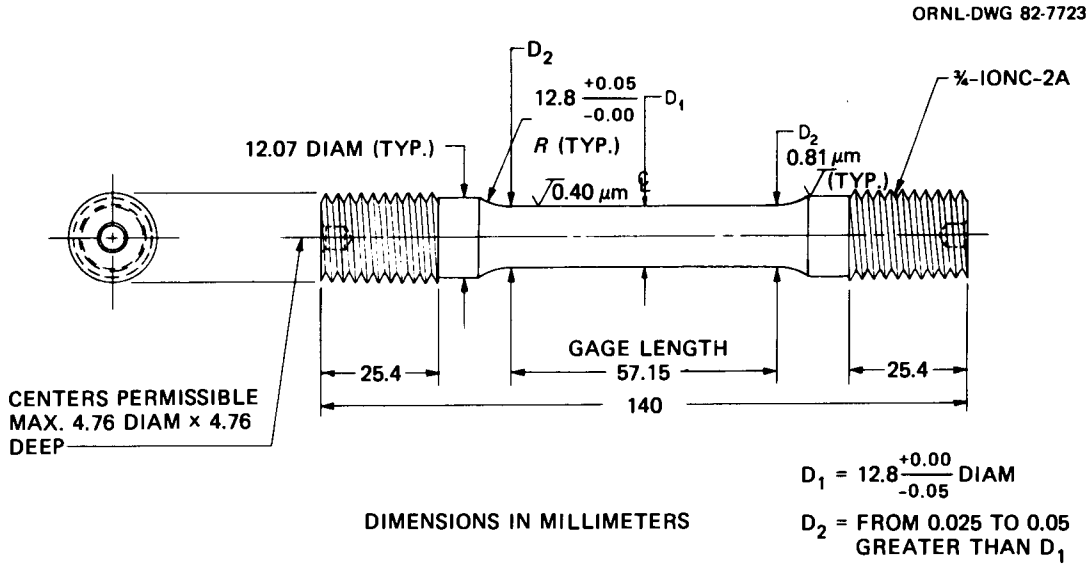


Fig. 2. Second type of tensile specimen used for testing modified 9 Cr-1 Mo steel.

in diameter (Fig. 1), but a few specimens were machined to 12.8 mm (0.505 in.) in diameter (Fig. 2) in order to compare the effect of specimen size on tensile properties. A few tests were also conducted on full-size tubular specimens. The tubes tested had 51-mm ODs and 6.35-mm walls (2 by 0.25 in.). Specimens from normalized and tempered (1040°C for 1 h, 760°C for 1 h) plates of heats 30383, 30394, and 30176 were subsequently given PWHT at 732°C for 1, 14, 28, 42, and 112 h.

Most of the specimens from the tempering temperature—time study were tested at room temperature. However, specimens from plates tempered at 732 and 746°C were tested at room temperature and at 204, 427, and 649°C. Specimens from plates tempered at 774°C were tested at room temperature and at 93, 204, 316, 427, 538, 649, and 760°C. Specimens from the plates given the nominal treatment of 760°C for 1 h were tested at room temperature and at 38, 93, 149, 204, 316, 371, 427, 482, 538, 593, 649, 704, and 760°C. The PWHT specimens were tested at room temperature and at 593°C. All tests were conducted in air with an Instron machine. The nominal strain rate used during these tests was 0.005/min.

We measured Rockwell hardness on the unstressed portion of the specimens tensile tested at room temperature and conducted Charpy impact tests at room temperature and at 204°C on specimens from each of the tempered blocks.

TEST RESULTS

Tensile data for various tempering and PWHT conditions are presented in Tables 3 through 7. Room-temperature tensile data (0.2% yield), ultimate tensile strength, uniform elongation, total elongation, and reduction of area for various temperature and time combinations were fitted to the Holloman-Jaffe (HJ) parameter.[5] This parameter is given by

$$HJ = T(C + \log t) \ , \tag{1}$$

where T is temperature (Kelvin), t is time in (h), and C is the HJ constant. The optimized value of C for the two heats (30176 and 30394) used was determined to be 22.3.

The HJ parameter [5] was derived from tempering studies involving various time-temperature combinations. Holloman and Jaffe felt that the tempering process was diffusion controlled and therefore that the tempering temperature and time should be exchangeable to obtain the same level of hardness. Using the diffusion equation and taking into account that the activation energy is a function of hardness (strength), Holloman-Jaffe derived, Eq. (1). The value of constant C in this equation is obtained for the time-temperature conditions that yield the same value of the property. In this study, we derived the constant for the same value of yield strength. The same value of the constant was found to be suitable for ductility, hardness, and impact energy values, as discussed later in this report.

The tensile properties are plotted against the HJ parameter in Figs. 3 through 7. The best-fit curve, which is a second-degree polynomial, is also included in each figure. The recommended room-temperature specified minimum values for this alloy are yield, 414 MPa; ultimate tensile, 585 MPa; total elongation, 18%; and reduction of area,

Table 3. Tensile test data for heat 30176 of modified 9 Cr-1 Mo steel normalized at 1040°C for 1 h and tempered at 760°C for 1 h

Test temperature (°C)	Strength (MPa)		Elongation (%)		Reduction of area (%)
	0.2% Yield	Ultimate tensile	Uniform	Total	
		6.35-mm-diam Specimens			
25	519	656	6.56	21.00	71.99
38	532	649	6.38	24.10	71.81
93	510	633	4.50	21.90	72.81
149	489	600	5.13	22.30	72.89
204	484	595	4.50	22.12	73.09
260	476	574	4.25	21.60	73.29
316	465	562	4.05	18.40	72.03
371	462	558	4.18	18.95	71.38
427	447	535	4.42	21.35	69.92
482	427	489	2.55	25.90	77.21
538	392	414	1.47	27.23	83.46
593	305	325	0.90	31.32	88.99
649	209	234	1.69	38.25	89.96
704	131	158	2.34	34.30	91.06
760	65	88	3.16	59.83	96.07
		12.8-mm-diam Specimens			
25	629	751	6.52	26.65	65.48
93	601	697	4.65	21.60	70.18
204	579	668	3.90	18.60	71.26
316	533	630	3.29	17.33	68.41
427	543	599	3.20	20.45	69.95
538	431	458	1.07	28.80	83.09
649	229	272	1.80	37.72	91.59
760	62	83	4.39	55.75	96.36
760	83	104	2.36	43.71	96.10

Table 4. Tensile test data for heat 30394 of modified 9 Cr-1 Mo steel normalized at 1040°C for 1 h and tempered at 760°C for 1 h

Test temperature (°C)	Strength (MPa)		Elongation (%)		Reduction of area (%)
	0.2% Yield	Ultimate tensile	Uniform	Total	
		6.35-mm-diam Specimens			
25	578	715	7.66	26.00	69.05
38	575	711	7.81	27.52	67.63
93	551	682	6.09	23.15	70.33
149	538	664	6.10	23.23	70.75
204	527	666	5.38	21.63	71.44
260	518	641	4.96	19.11	69.10
316	504	627	4.86	21.02	69.19
371	496	617	4.81	20.60	67.56
427	484	610	5.20	24.27	73.06
482	457	526	3.07	29.25	78.10
538	403	467	1.36	34.75	85.29
593	312	346	1.16	37.75	88.44
649	209	243	1.89	38.45	88.71
704	137	170	2.44	33.80	89.69
760	73	97	3.28	40.00	92.85
		12.8-mm-diam Specimens			
25	577	778	7.56	25.13	69.18
25		690	8.37	23.32	69.33
25	619	746	6.90	21.21	65.84
93	602	719	5.51	21.05	68.14
204	570	681	4.71	19.35	68.84
316	562	658	4.21	18.38	65.18
427	517	603	4.19	22.41	71.34
538	423	452	1.35	30.93	82.54
649	220	264	1.58	36.90	90.68
760	63	83	3.23	51.75	94.99
760	62	88	3.86	50.82	89.47

Table 5. Tensile test data for heat 30176 of modified 9 Cr-1 Mo steel normalized at 1040°C for 1 h and tempered at various times and temperatures

Tempering conditions		Test temperature (°C)	Strength (MPa)		Elongation (%)		Reduction of area (%)
Temperature (°C)	Time (h)		0.2% Yield	Ultimate tensile	Uniform	Total	
746	1	25	700	806	4.61	19.25	69.46
746	1	204	640	726	3.42	21.50	71.15
746	1	427	591	668	1.94	20.10	71.61
746	1	649	281	306	1.41	34.20	89.01
732	1	25	722	820	4.54	19.00	67.08
732	1	204	666	751	2.72	19.13	71.28
732	1	427	611	672	2.31	20.19	71.08
732	1	649	278	325	1.26	34.25	87.08
774	1	25	524	657	6.82	26.50	76.03
774	1	93	502	623	5.60	25.99	77.11
774	1	204	476	585	4.86	23.99	77.81
774	1	316	462	555	4.51	21.80	74.74
774	1	427	443	527	4.27	23.75	75.57
774	1	538	372	403	1.17	33.22	87.46
774	1	649	194	227	1.70	40.65	94.20
774	1	760	69	96	3.93	55.50	96.18
760	2	25	497	638	7.24	27.75	75.14
760	4	25	472	619	8.25	28.10	74.86
732	4	25	630	735	4.82	22.90	72.11
732	16	25	484	625	7.41	25.66	77.36
788	0.5	25	503	642	7.56	26.90	76.49
788	1	25	464	621	8.70	27.11	77.21
788	2	25	457	608	8.85	29.10	75.36
788	4	25	441	600	8.56	31.25	77.32
816	0.25	25	464	615	8.22	29.33	74.92
816	1	25	444	598	8.67	30.73	74.94

Table 6. Tensile test data for heat 30394 of modified 9 Cr-1 Mo steel normalized at 1040°C for 1 h and tempered at various times and temperatures

Tempering conditions		Test temperature (°C)	Strength (MPa)		Elongation (%)		Reduction of area (%)
Temperature (°C)	Time (h)		0.2% Yield	Ultimate tensile	Uniform	Total	
746	1	25	676	797	5.83	23.10	66.30
746	1	204	632	747	4.02	20.15	67.96
746	1	427	576	655	2.97	19.60	69.28
746	1	649	252	287	1.71	34.95	86.55
732	1	25	736	850	5.44	18.20	63.13
732	1	204	701	780	3.50	18.23	66.74
732	1	427	631	697	2.60	20.32	67.71
732	1	649	300	326	1.38	30.90	82.71
774	1	25	538	691	8.17	25.38	70.40
774	1	93	509	652	7.12	23.70	72.72
774	1	204	491	621	5.87	22.38	73.87
774	1	316	474	612	5.63	23.30	70.52
774	1	427	450	561	5.49	27.20	74.70
774	1	538	370	405	1.57	38.11	85.99
774	1	649	197	226	1.12	63.21	91.74
774	1	760	72	97	3.74	60.45	93.03
760	2	25	528	673	8.02	26.94	71.26
760	4	25	499	659	9.10	26.75	70.74
732	4	25	642	766	5.97	23.10	66.17
732	16	25	513	668	8.35	29.11	70.64
788	0.5	25	526	675	7.81	26.50	70.43
788	1	25	490	655	9.06	26.88	72.49
788	2	25	485	648	9.61	28.73	71.32
788	4	25	474	642	10.16	30.30	70.57
816	0.25	25	490	651	9.47	28.20	71.14
816	1	25	469	637	10.06	30.50	73.67

Table 7. Effect of simulated postweld heat treatment time on tensile properties of three heats of modified 9 Cr-1 Mo steel tested at a strain rate of 0.004/min

Heat	PWHT[a] (h)	Strength (MPa)		Elongation (%)		Reduction of area (%)
		Yield	Ultimate tensile	Uniform	Total	
			Tested at 25°C			
30176	1	519	652	7.53	26.10	73.00
30383	1	534	684	8.50	26.80	67.32
30394	1	566	709	7.61	24.85	70.38
30176	14	486	637	7.29	27.30	73.52
30383	14	515	675	9.72	26.85	68.02
30394	14	514	676	8.60	28.70	71.35
30176	28	480	623	8.37	29.05	73.27
30383	28	496	658	9.44	25.05	67.18
30394	28	497	659	9.77	28.71	71.98
30176	42	481	630	8.09	28.10	74.56
30383	42	491	659	9.32	26.50	69.68
30394	42	486	652	10.20	27.10	71.93
30176	112	454	603	9.48	29.10	75.16
30383	112	472	638	10.53	31.95	66.48
30394	112	467	636	9.94	25.10	72.65
			Tested at 593°C			
30176	1	301	323	1.07	39.20	89.67
30383	1	290	323	1.07	43.35	84.91
30394	1	314	342	0.90	41.66	91.39
30176	14	290	310	0.90	42.70	91.91
30383	14	293	314	1.03	44.88	89.23
30394	14	299	317	1.11	36.20	89.92
30176	28	282	305	0.94	42.80	90.22
30383	28	279	310	0.97	43.30	91.45
30394	28	293	313	1.04	33.45	90.98
30176	42	278	303	1.19	47.20	91.79
30383	42	282	305	1.25	51.45	91.57
30394	42	300	317	1.03	46.70	90.86
30176	112	281	296	1.42	42.00	91.01
30383	112	269	296	1.11	40.35	90.34
30394	112	280	302	1.05	39.35	91.47

[a]PWHT, postweld heat treated.

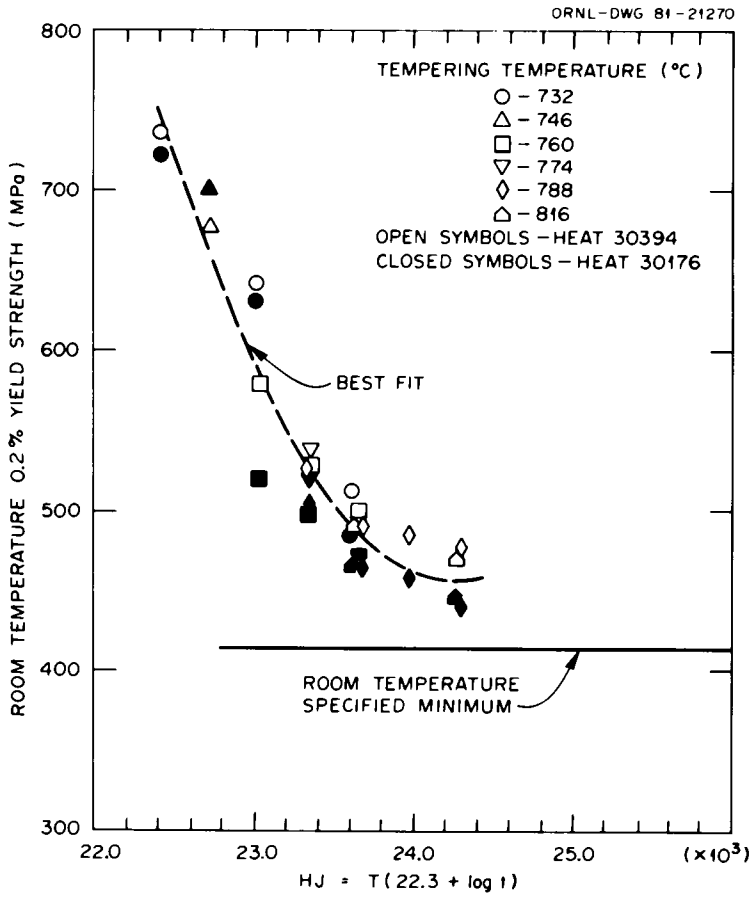


Fig. 3. Room-temperature 0.2% yield strength as a function of the Holloman-Jaffe (HJ) parameter for various tempering temperature and time combinations on two commercial heats of modified 9 Cr-1 Mo steel.

55%. These values are also included in the figures for comparison. The figures show that tempering temperature and time are exchangeable for the temperature and time range investigated here; however, the relationship is not vaild outside the range of conditions investigated here. This is true for both the strength and ductility properties.

Because the PWHT specimens had already been tempered, their HJ parameters were determined as follows. The as-tempered HJ parameter and the PWHT temperature were substituted into Eq. (1), and a PWHT time equivalent to the temper was calculated. To this equivalent PWHT time was added the actual PWHT time to obtain a total effective heat treatment time. This, in turn, was used with the PWHT temperature in Eq. (1) to get the HJ parameter for the combined heat treatment.

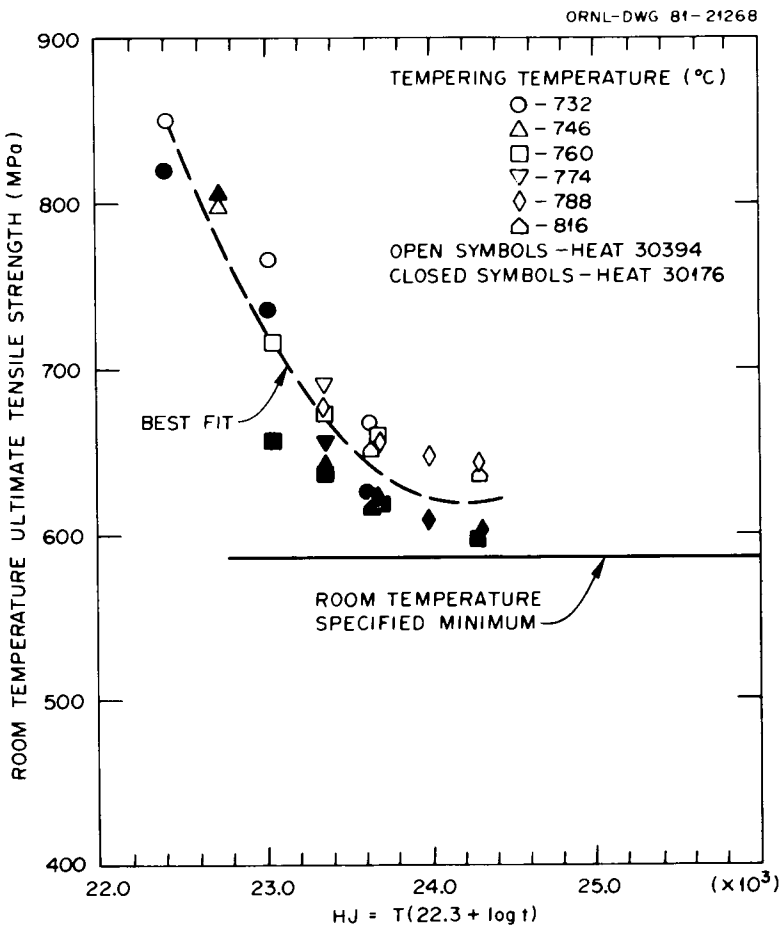


Fig. 4. Room-temperature ultimate tensile strength as a function of the Holloman-Jaffe (HJ) parameter for various tempering temperature and time combinations on two commercial heats of modified 9 Cr-1 Mo steel.

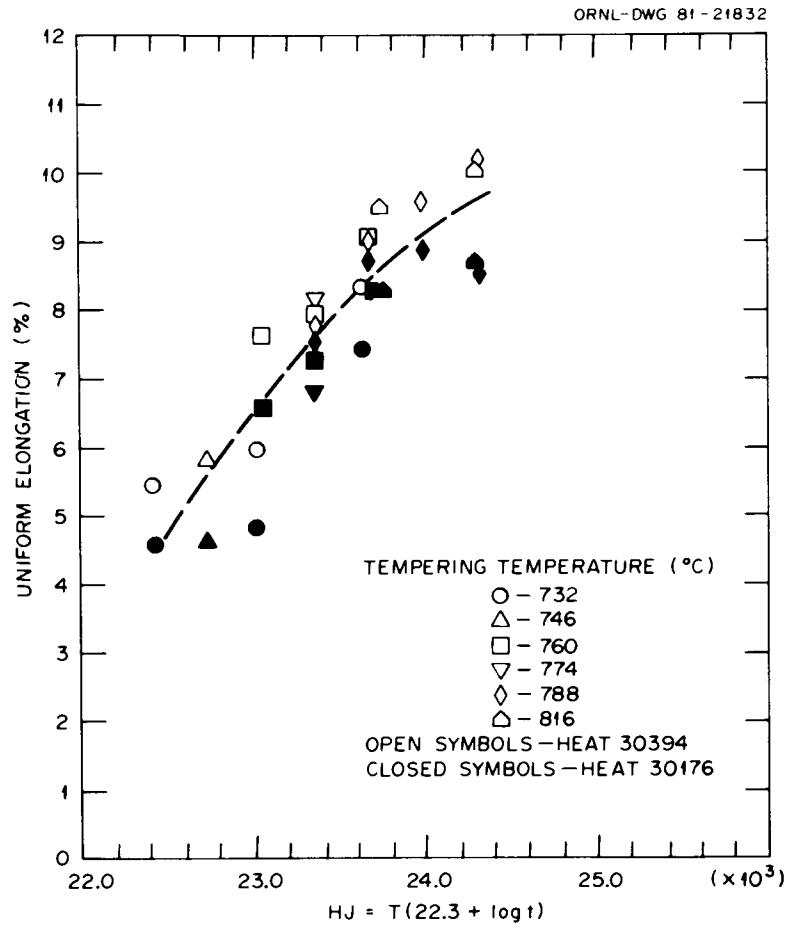


Fig. 5. Room-temperature uniform elongation as a function of the Holloman-Jaffe (HJ) parameter for various tempering temperature and time combinations on two commercial heats of modified 9 Cr-1 Mo steel.

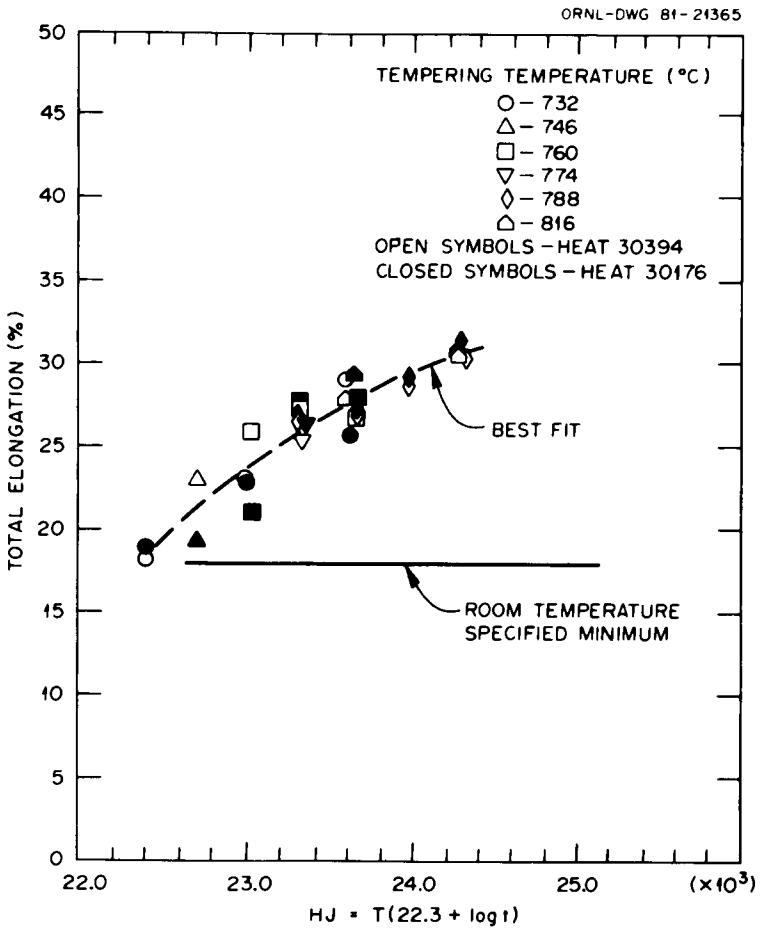


Fig. 6. Room-temperature total elongation as a function of the Holloman-Jaffe (HJ) parameter for various tempering temperature and time combinations on two commercial heats of modified 9 Cr-1 Mo steel.

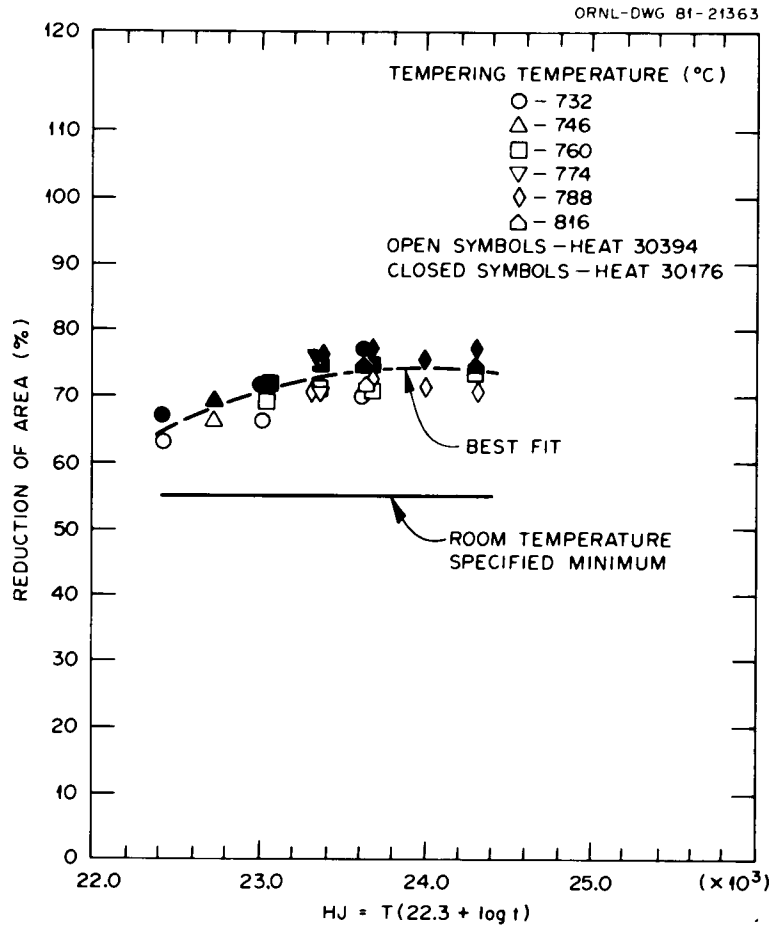


Fig. 7. Room-temperature reduction of area as a function of the Holloman-Jaffe (HJ) parameter for various tempering temperature and time combinations on two commercial heats of modified 9 Cr-1 Mo steel.

The tensile data for material with various PWHT times are compared with the as-tempered material in Figs. 8 through 12. The values for the PWHT samples, plotted against the HJ parameter obtained as described, are simply added to the plots and best-fit curves for the as-tempered material in Figs. 3 through 7. The data after tempering and PWHT agree well with the data after tempering only. This agreement implies that the HJ parameter can be used to select both tempering temperature—time and PWHT temperature—time combinations to obtain the desirable room-temperature tensile properties.

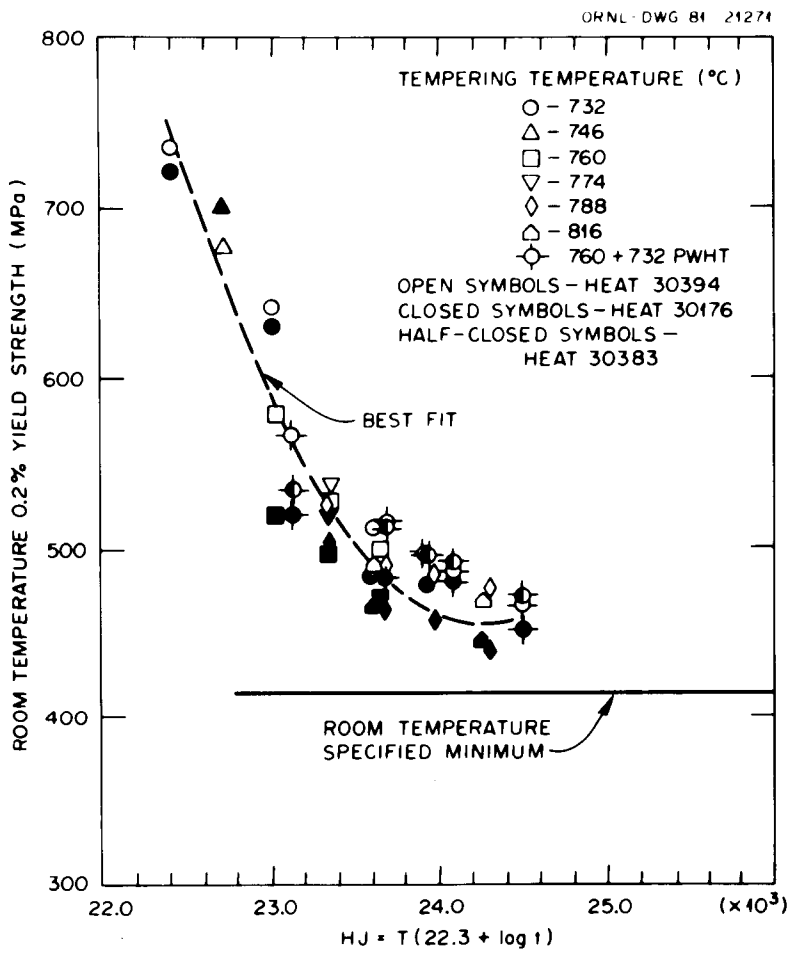


Fig. 8. Room-temperature 0.2% yield strength as a function of the Holloman-Jaffe (HJ) parameter for various tempering and postweld heat treatment temperature and time combinations on three commercial heats of modified 9 Cr-1 Mo steel.

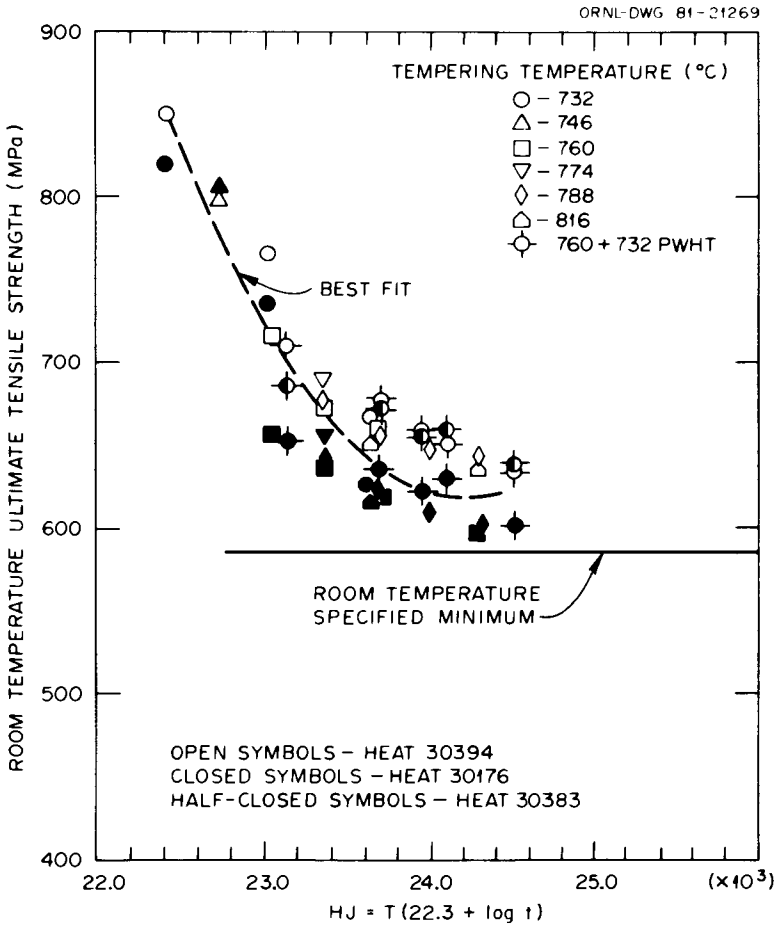


Fig. 9. Room-temperature ultimate tensile strength as a function of the Holloman-Jaffe (HJ) parameter for various tempering and post-weld heat treatment temperature and time combinations on three commercial heats of modified 9 Cr-1 Mo steel.

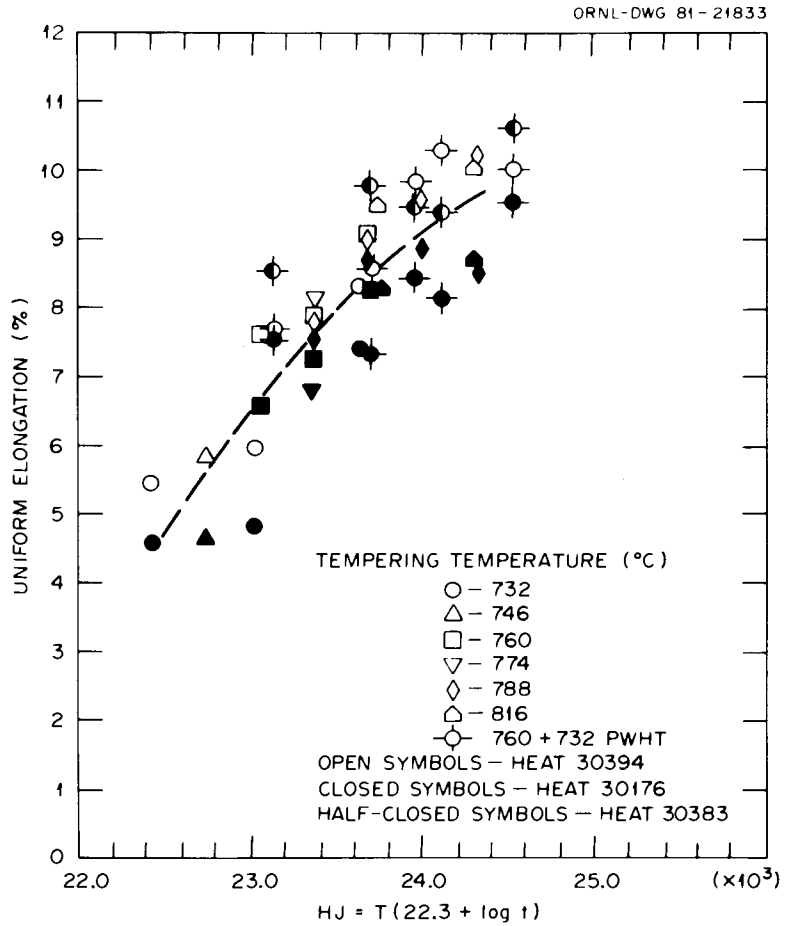


Fig. 10. Room-temperature uniform elongation as a function of the Holloman-Jaffe (HJ) parameter for various tempering and postweld heat treatment temperature and time combinations on three commercial heats of modified 9 Cr-1 Mo steel.

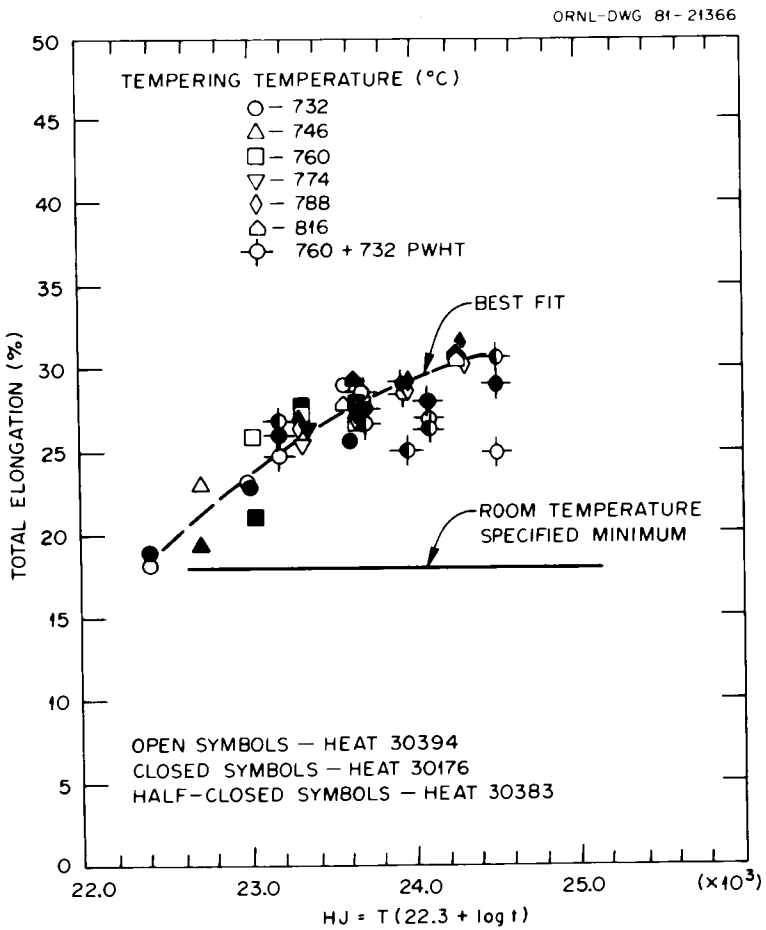


Fig. 11. Room-temperature total elongation as a function of the Holloman-Jaffe (HJ) parameter for various tempering and postweld heat treatment temperature and time combinations on three commercial heats of modified 9 Cr-1 Mo steel.

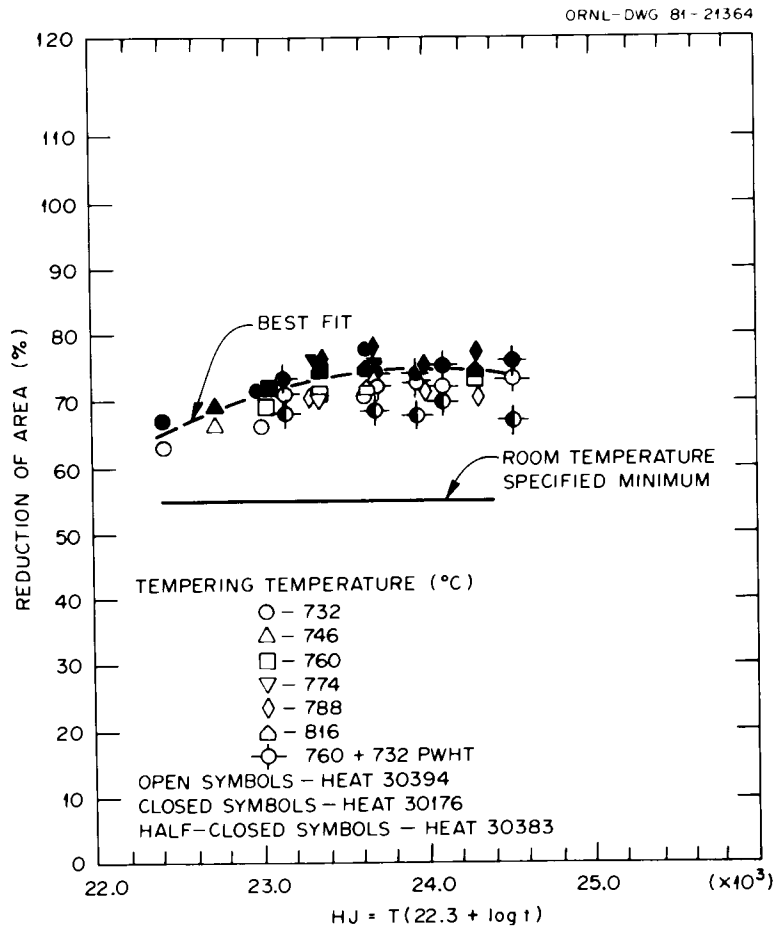


Fig. 12. Room-temperature reduction of area as a function of the Holloman-Jaffe (HJ) parameter for various tempering and postweld heat treatment temperature and time combinations on three commercial heats of modified 9 Cr-1 Mo steel.

The ASTM specification for modified 9 Cr-1 Mo steel (grade 91) recommends a range for ultimate tensile strength at room temperature. To determine the minimum tempering temperature required to keep the tensile strength below the maximum ultimate tensile strength, we plotted the ultimate tensile strength as a function of tempering temperature in Fig. 13. This figure shows that the minimum tempering temperature should be about 732°C and the maximum about 770°C for a tempering time of 1 h. The HJ parameter developed in this study can be used to determine the more desirable tempering temperature and time combinations to obtain ultimate tensile strength values within the specified range.

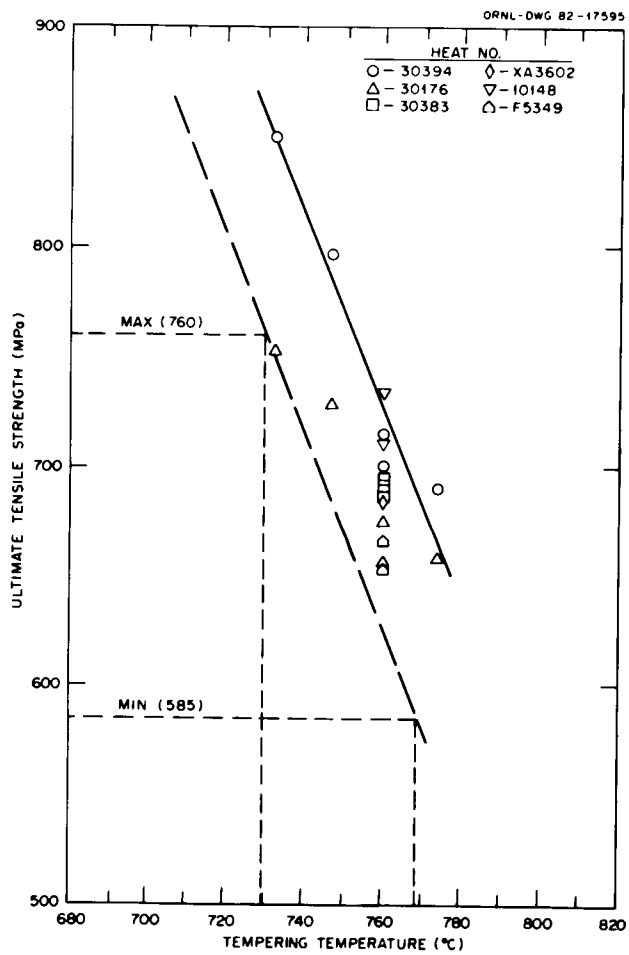


Fig. 13. Room-temperature ultimate tensile strength as a function of tempering temperature for six commercial heats of modified 9 Cr-1 Mo steel. The specified minimum and maximum ultimate tensile strength values are shown in this figure. According to this figure a tempering temperature of 732°C will produce material of maximum ultimate tensile strength. The higher tempering temperatures will produce the material with differing strength levels.

SPECIMEN GEOMETRY EFFECT

Figures 14 through 18 show the tensile properties measured on 12.83-mm-diam specimens plotted against properties measured on 6.35-mm-diam specimens under the same conditions. These plots include data taken from room temperature to 760°C. The figures show only minor differences in properties between the specimens of the two sizes. The differences observed might be due in part to variations between the two plates from which the specimens of the two sizes were made. From the results in Figs. 14 through 18, however, we conclude that the HJ parameter derived for 6.35-mm-diam specimens should also apply to 12.83-mm-diam specimens.

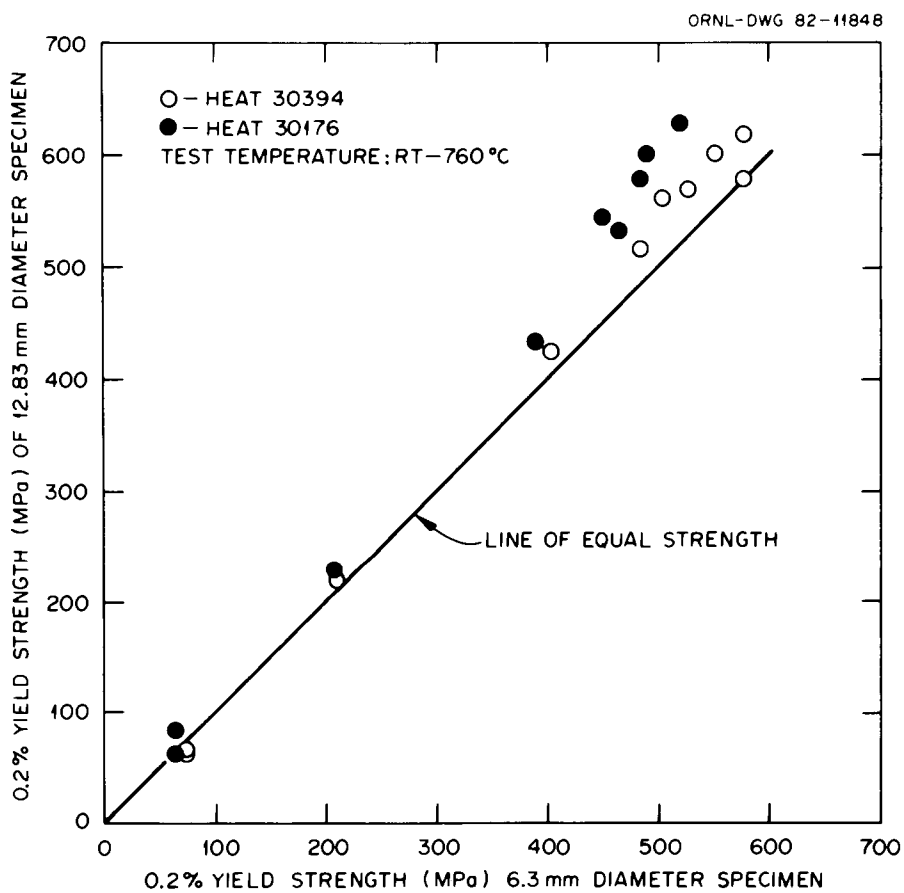


Fig. 14. Plot of 0.2% yield strength of 12.83-mm-diam specimens against that of 6.35-mm-diam specimens from two heats of modified 9 Cr-1 Mo steel. Data are for a test temperature range from room temperature to 760°C. Line of equal strength is also included.

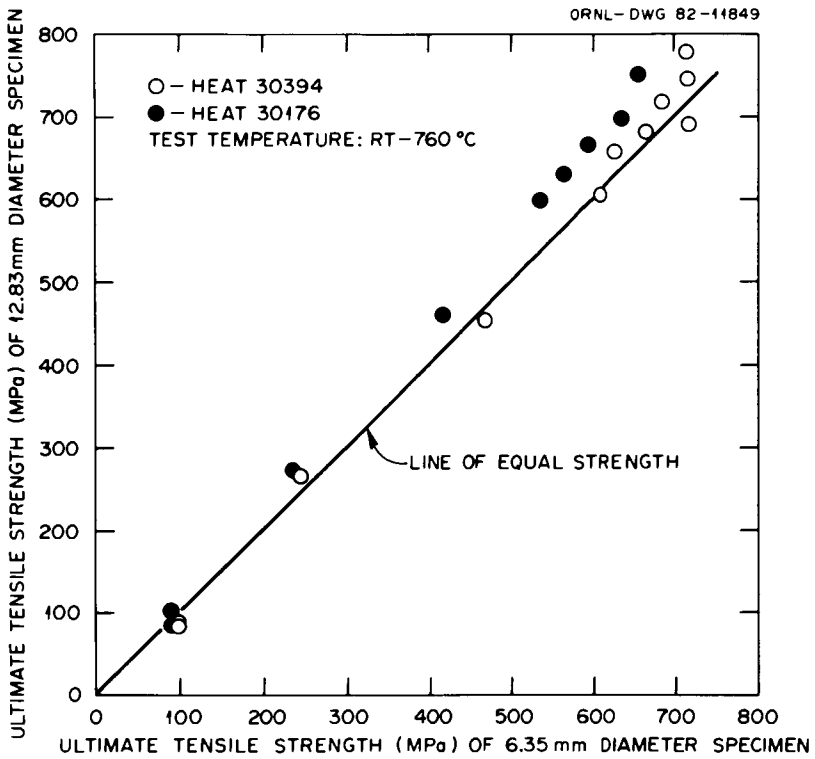


Fig. 15. Plot of ultimate tensile strength of 12.83-mm-diam specimens against that of 6.35-mm-diam specimens from two heats of modified 9 Cr-1 Mo steel. Data are for a test temperature range from room temperature to 760°C. Line of equal strength is also included.

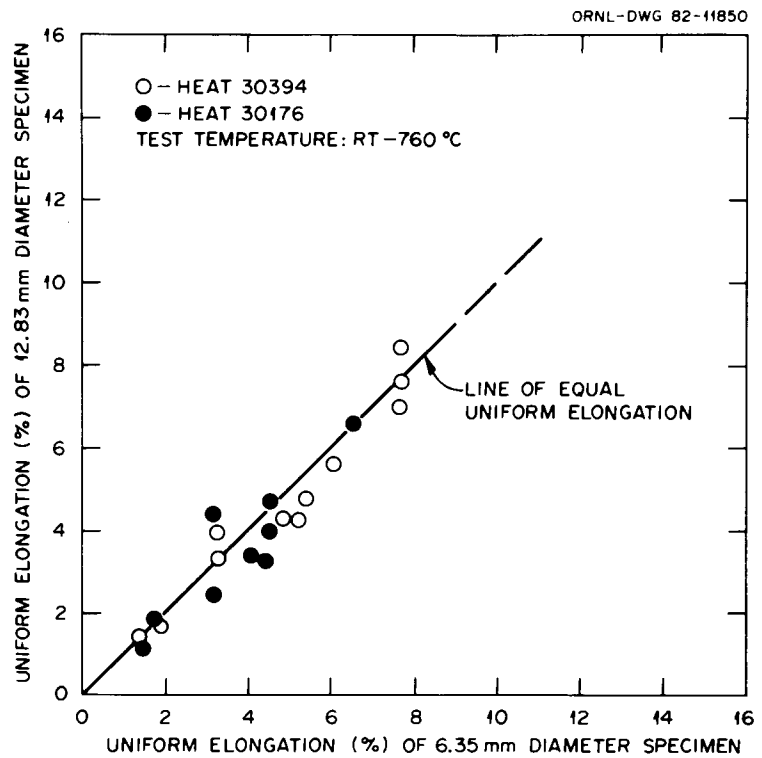


Fig. 16. Plot of uniform elongation of 12.83-mm-diam specimens against that of 6.35-mm-diam specimens from two heats of modified 9 Cr-1 Mo steel. Data are for a test temperature range from room temperature to 760°C. Line of equal uniform elongation is also included.

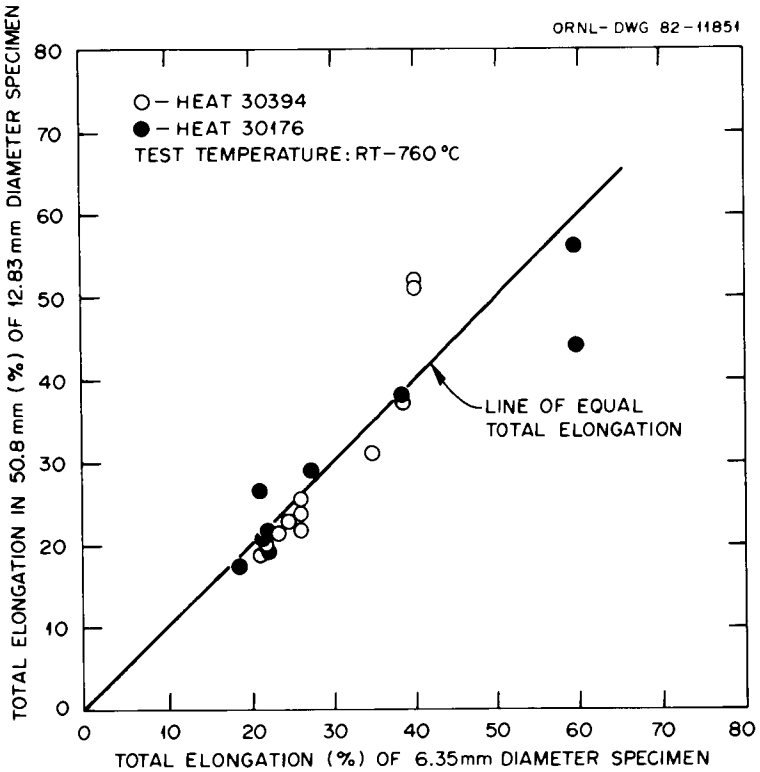


Fig. 17. Plot of total elongation in 50.8 mm of 12.83-mm-diam specimens against that in 25.4 mm of specimens from two heats of modified 9 Cr-1 Mo steel. Data are for a test temperature range from room temperature to 760°C. Line of equal total elongation is also included.

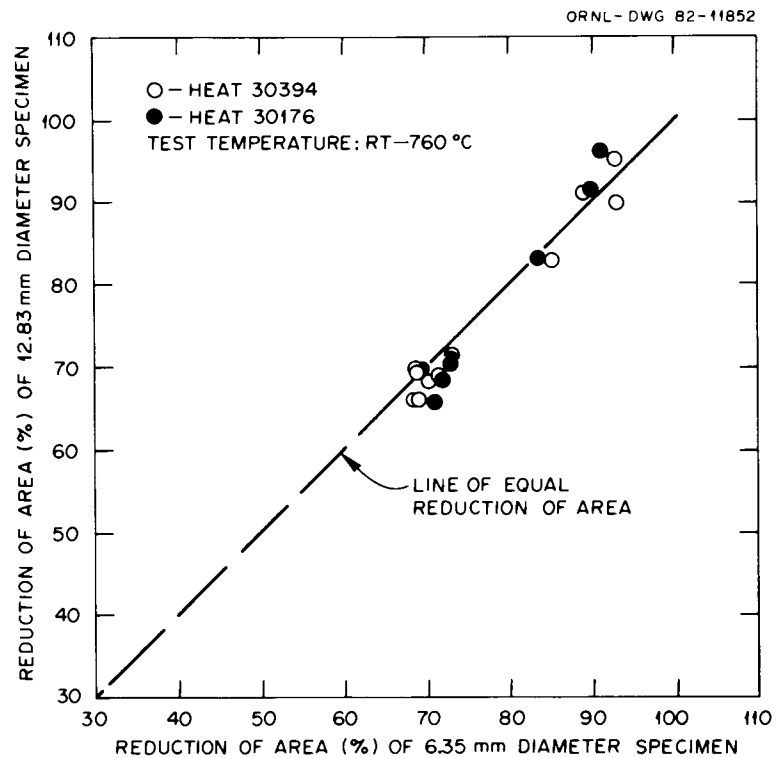


Fig. 18. Plot of reduction of area of 12.83-mm-diam specimens against that of 6.35-mm-diam specimens from two heats of modified 9 Cr-1 Mo steel. Data are for a test temperature range from room temperature to 760°C. Line of equal reduction of area is also included.

Figure 19 compares total elongation data on full-size tubular specimens with data on the 6.35-mm-diam bars of Fig. 6. This figure shows that the data on the solid specimens are rather conservative; thus, the full-size tubular specimens are expected to perform better in elongation.

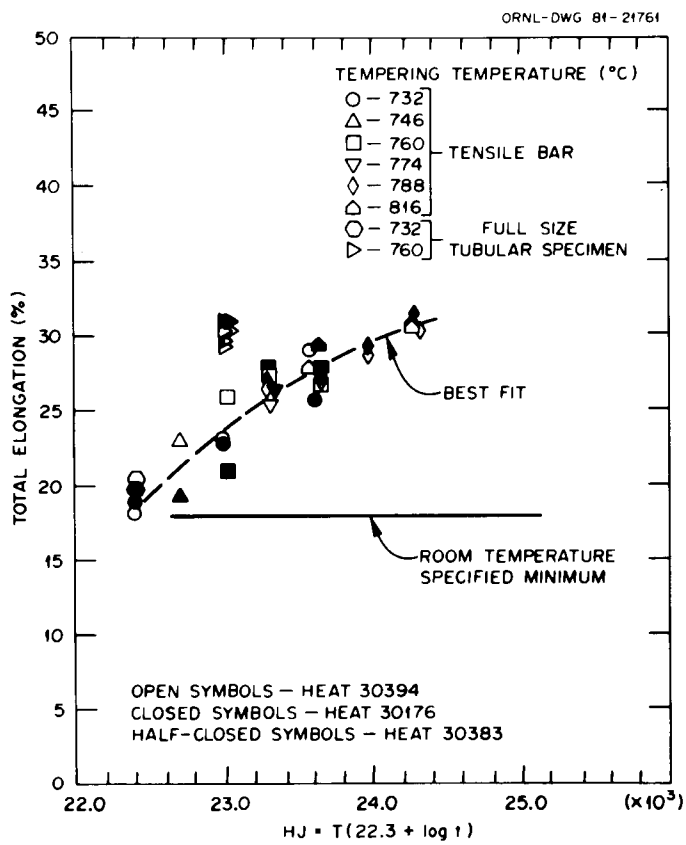


Fig. 19. Comparison of total elongation values on full-size tubular specimens with the Holloman-Jaffe (HJ) plot on the tensile bars. Note that total elongation values for the full-size tubular specimens are higher than the values observed for tensile bars.

EFFECT OF TEMPERING TEMPERATURE ON ELEVATED-TEMPERATURE TENSILE PROPERTIES

Tensile properties of heats 30176 and 30394 after tempering at various temperatures for 1 h are plotted as a function of test temperature in Figs. 20 through 23. The minimum property curves based on room-temperature specified values are also included for comparison. These figures show the following:

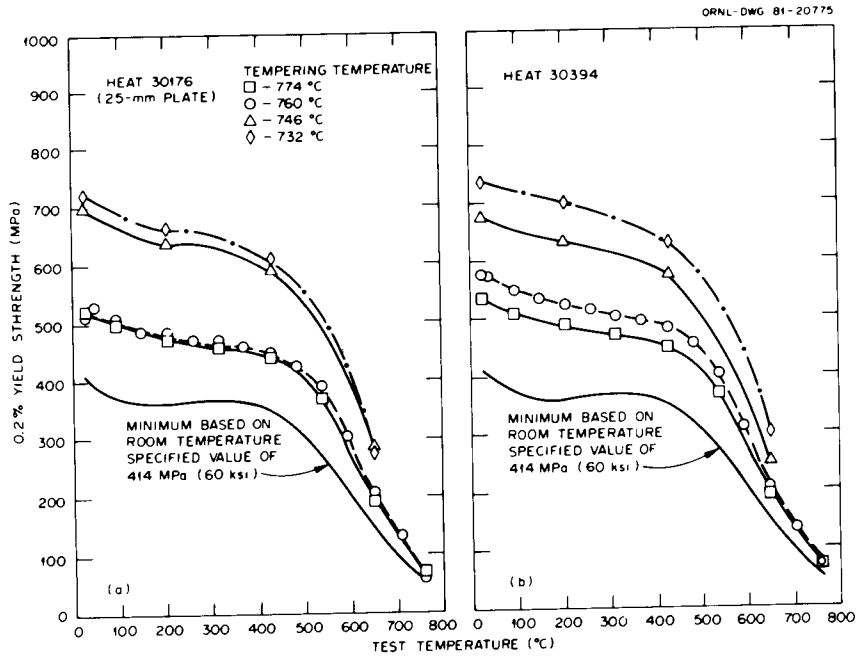


Fig. 20. The 0.2%-offset yield strength as a function of test temperature for (a) heat 30176 and (b) heat 30394 of modified 9 Cr-1 Mo steel tempered at 732, 746, 760, and 774°C for 1 h. The minimum curve based on the room-temperature specified value of 414 MPa (60 ksi) for yield strength is also included.

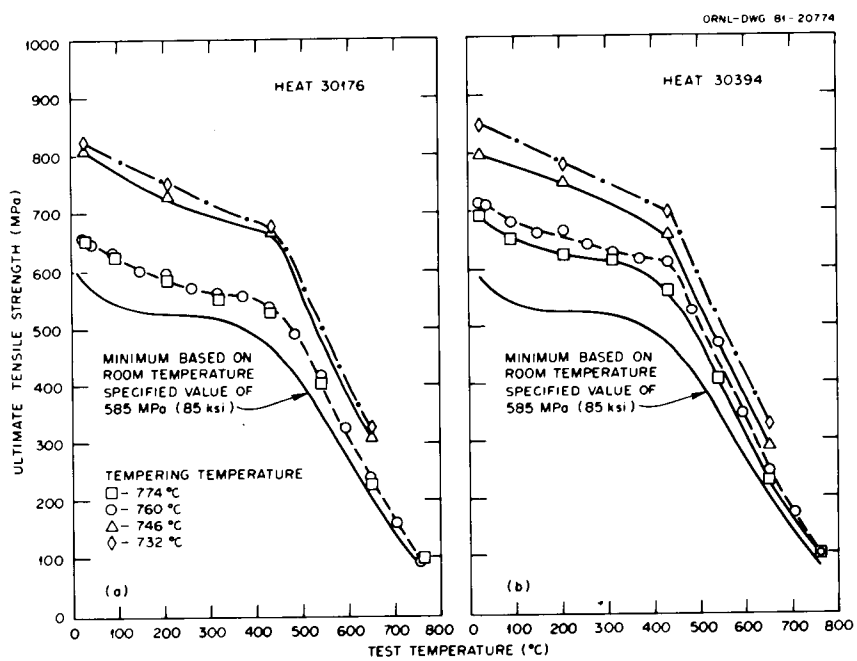


Fig. 21. Ultimate tensile strength as a function of test temperature for (a) heat 30176 and (b) heat 30394 of modified 9 Cr-1 Mo steel tempered at 732, 746, 760, and 774°C for 1 h. The minimum curve based on the room-temperature specified value of 586 MPa (85 ksi) for ultimate tensile strength is also included.

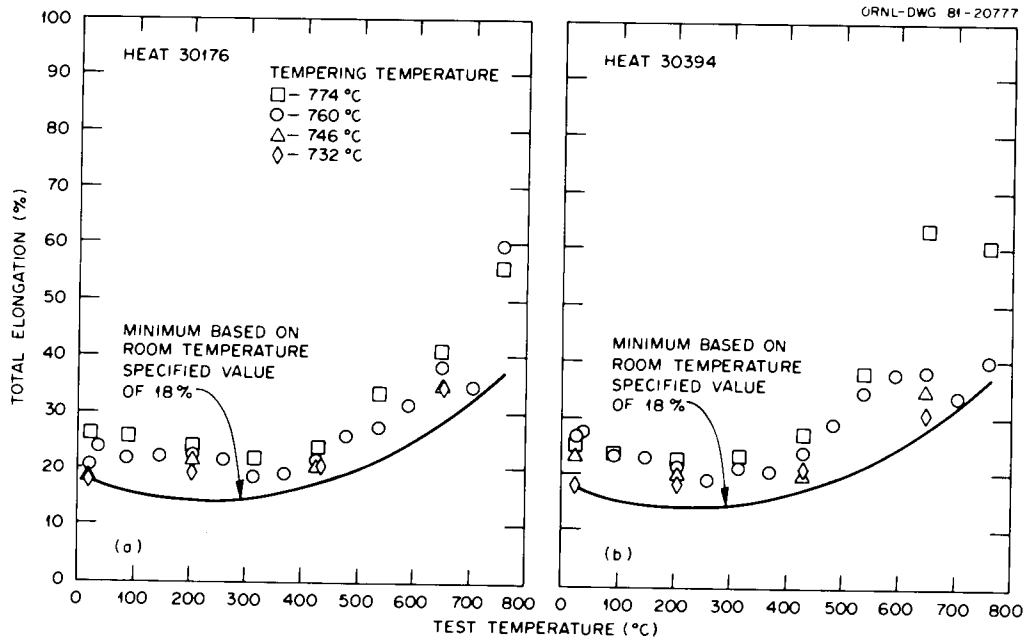


Fig. 22. Total elongation as a function of test temperature for (a) heat 30176 and (b) heat 30394 of modified 9 Cr-1 Mo steel tempered at 732, 746, 760, and 774°C for 1 h. The minimum curve based on the room-temperature specified value of 18% for total elongation is also included.

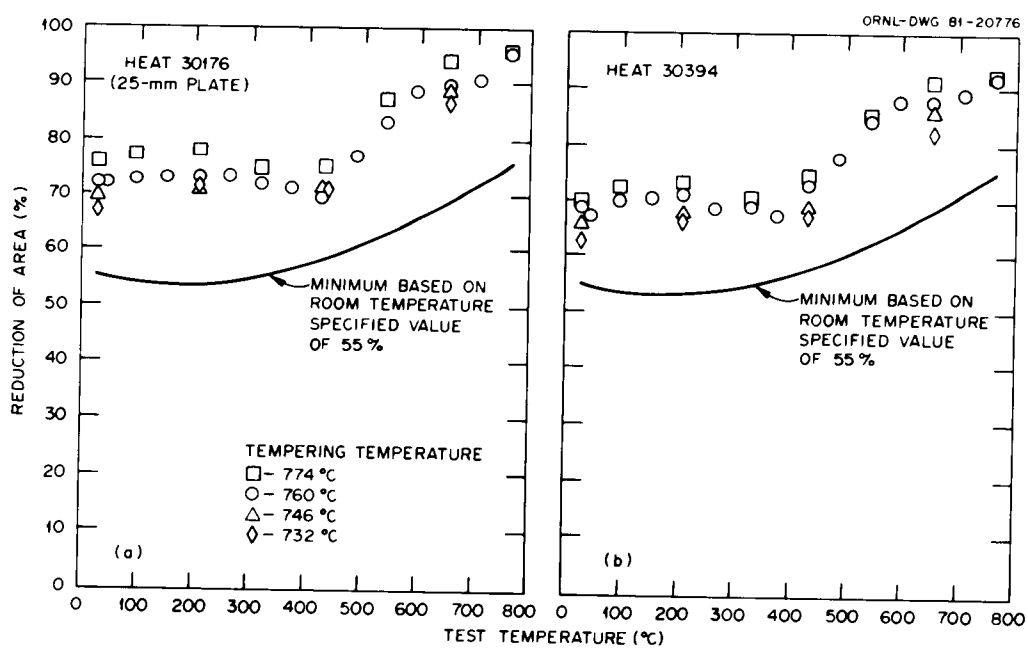


Fig. 23. Reduction of area as a function of test temperature for (a) heat 30176 and (b) heat 30394 of modified 9 Cr-1 Mo steel tempered at 732, 746, 760, and 774°C for 1 h. The minimum curve based on the room-temperature specified value of 55% for reduction of area is also included.

1. Tempering at 774°C, slightly higher than the nominal temperature of 760°C, has only a small effect on the tensile properties for the entire test temperature range.

2. Tempering at a temperature (746°C) slightly lower than 760°C significantly increases strength properties with only a small decrease in ductility.

3. Lowering the tempering temperature has more influence on strength properties than does an equal increase in tempering temperature.

4. The minimum property curves based on room-temperature specified values apply well to the strength and ductility data in all cases.

HARDNESS DATA

Hardness data for various tempering temperature and time combinations are listed in Table 8 and are plotted as a function of the HJ parameter in Fig. 24. This figure illustrates that the HJ parameter with a constant of 22.3 can also describe the hardness data.

Table 8. Summary of Charpy impact energy and hardness data for various tempering temperatures and times on two heats of modified 9 Cr-1 Mo steel

Tempering conditions[a]		Charpy energy (J)				Hardness (R_B)[b]	
		Room temperature		204°C			
Temperature (°C)	Time (h)	Heat 30394	Heat 30176	Heat 30394	Heat 30176	Heat 30394	Heat 30176
732	1	64.0	108	143	152	99.5	98.0
732	4	76.6	78	142	161	94.5	95.2
732	16	165.0	173	187	198	90.0	90.5
746	1	68	83	150	155	97.5	97.7
760	1	104	171	190	193	95.6	93.0
760	2	135	183	197	187	90.9	90.8
760	4	142	178	190	200	89.3	89.1
774	1					93.4	90.9
788	0.5	125	166	187	205	90.1	91.5
788	1	175	175	197	233	89.3	89.5
788	2	171	203	199	191	88.8	88.9
788	4	157	182	200	203	89.0	88.3
816	0.25	138	182	206	209	88.8	89.5
816	1	168	211	197	245	87.2	88.6

[a]All plates were normalized at 1040°C for 1 h before tempering.

[b]RB, Rockwell hardness, using B scale.

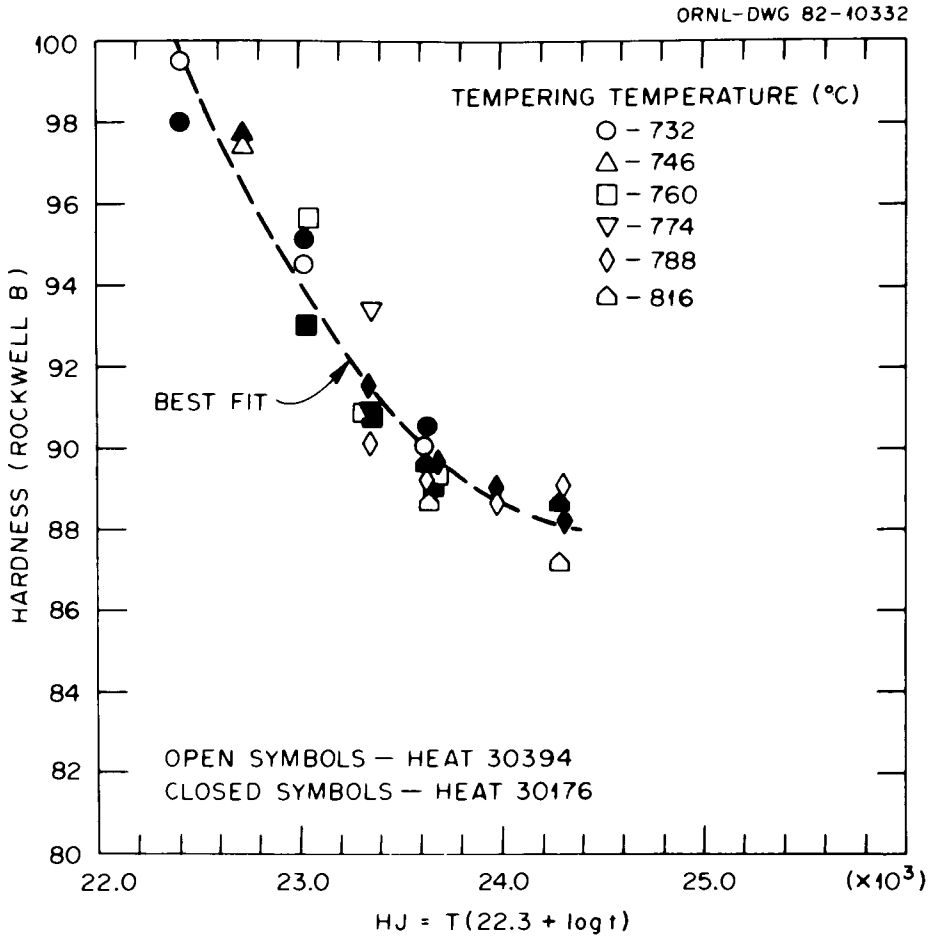
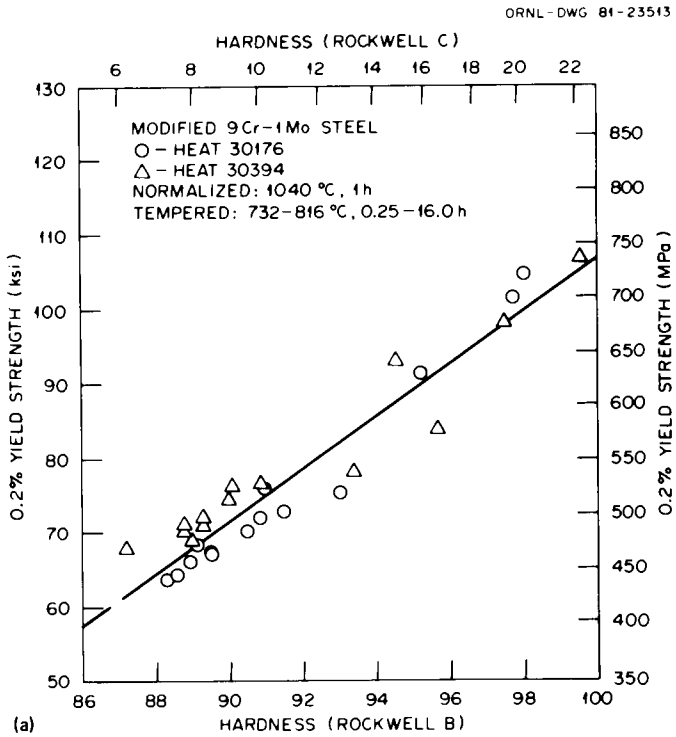


Fig. 24. Room-temperature hardness as a function of Holloman-Jaffe (HJ) parameter for various tempering temperature and time combinations on two commercial heats of modified 9 Cr-1 Mo steel.

CORRELATION OF YIELD AND ULTIMATE TENSILE STRENGTHS WITH HARDNESS

For certain applications, alloys are required to meet specified yield and ultimate tensile strengths without exceeding a certain hardness value. Thus, a relationship of yield and ultimate tensile strengths to hardness is also required for a range of tempering temperature and time conditions. Such plots for the two heats of modified 9 Cr-1 Mo steel are shown in Fig. 25. This figure shows that both the yield and ultimate tensile strengths are linearly related to hardness. Figure 25 can be used to check for both the tensile strength and hardness criteria for the alloy.



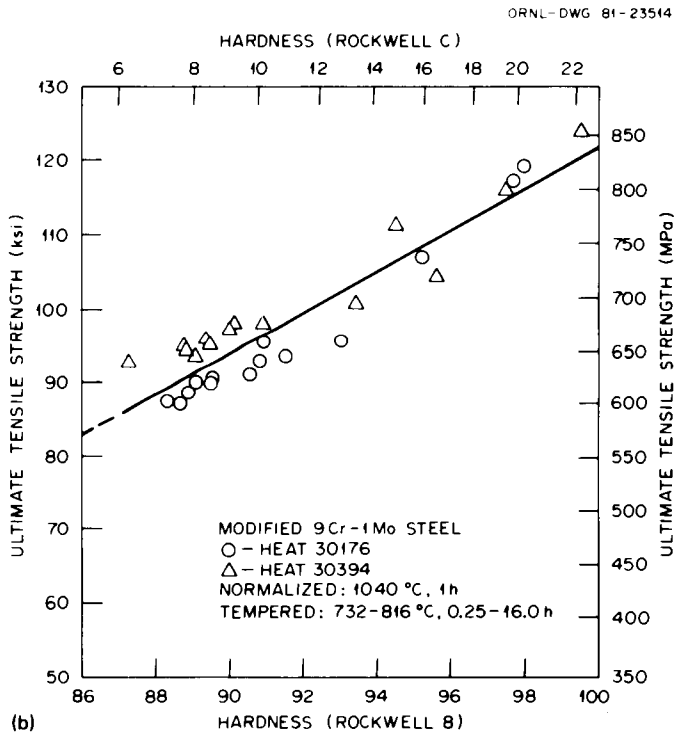


Fig. 25. Room-temperature strength versus hardness for two commercial heats of modified 9 Cr-1 Mo steel. (a) Yield. (b) Ultimate.

CHARPY IMPACT DATA

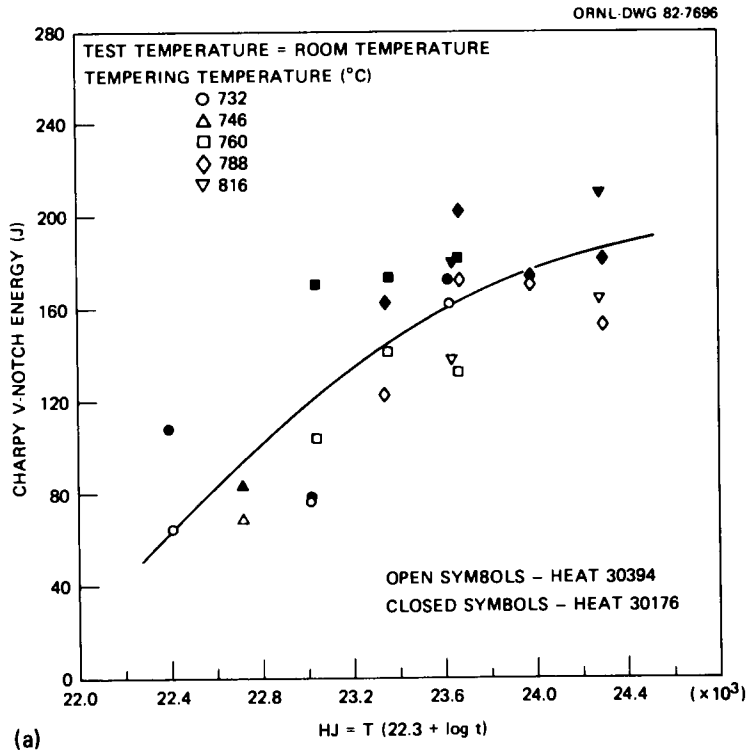
Charpy V-notch impact energy data at room temperature and 204°C for various tempering temperature and time combinations are listed in Table 8. Impact energy values at these temperatures are plotted as a function of the HJ parameter in Fig. 26. The HJ parameter constant of 22.3, taken from the analysis of room-temperature tensile data, appears to describe the Charpy impact data as well. This capability implies that the tempering temperature and time can also be traded off for obtaining approximately the same value of the Charpy impact energy.

MICROSTRUCTURE

The unstressed portions of room-temperature tensile-tested specimens for various tempering temperature and time combinations for heat 30394 were mounted for optical and scanning electron microscopy. All specimens were etched with Vilella's reagent. The optical microstructure after tempering at 732°C for 1 h is shown in Fig. 27. The same specimen examined in the scanning electron microscope (SEM) shows more details (Fig. 28). Both these figures show the presence of precipitates at the prior austenite grain boundaries and in the matrix. A higher magnifiation SEM [Fig. 28(b)] shows that the particle sizes at the grain boundaries and in the matrix are nearly the same. These precipitates have been identified previously as $M_{23}C_6$ and MC (ref. 4).

Figure 29 compares the optical microstructure of two specimens with the same HJ parameter: (a) tempered at 732°C for 4 h and (b) tempered at 760°C for 1 h. The optical micrographs show similar microstructures, and microhardness values are quite similar.

Figure 30 shows the optical microstructures of specimens with the same HJ parameter produced under different tempering conditions. Their optical microstructure and microhardness values are quite similar. Figure 31 compares the SEMs for equivalent tempering conditions of 760°C for 4 h and of 816°C for 15 min. These micrographs show that the particle size and density for the equivalent tempering conditions are quite similar.



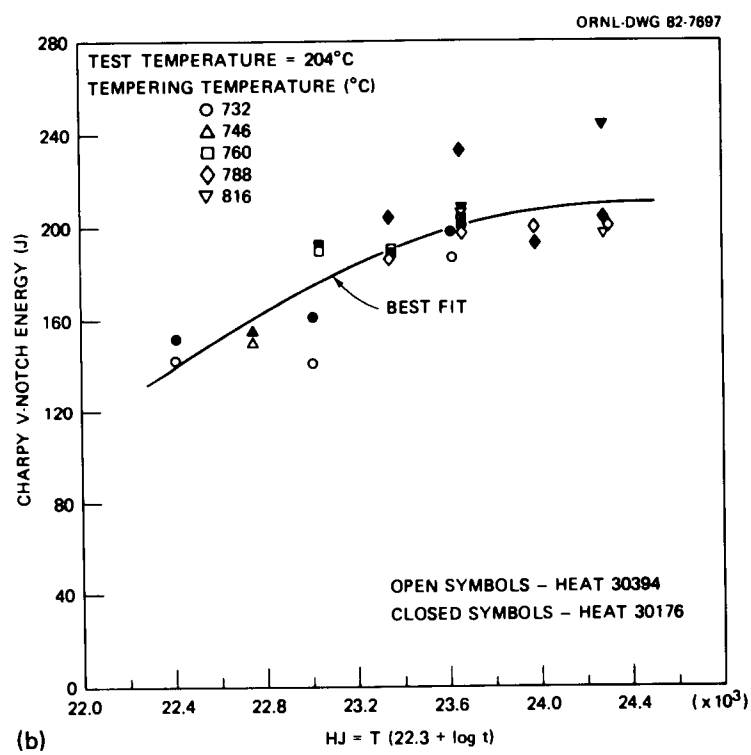
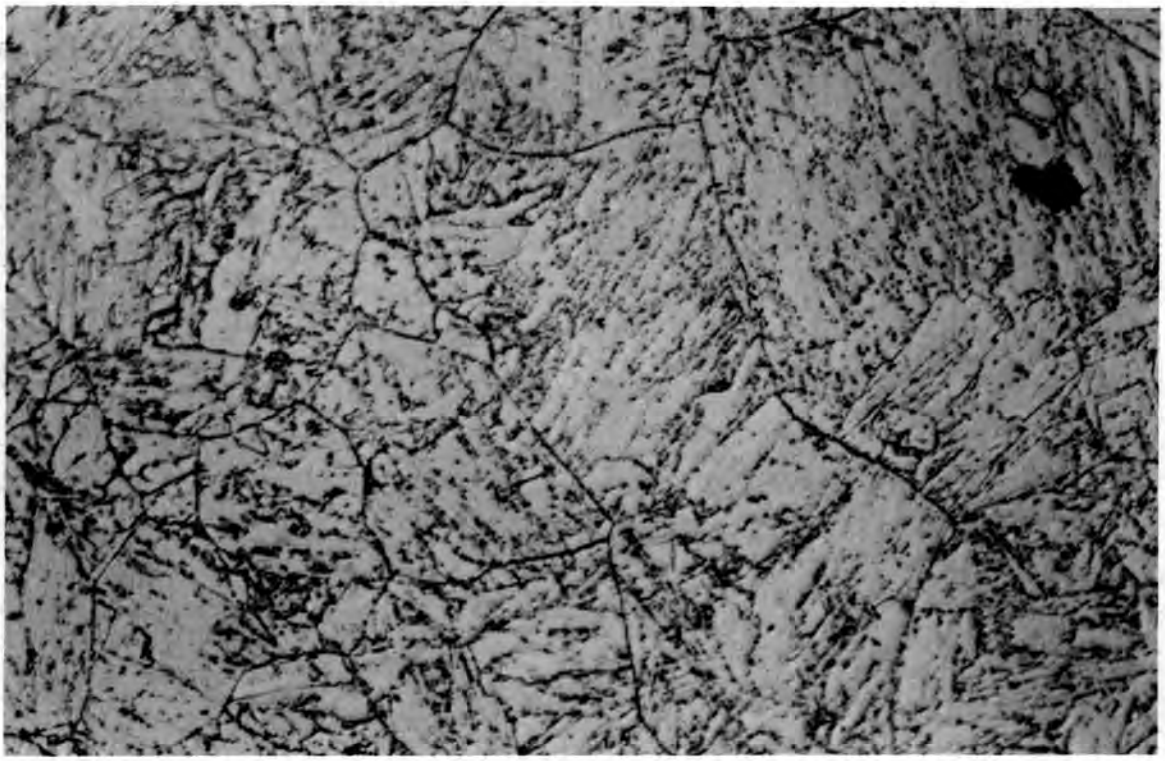


Fig. 26. Relation between Charpy impact energy and Holloman-Jaffe (HJ) parameter for two heats of modified 9 Cr-1 Mo steel with various tempering time-temperature combinations. (a) Room temperature. (b) 204°C.

Y-183984



13.4 μm

Fig. 27. Optical microstructure after tempering at 732°C for 1 h for heat 30394 of modified 9 Cr-1 Mo steel. The material was normalized at 1040°C for 1 h before tempering. Microhardness of this specimen is 275 ± 3 dph.

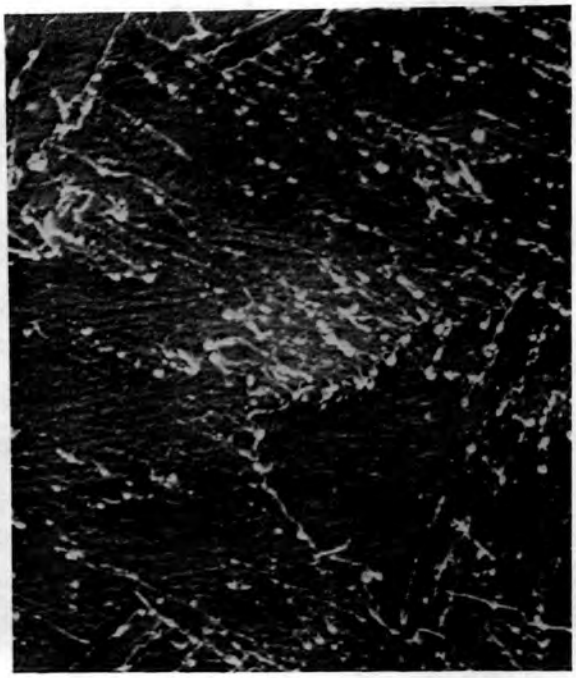
Figure 32 shows the optical microstructure for equivalent conditions produced by tempering at 788°C for 4 h and at 816°C for 1 h. Figure 33 shows the SEMs for the same specimens. Once again, the same value of the HJ parameter produces similar microstructures.

A typical transmission electron micrograph for a specimen tempered at 760°C for 1 h (Fig. 34) shows that the tempered martensite consists of a dislocation substructure with carbides occurring on both the grain boundaries and the subboundaries. The hardening or strengthening of tempered martensite arises from the subboundaries and the particles. The optical and scanning micrographs have shown only the changes in carbide particle size and density. However, the observed change in hardness and strength due to various tempering conditions is probably caused by both substructure and carbide coarsening.

M-13114

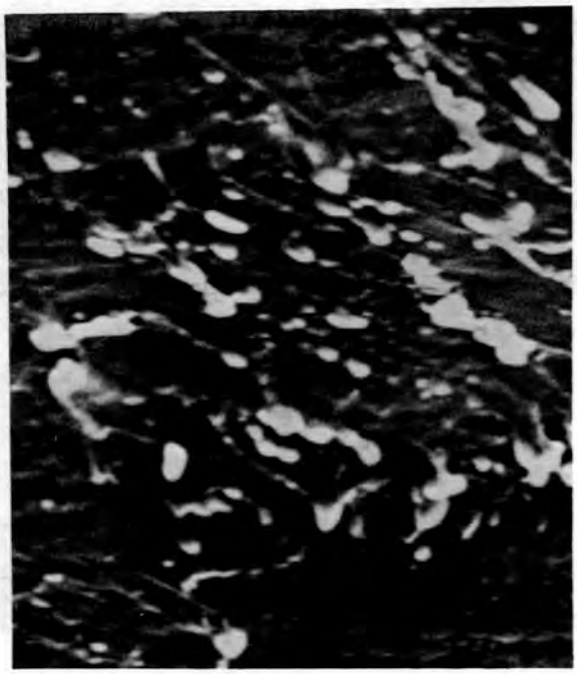
(a)

M-13115



(b)

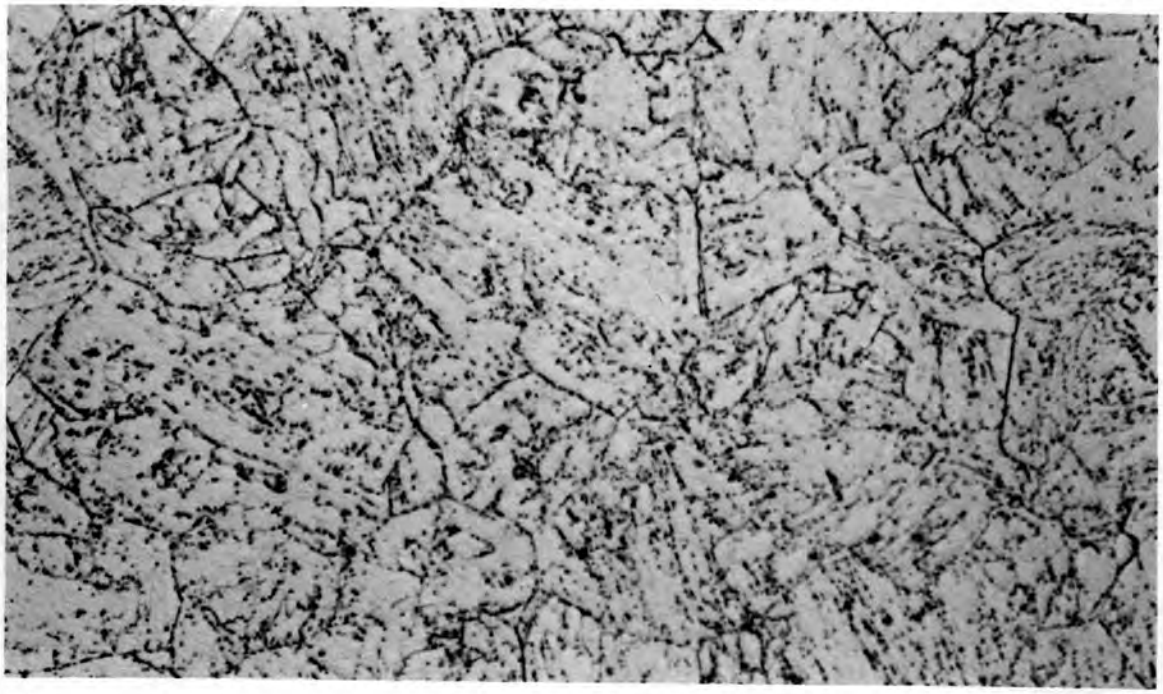
M-13116



(c)

Fig. 28. Scanning electron micrographs of heat 30394 of modified 9 Cr-1 Mo steel tempered at 732°C for 1 h after normalizing for 1 h at 1040°C.

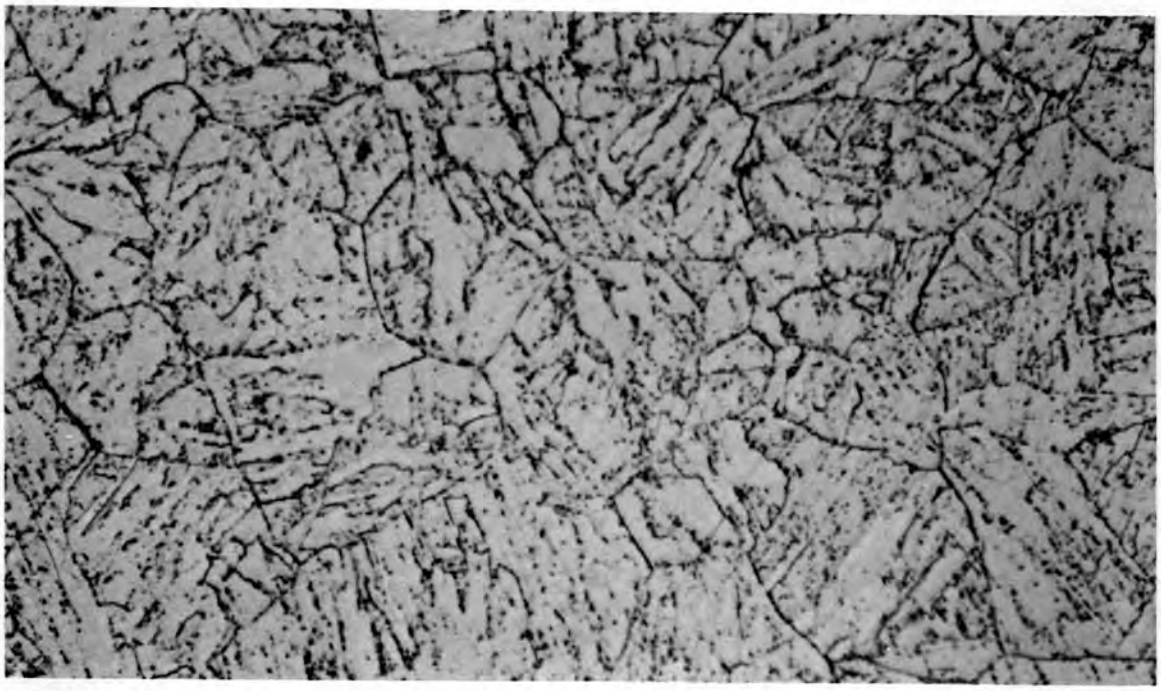
Y-183985



(a)

13.4 μm

Y-183986



(b)

Fig. 29. Optical microstructure after tempering heat 30394 of modified 9 Cr-1 Mo steel at (a) 732°C for 4 h and (b) 760°C for 1 h. Microhardnesses of these specimens are 243 ± 3 dph, respectively. These tempering treatments produce the same value of the Holloman-Jaffe parameter.

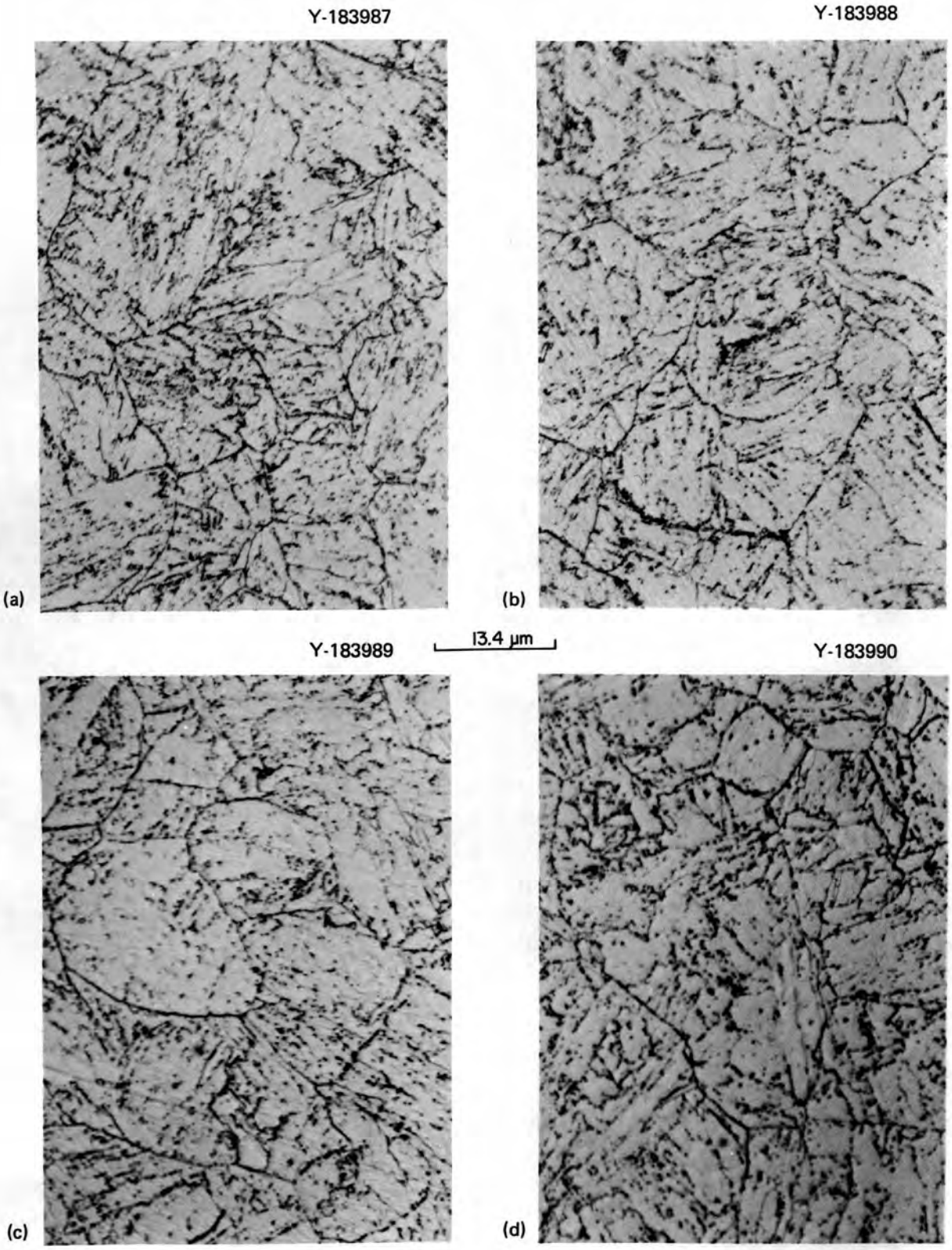


Fig. 30. Optical microstructure after tempering heat 30394 of modified 9 Cr-1 Mo steel at (a) 732°C for 16 h, (b) 760°C for 4 h, (c) 788°C for 1 h, and (d) 816°C for 15 min. Microhardnesses of these specimens are (a) 214.6 ± 0.8, (b) 210.6 ± 1.8, (c) 206 ± 0.6, and (d) 210 ± 2.8 dph. All tempering treatments produced the same value of the Holloman-Jaffe parameter.

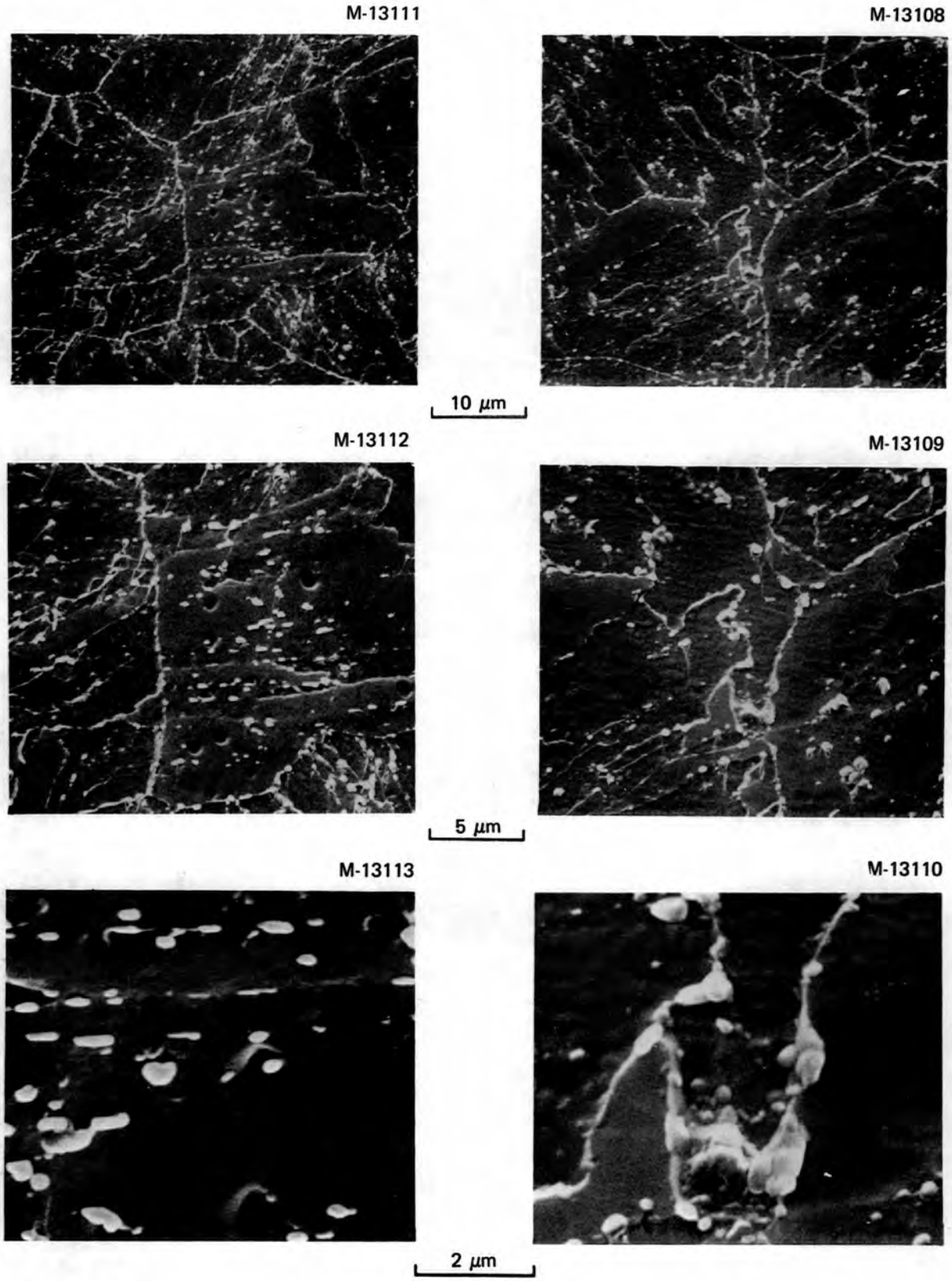
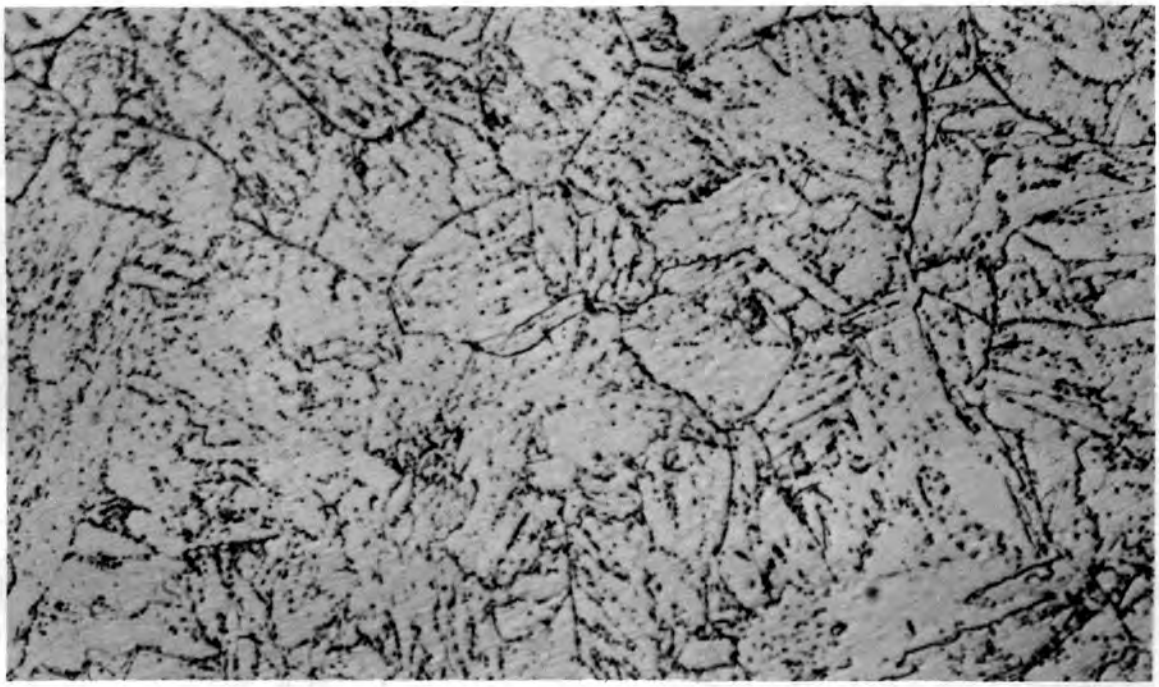


Fig. 31. Scanning electron micrographs of heat 30394 of modified 9 Cr-1 Mo steel. Left, tempered at 760°C for 4 h. Right, tempered at 816°C for 15 min.

Y-183991



(a)

13.4 μm

Y-183992

(b)

Fig. 32. Optical microstructure after tempering heat 30394 of modified 9 Cr-1 Mo steel at (a) 788°C for 4 h and (b) 816°C for 1 h. Microhardnesses of these specimens are 206.5 ± 3.5 and 199 ± 4, respectively. These treatments produce the same value of the Holloman-Jaffe parameter.

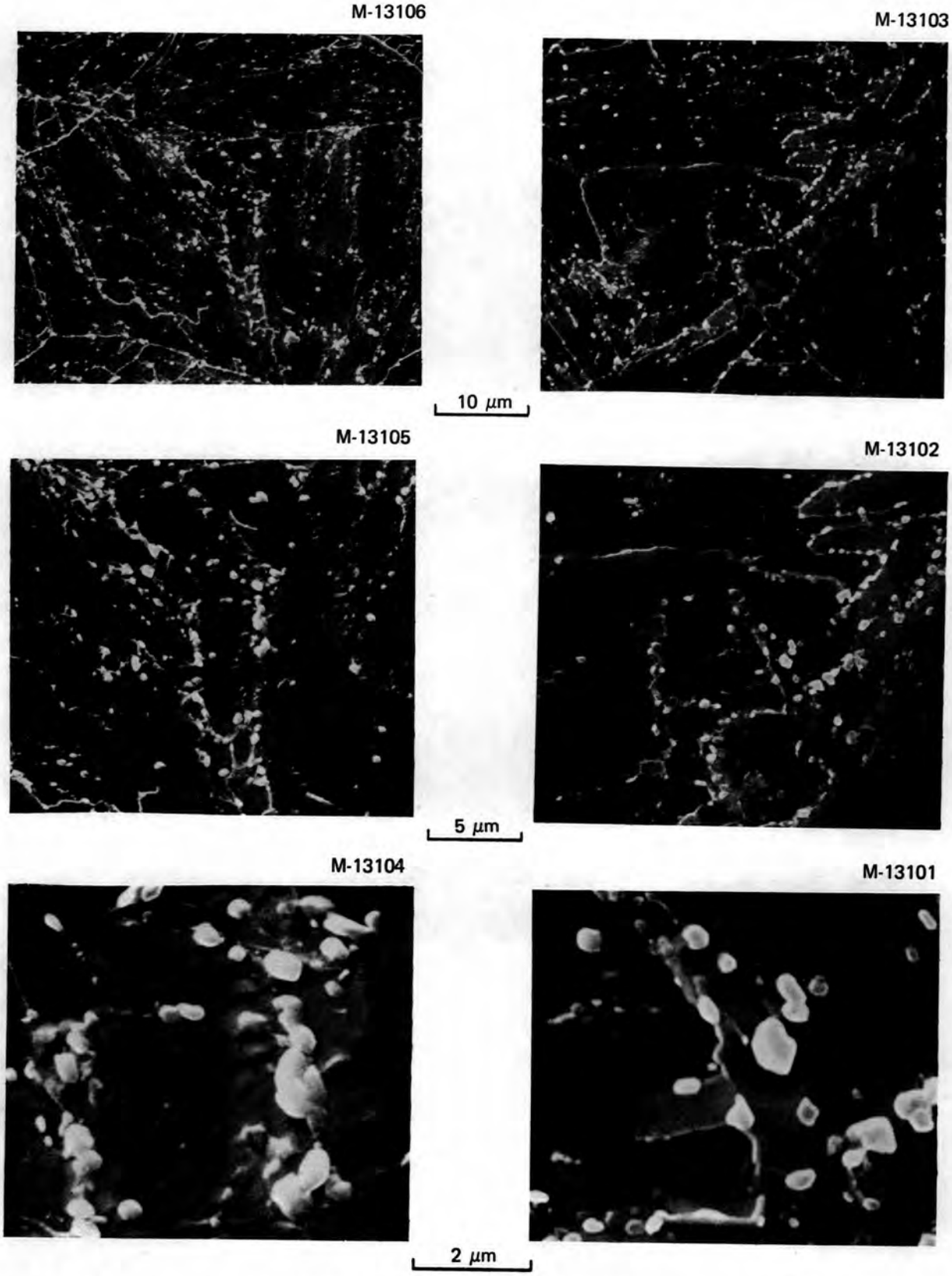


Fig. 33. Scanning electron micrographs of heat 30394 of modified 9 Cr-1 Mo steel. Left, tempered at 788°C for 4 h. Right, tempered at 816°C for 1 h.

Y-181757

0.25 μm

Fig. 34. Transmission electron micrograph of a specimen normalized at 1040°C for 1 h and tempered at 760°C for 1 h. The micrograph shows that tempered martensite consists of dislocation substructure and carbides ($M_{23}C_6$ and MC) on both the grain and subgrain boundaries.

SUMMARY AND CONCLUSIONS

The effects of various tempering temperatures and times on the room-temperature tensile properties, the hardness, and the Charpy impact energy at room temperature and at 204°C were investigated for two commercial heats of modified 9 Cr-1 Mo steel. The tempering temperature and time were found to be exchangeable by an HJ parameter. It is given by $HJ = T(C + \log t)$, where T is the temperature in Kelvin, t is the time in hours, and C is a constant with a value of 22.3. The HJ parameter derived for the tempering conditions was also found to be suitable for describing the changes in tensile properties for PWHT at 732°C for various times. The yield and ultimate tensile strength data at room temperature were plotted as functions of hardness. The changes in elevated-temperature tensile properties by tempering for 1 h at various temperatures were compared with the minimum property curves based on room-temperature specified properties. The unstressed portions of room-temperature tensile-tested specimens for various tempering temperatures and times were examined for their microstructure. They were etched with Vilella's reagent and examined by optical and scanning electron microscopy. We reached the following conclusions from this work.

1. Changes in room-temperature tensile properties (strength and ductility), hardness, and Charpy impact energy at room temperature and at 204°C due to various tempering temperatures and times were described by the HJ parameter. The tempering temperature and time were found to be exchangeable within the tempering temperature range of 732 to 816°C and for times of 15 min to 16 h.

2. The HJ parameter based on the tempering temperature and time could also be used for describing the changes in tensile properties due to various PWHTs at 732°C from 1 to 112 h.

3. Relationships developed for 6.35-mm-diam specimens were also valid for 12.83-mm-diam specimens. The same relationships were also suitable for full-size tubular specimens.

4. The room-temperature yield and ultimate tensile strengths were linearly related to hardness. Such a correlation is desirable when the alloy is expected to meet both strength and hardness criteria.

5. Optical and scanning micrographs showed that tempering temperature and time combinations that produced the same value of the HJ parameter also produced the same microstructure.

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