HIGH-STRENGTH Fe-3Cr-W(Mo) STEEL FOR PETROCHEMICAL APPLICATIONS

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ABSTRACT

This paper describes the development of a new class of high strength Fe-3Cr-W(Mo) ferritic steel. The new steel has two grades A and B. The Grade A is a base Fe-3Cr-W(Mo) composition that is strengthened by optimum additions of C and V. The Grade B also contains 0.10 wt % Ta for additional high-temperature creep strength. Both alloys are air hardenble and are recommended for use in the normalized and tempered condition. The best combination of strength and toughness properties is obtained when both grades are austenitized at 2012^{o}F and tempered at 1345^{o}F. Both grades were commercially melted in 50-ton heats by electric furnace melting. The round and slab ingots from the 50-ton heats were forged into billets and rolled into plates by using processing conditions similar to those used for Fe-2.25Cr-1Mo steels. This paper has presented the Charpy impact, tensile, and creep data available to date on both Grades A and B. Tensile and creep data on Grades A and B are compared with the data on the commercially used grades T22, T23, T24, and the modified Fe-9Cr-1Mo Grade 91.

INTRODUCTION

Ferritic steels [1] such as 2.25Cr-1Mo, commonly known as Grade 22, is used for petrochemical applications such as catalytic crackers and coke drums. Being very large units, they use plates and forgings of Grade 22 ranging in thickness from 3 to 10 in. Fabrication of such large units require specialty equipment for forming the component shape from plates and forgings and long periods of time and large quantity of materials for welding. The postweld heat treatment (PWHT) of such units also requires very large furnaces and long times. Some of the units are so large that they can only be shipped as components and assembled in the field. Thus, there are significant incentives in developing higher strength grades of Fe-2.25Cr steels. This paper describes an effort that was funded by the Department of Energy to develop a new class of high-strength versions of ferritic steels in the United States. The paper presents the project status after 30 months of a 36-month project. This represents first the effort in the United States in developing the higher strength ferritic steels since the last government-funded effort during 1978 through 1982 that developed the high-strength version of Fe-9Cr-1Mo steel, Grade 91 [refs. 2,3].

ALLOY DEVELOPMENT

This project focused on developing a Fe-3Cr-W(Mo) alloy [4] with nominal W addition of 1.5 wt % and Mo of 0.75 wt %. The alloy is further modified by an addition of 0.25 wt % V. The alloy is also optimized for its C, Si, and Mn contents. The base Fe-3Cr-W(Mo) alloy is known as Grade A. A second grade of the same base composition with 0.10 wt % Ta addition is known as Grade B which has significantly higher creep strength than Grade A. This project is focusing on taking both grades to commercialization.

HEAT TREATMENTS

The alloy is recommended for use in normalized and tempered conditions. The nominal normalizing and tempering temperatures for Grades A and B are 1100 and 730°C, respectively. Holding time is a function of section thickness. Alloys were tested after both 700 and 730°C tempering treatments.

COMMERCIAL MELTING AND PROCESSING OF ALLOYS

Both Grades A and B were electric furnace melted into 50-ton heats followed by vacuum degassing at Ellwood Quality Steel. The 50-ton heats were cast into 27-in.-diam ingots and 12-in.-thick slabs. One each of the 27-in.-diam ingots from each grade was also remelted by electroslag remelting (ESR) and vacuum-arc remelting (VAR) and cast into 30-in.-diam ingots.

The 27- and 30-in.-diam ingots were hot-forged into 12-in.-diam rounds and rounded corner square billets. Both Grades A and B were forged in a manner similar to Grade 22. The rounded-corner forged billets were further hot-rolled into 3.75-in.-diam bar and 1-in.-thick plate. The hot-rolled bar will be used for producing seamless tubing at Plymouth Tube. The 12-in.-thick slabs were hot-rolled at ISG Plate – Coatesville into 1.5- and 3-in.-thick plates.

CHEMICAL ANALYSIS

The chemical analysis of the 50-ton electric furnace heats is shown in Table 1. This table includes the AIM chemistry, and as noted there were no problems encountered in meeting the target. Table 2 compares the chemical analysis of forgings from Grades A and B of the electric furnace, ESR, and VAR heats. This paper will compare the properties of Grades A and B with commercially used T22 and T91 and recent high-strength alloys, T23 and T24. Chemical analysis of these alloys is compared in Table 3.

Table 1: Chemical analysis of 50-ton heats of Grades A and B melted in electric furnace followed by vacuum degassing

Element	Weight percent							
	Grade A, Heat L7974				Grade B, Heat L8644			
	27-in. Round			12-in. Slab	27-in. Round			12-in. Slab
	AIM	Vendor	Check	Vendor	AIM	Vendor	Check	Vendor
Carbon	0.10	0.11	0.099	0.11	0.10	0.11	0.11	0.11
Manganese	0.35	0.36	0.34	0.36	0.35	0.36	0.35	0.36
Phosphorus	0.01[a]	0.007	0.009	0.007	0.01[a]	0.008	0.009	0.008
Sulfur	0.01[a]	0.002	0.003	0.002	0.01[a]	0.002	0.002	0.002
Silicon	0.2	0.21	0.21	0.21	0.2	0.2	0.2	0.2
Nickel	0.02[a]	0.15	0.15	0.15	0.02[a]	0.12	0.12	0.12
Chromium	3.00	2.99	2.97	2.99	3.00	3.01	3.02	3.01
Molybdenum	0.75	0.76	0.73	0.76	0.75	0.74	0.73	0.74
Vanadium	0.25	0.249	0.22	0.249	0.25	0.236	0.21	0.236
Columbium	----	----	0.002	----	----	----	0.002	----
Titanium	----	----	0.003	----	----	----	0.004	----
Cobalt	----	----	0.014	----	----	----	0.016	----
Copper	----	0.11	0.11	0.11	----	0.17	0.17	0.17
Aluminum	----	0.013	0.008	0.013	----	0.011	0.006	0.011
Boron	0.01[a]	0.0002	<0.001	0.0002	0.01[a]	0.0001	<0.001	0.0001
Tungsten	1.5	1.55	1.68	1.55	1.5	1.48	1.62	1.48
Arsenic	----	----	0.005	----	----	----	0.006	----
Tin	----	----	0.008	----	----	----	0.009	----
Zirconium	----	----	<0.001	----	----	----	<0.001	----
Nitrogen	----	----	0.009	----	----	----	0.011	----
Oxygen	----	----	0.004	----	----	----	0.001	----
Hydrogen	----	1.6[b]	----	2.2[b]	----	1.3[b]	----	2.3[b]
Tantalum	----	----	----	----	0.10	0.107	0.1	0.107

[a]Maximum
[b]Parts per million

RESULTS AND DISCUSSION

The commercial heats of Grades A and B are being tested for their Charpy-impact, tensile, and creep properties. Each of these properties is presented below.

CHARPY IMPACT

The Charpy-impact tests were conducted on the rounded-corner 6-in.-square forged billets in both longitudinal and transverse orientations. All data reported here are for preferred tempering temperature of 730°C. The Charpy-impact energy and lateral expansions for Grades A and B in the electric-furnace-melted condition are shown in Figs. 1 and 2. These data show that both alloys have very similar impact properties. The longitudinal values are better than transverse properties. The 40 ft-lb transition temperature for longitudinal orientation is between -30 to -40°F for the two grades. For transverse orientation, the 40 ft-lb transition temperature is between 0 and +15°F. The 20-mil (0.02-in.) lateral expansion temperature varies from 0 to -60°F. It is -60°F for Grade A in the longitudinal orientation.

Table 2: Change in chemical analysis of electric-furnace-melted 50-ton Heats of Grades A and B after electronslag-remelting and vacuum-arc-remelting processes

Element	Heat (wt %)					
	Grade A			Grade B		
	Electric 79741	ESR[a] 79742	VAR[b] 79743	Electric 86441	ESR[a] 86442	VAR[b] 86443
C	0.099	0.11	0.11	0.11	0.11	0.11
Mn	0.34	0.33	0.25	0.35	0.33	0.22
P	0.009	0.008	0.008	0.009	0.009	0.009
S	0.003	0.001	0.001	0.002	0.001	0.001
Si	0.21	0.15	0.21	0.2	0.15	0.2
Ni	0.15	0.15	0.21	0.12	0.12	0.12
Cr	2.97	2.95	2.97	3.02	3.03	3.03
Mo	0.73	0.74	0.74	0.73	0.72	0.72
V	0.22	0.22	0.22	0.21	0.21	0.21
Cb	0.002	0.001	0.002	0.002	0.002	0.002
Ti	0.003	0.003	0.003	0.004	0.003	0.003
Co	0.014	0.013	0.013	0.016	0.016	0.016
Cu	0.11	0.11	0.11	0.17	0.17	0.15
Al	0.008	0.005	0.008	0.006	0.016	0.016
B	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
W	1.68	1.67	1.68	1.62	1.61	1.61
As	0.005	0.007	0.007	0.006	0.008	0.007
Sn	0.008	0.008	0.008	0.009	0.01	0.01
Zr	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
N	0.009	0.013	0.004	0.011	0.012	0.004
O	0.004	0.001	<0.001	0.001	0.001	<0.001
Ta	----	<0.001	<0.01	0.1	0.08	0.1

[a]ESR = electroslag remelting.
[b]VAR = vacuum-arc remelting.

The Charpy properties for Grade B in the electric-furnace-melted and VAR conditions are compared in Fig. 3 and 4. These plots show that VAR results in a significant improvement in Charpy-impact properties of Grade B alloy. For example, the 40 ft-lb transition temperature is lowered by nearly 40°F both in the longitudinal and transverse orientations. Similar lowering in temperature is noted for 20-mil (0.020-in.) lateral expansion values.

Tensile tests were conducted on 0.505-in. specimens at temperatures from room temperature to 1300°F. All tests were at a strain rate of $1 \times 10^{-3} s^{-1}$, and the same strain rate was maintained throughout the tests. Tensile properties for electric-furnace-melted Grades A and B are plotted as a function of temperature in Figs. 5 and 6. Data for alloys T22, T23 and T24 are also included for comparison. This figure shows only a

Table 3:Chemical analysis of commercial alloys used for property comparison with Grades A and B of this investigation

Element	**Alloy (wt %)**			
	Commercial / Near Commercial			
	T22[a]	**T23[a,c]**	**T24[a,d]**	**T91[a,e]**
C	0.15 max	0.04-0.10	0.05-0.10	0.08-0.12
Si	0.25-1.00	0.50 max	0.15-0.45	0.20-0.50
Mn	0.30-0.60	0.10-0.60	0.30-0.70	0.30-0.60
P	0.030 max	0.030 max	0.020 max	0.020 max
S	0.030 max	0.010 max	0.010 max	0.010 max
Cr	1.9-2.6	1.9-2.6	2.2-2.6	8.0-9.5
Mo	0.87-1.13	0.05-0.30	0.90-1.10	0.85-1.05
N	*b*	0.030 max	0.12 max	0.030-0.070
W	*b*	1.45-1.75	*b*	*b*
V	*b*	0.20-0.30	0.20-0.30	0.18-0.25
Nb	*b*	0.02-0.08	*b*	0.06-0.10
Ta	*b*	*b*	*b*	*b*
B	*b*	0.0005-0.0060	0.0015-0.0070	*b*
Ti	*b*	*b*	0.05-0.10	*b*
Ni	*b*	*b*	*b*	0.40 max
Al	*b*	0.030 max	0.020 max	0.040 max
Fe	*f*	*f*	*f*	*f*

[a]ASTM A213.
[b]Not specified.
[c]Code Case 2199.
[d]Code Case draft.
[e]Code approved.
[f]Balance.

small difference in the properties of Grades A and B. However, the yield and ultimate tensile strength properties are nearly 25 to 30 ksi higher than the highest strength alloy, T23. This improvement is considered very significant, especially at test temperature of 1200°F.

A comparison of tensile properties of Grade B in electric-furnace-melted and VAR conditions are shown in Figs. 7 and 8. This figure shows that VAR reduces the strength properties somewhat. Even with the reduction in properties, Grade B is nearly 15 to 20 ksi stronger than alloy T23. The chemical analysis in Table 2 shows that VAR reduces the nitrogen content from 0.012 to 0.004 wt %. It is believed that this reduction in nitrogen content is responsible for reducing strength properties and improvement in impact properties, as noted in Figs. 3 and 4.

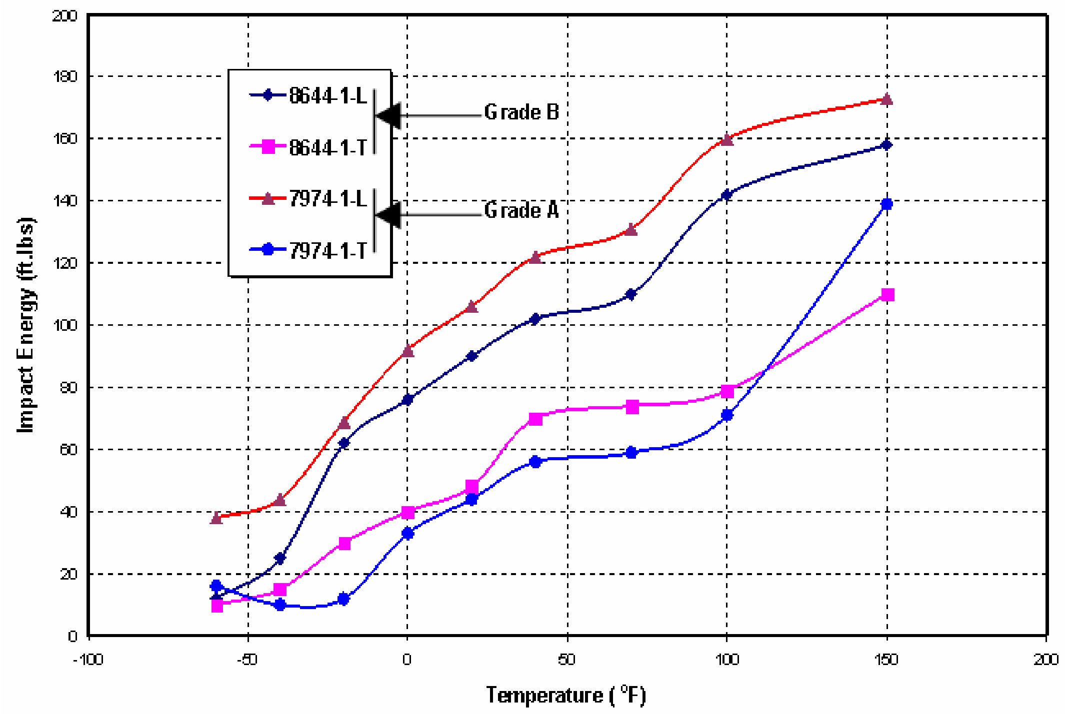


Figure 1: Comparison of Charpy-impact energy values for electric-furnace-melted and forged billets of 50-ton heats of Grades A and B of Fe-3Cr-W(Mo) alloys. Data for both longitudinal and transverse orientations are included.

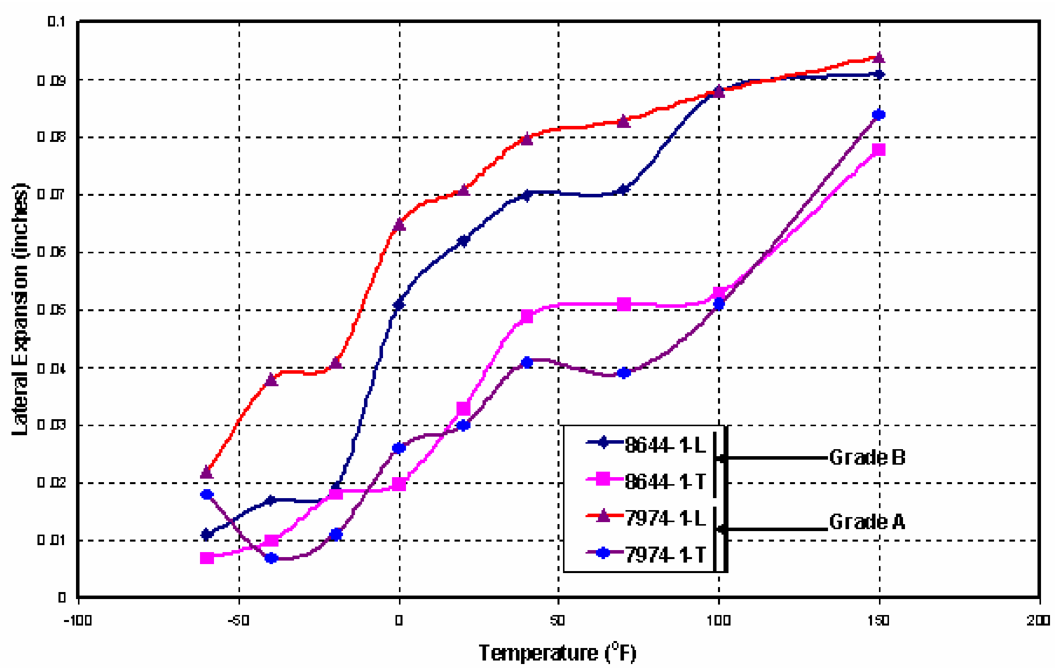


Figure 2: Comparison of lateral expansion of Charpy-impact-tested specimens of electric-furnace-melted and forged billets of 50-ton heats of Grades A and B of Fe-3Cr-W(Mo) alloys. Data for both longitudinal and transverse orientations are included.

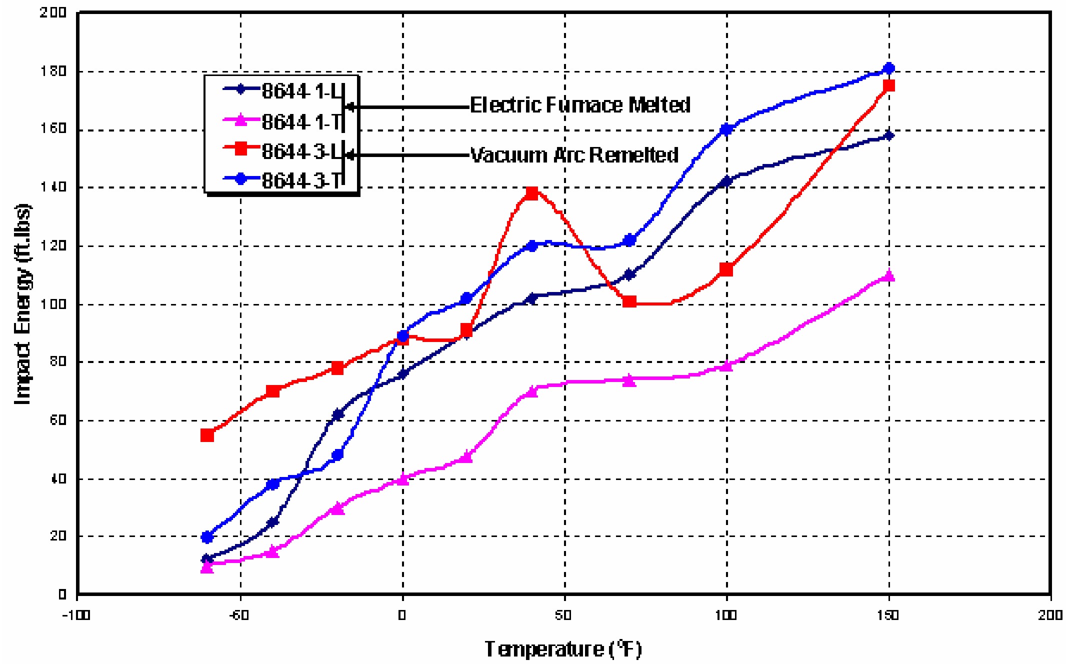


Figure 3: Comparison of Charpy-impact energy values for forged billets of 50-ton heats of Grade B melted by electric furnace and vacuum-arc remelting. Data for both longitudinal and transverse orientations are included.

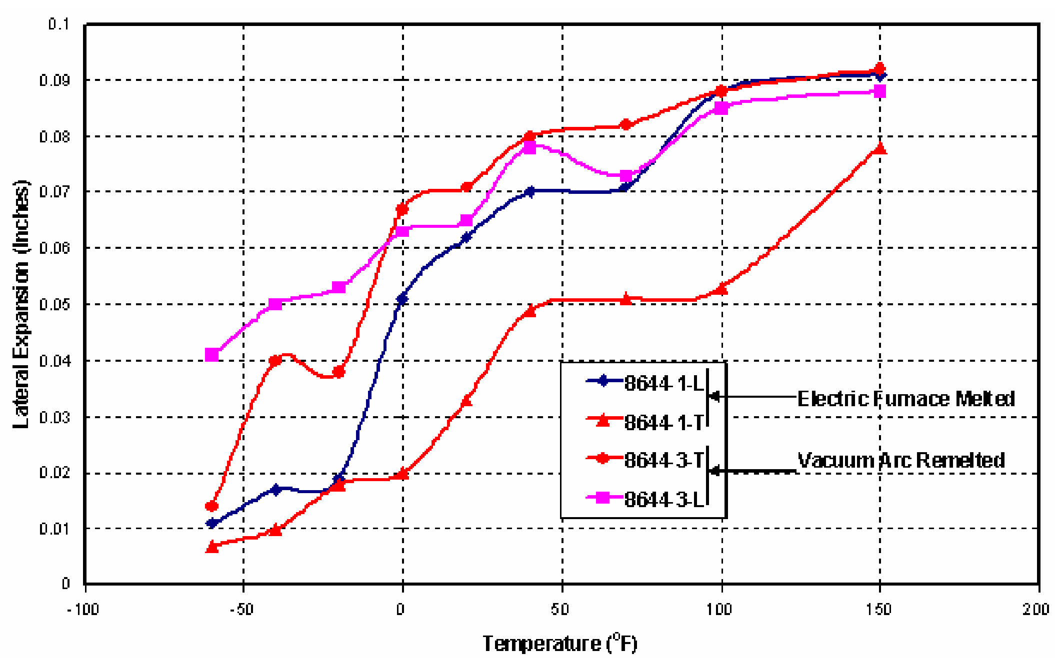
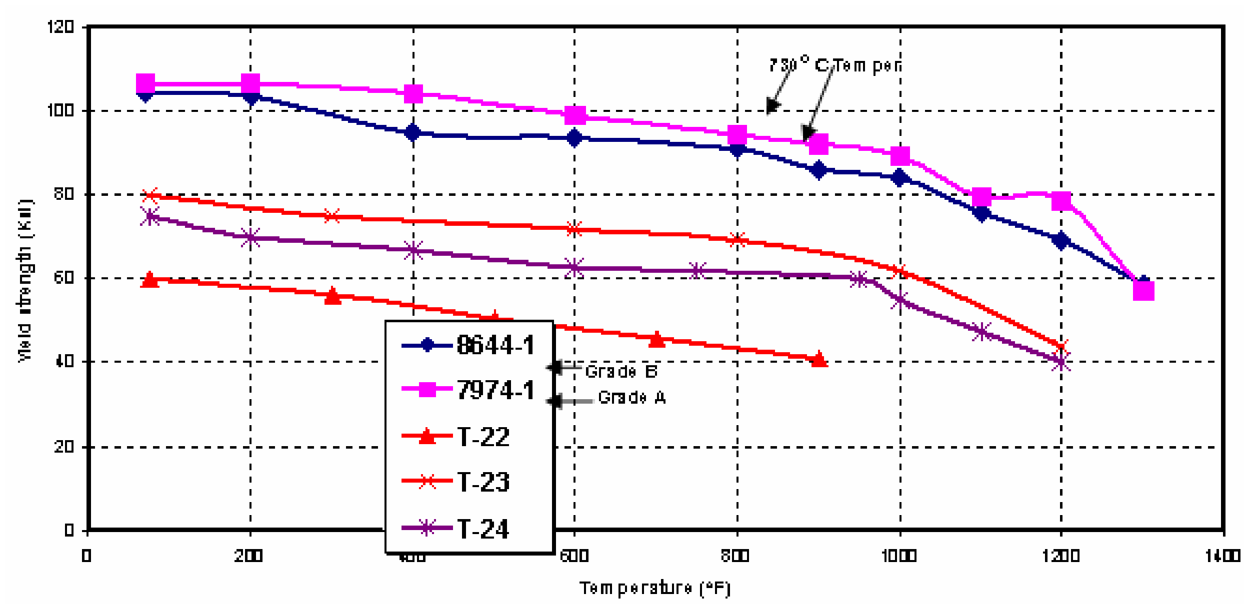
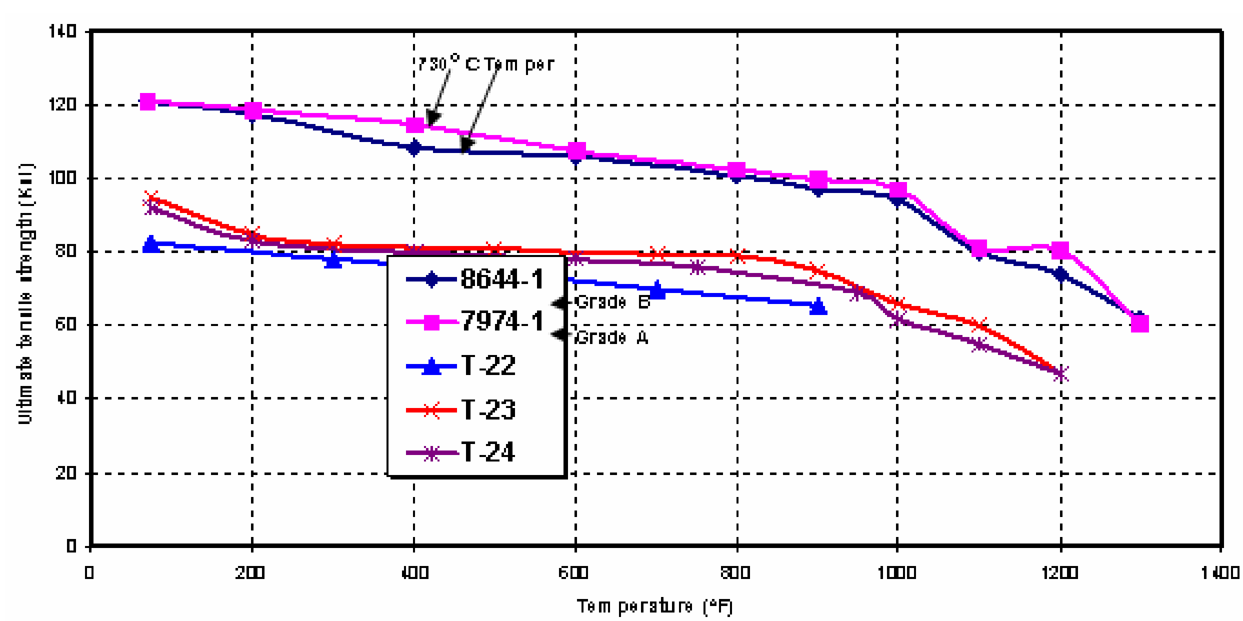


Figure 4: Comparison of lateral expansion of Charpy-impact-tested specimens for forged billets of 50-ton heats of Grade B melted by electric furnace and vacuum-arc remelting. Data for both longitudinal and transverse orientations are included.

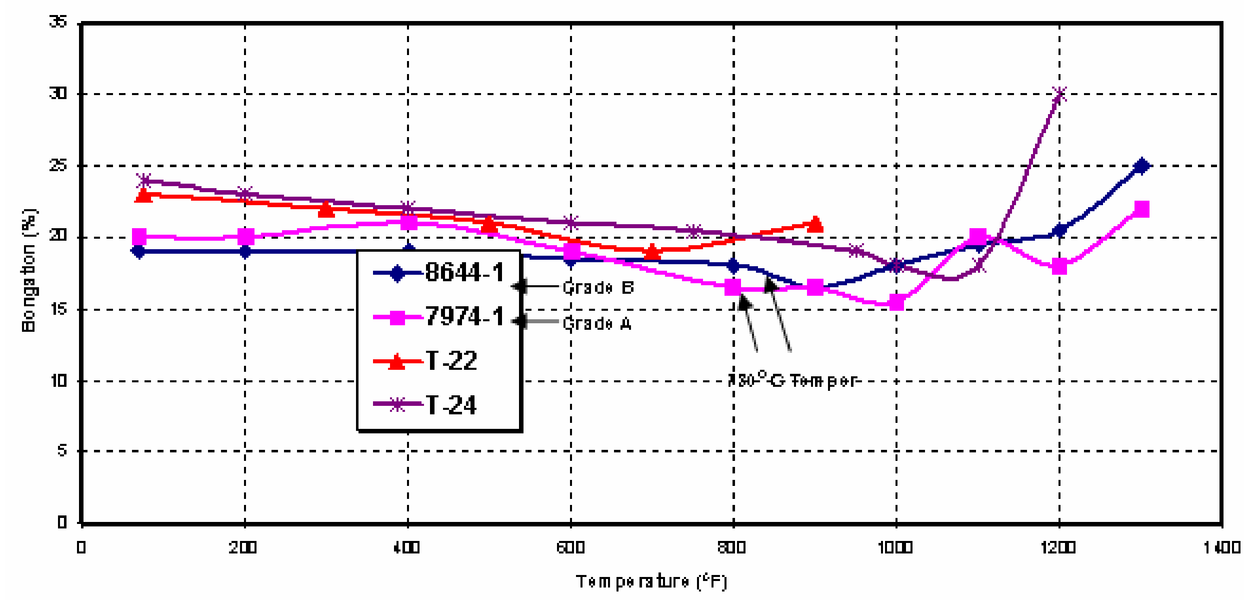


(a)



(b)

Figure 5: Comparison of tensile properties for electric-furnace-melted and forged billets of 50-ton heats of Grades A and B of Fe-3Cr-W)Mo) alloys. Data for commercial alloys T22, T23, and T24 are also included for comparison: (a) yield strength and (b) ultimate tensile strength.



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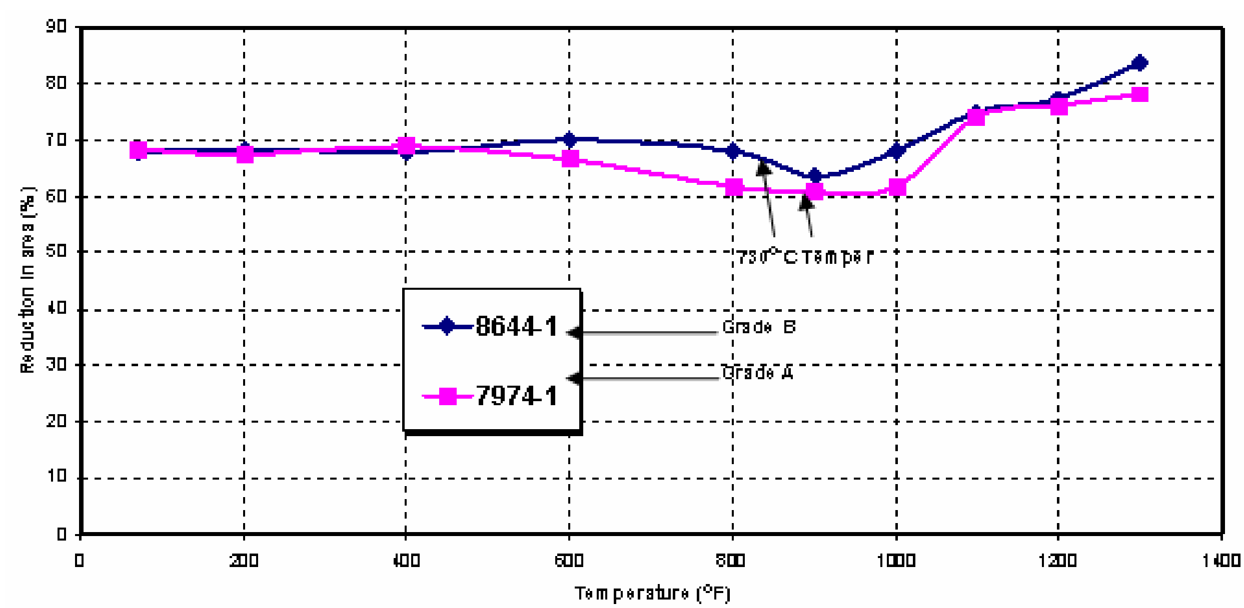
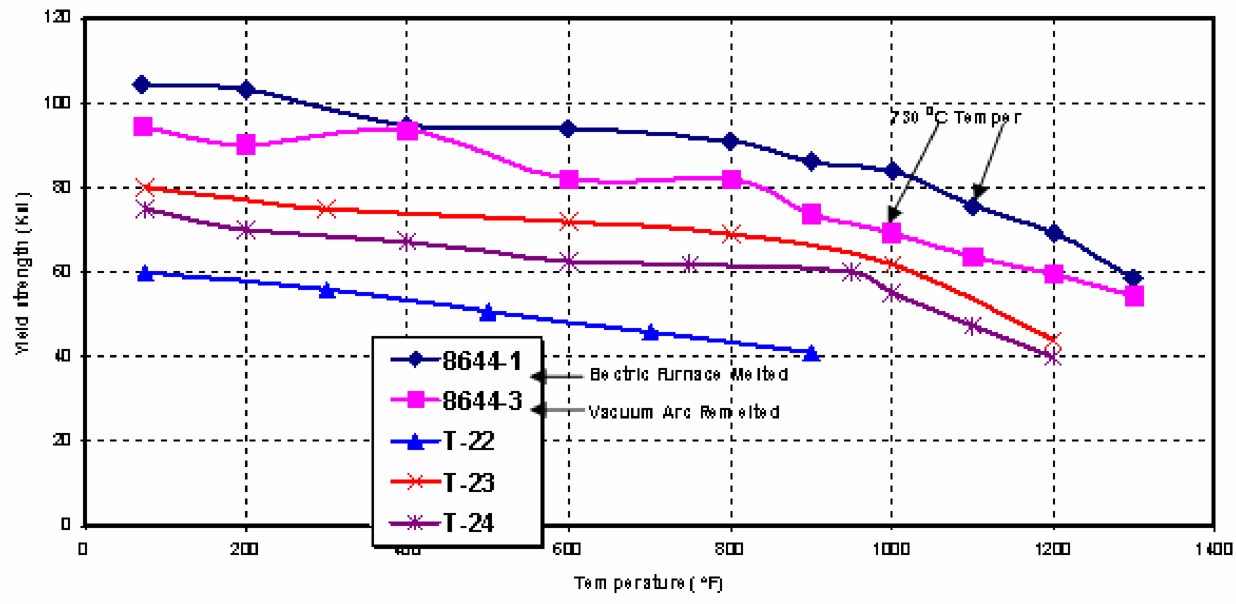


(b)

Figure 6: Comparison of tensile properties for electric-furnace-melted and forged billets of 50-ton heats of Grades A and B of Fe-3Cr-W)Mo) alloys. Data for commercial alloys T22, T23, and T24 are also included for comparison: (a) total elongation and (b) reduction of area.



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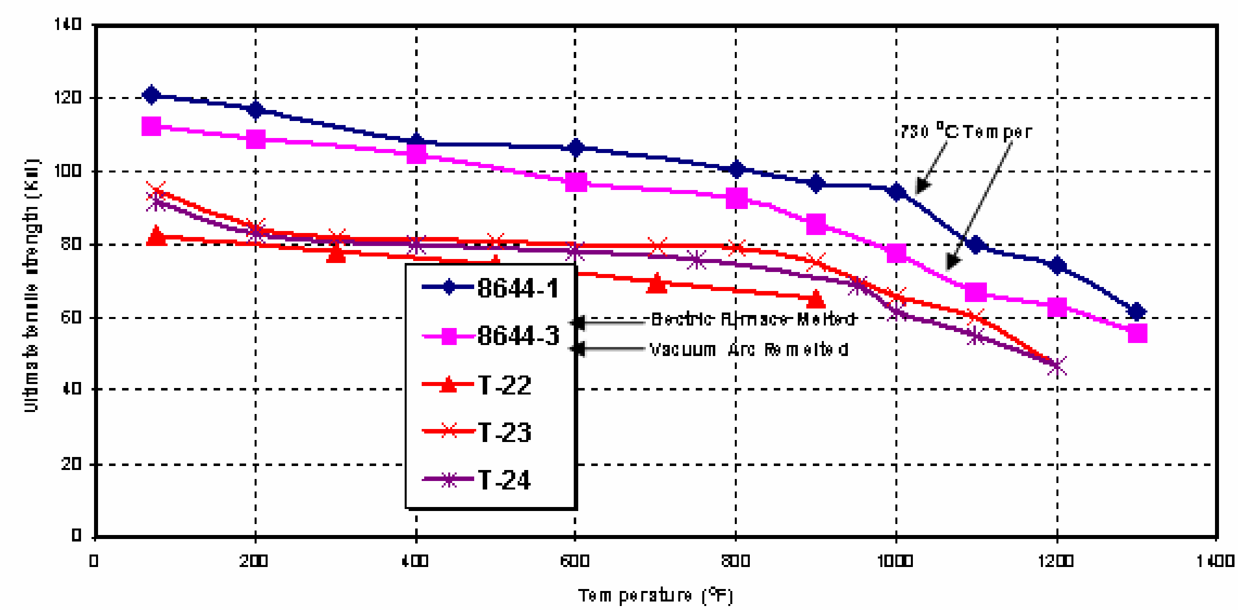
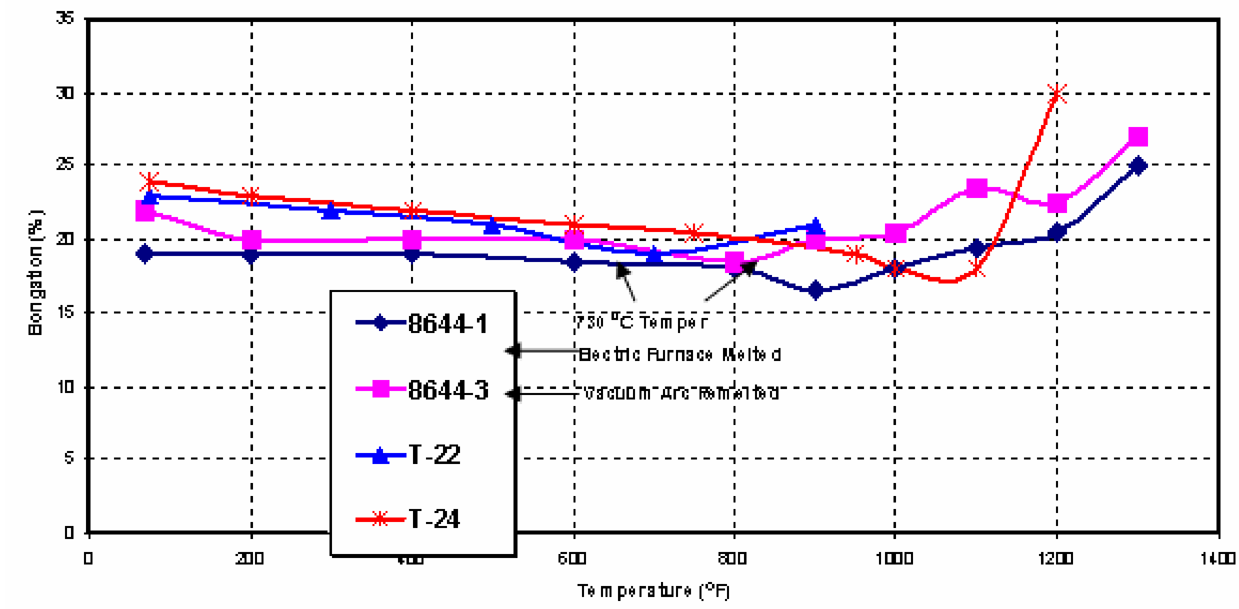
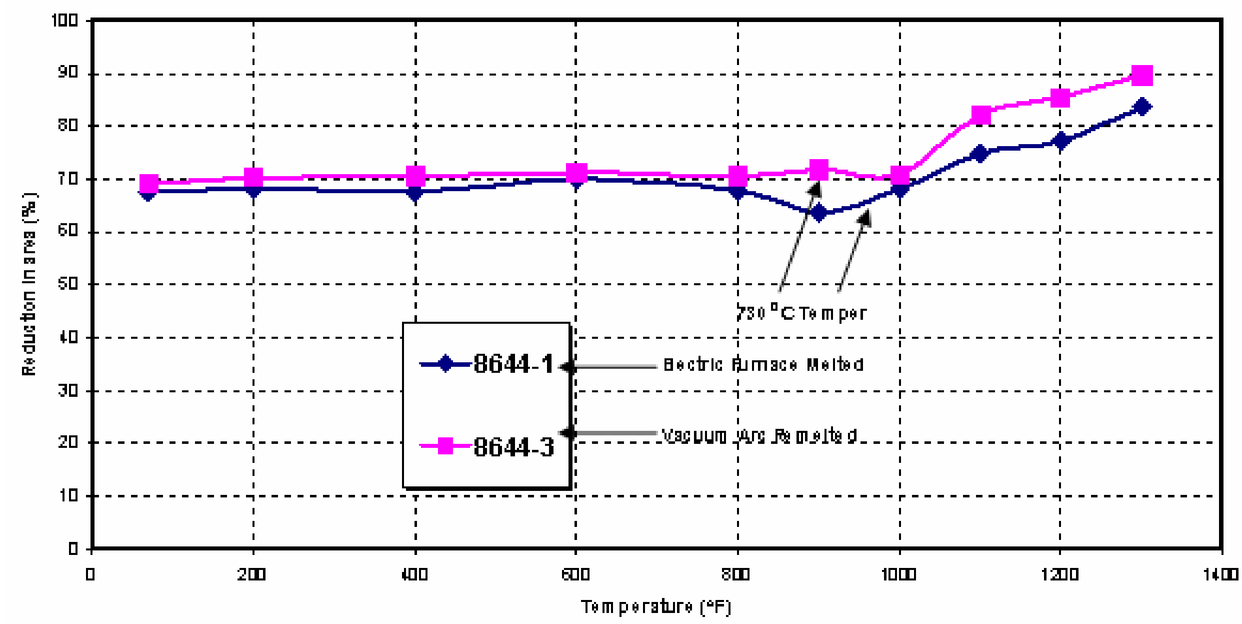


(b)

Figure 7: Comparison of tensile properties for forged billets of 50-ton heats of Grade B melted by electric furnace and vacuum-arc remelting. Data for commercial alloys T22, T23, and T24 are also included for comparision: (a) yield strength and (b) ultimate tensile strength.



(a)



(b)

Figure 8: Comparison of tensile properties for forged billets of 50-ton heats of Grade B melted by electric furnace and vacuum-arc remelting. Data for commercial alloys T22, T23, and T24 are also included for comparision: (a) total elongation and (b) reduction of area.

The creep tests are in progress on both Grades A and B after tempering at 700 and 730°C. Data available to date is only for tempering temperature of 700°C. Creep tests are being conducted in the temperature range of 900 to 1300°F and at stresses to yield 100-, 1000-, and 10,000-h rupture lives. The stress-to-rupture values for Grade A are plotted as a function of Larsen-Miller parameter (LMP) in Fig. 9. Eight creep test points on the 50-ton heat are included in this figure. Four of the eight tests have ruptured, and the other four are in progress, as indicated by the arrows next to the data points. The LMP line, based on data for experimental heats, is included for comparison. This figure shows that the predicted LMP line describes well the rupture behavior of the 50-ton heat of Grade A. It is expected that the tests in progress will continue to support the same trend for long-term data.

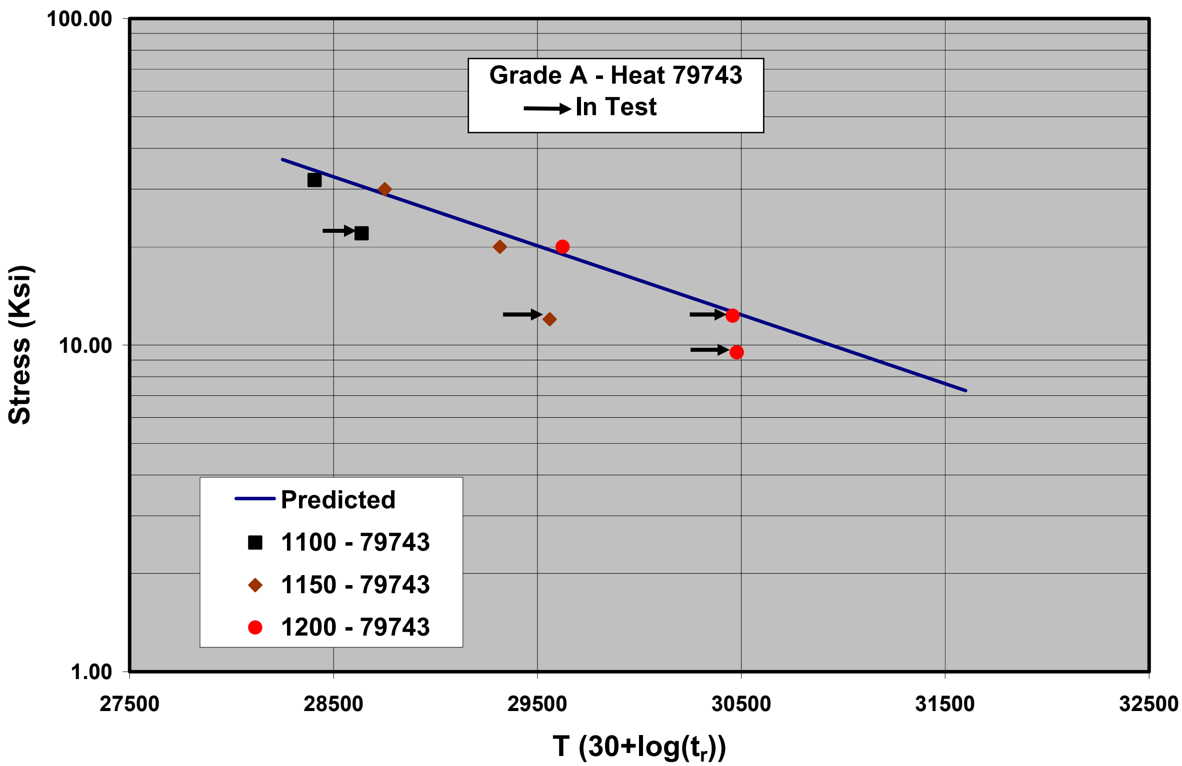


Figure 9: Plot of stress-to-rupture versus Larsen-Miller parameter (LMP) for forged billets of a 50-ton heat of Grade A. The predicted LMP, based on experimental heats, is included for comparison.

The creep-rupture data for 50-ton hats of Grade B are plotted in Fig. 10. This plot also includes the LMP based on experimental heats. A total of five tests have ruptured for one heat (86441) and two tests for the second heat (86442). Data for heat 86441 are on specimens in transverse orientation and for heat 86442 are on longitudinal orientation. Data in Fig. 10 show that the LMP predicts the creep-rupture behavior of longitudinal specimens of 50-ton heat (heat 86442) of Grade B well.

However, the data on the transverse specimens of Grade B of heat 86441 are slightly lower in strength. Since experimental data were only developed for the longitudinal orientation, the data in Fig. 10 suggest that transverse orientation is slightly weaker than the longitudinal orientation for the forged billet used for these test data.

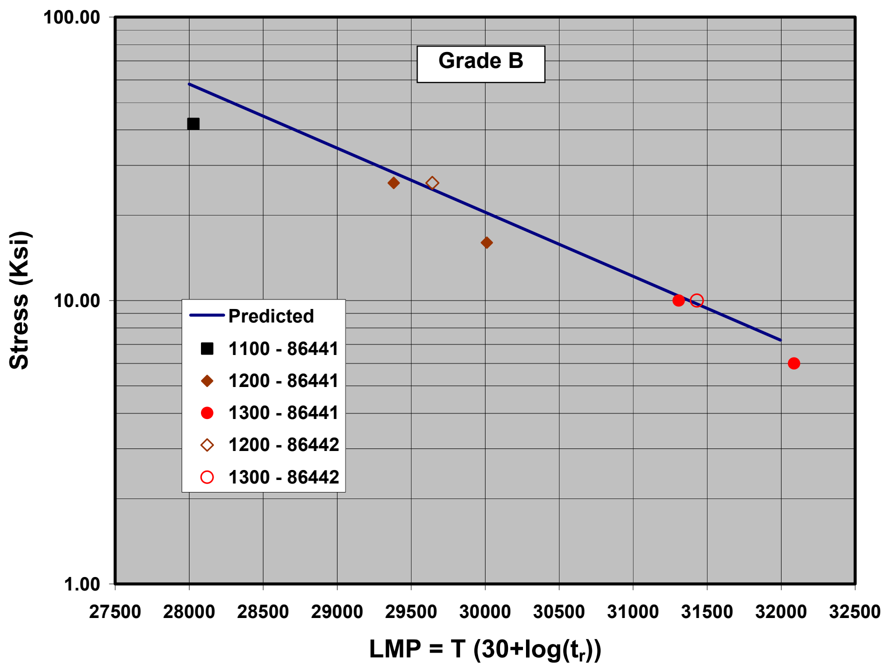


Figure 10: Plot of stress-to-rupture versus Larsen-Miller parameter (LMP) for forged billets of two 50-ton heats of Grade B. The predicted LMP, based on experimental heats, is included for comparison.

The predicted values of stress to rupture versus LMP for Grades A and B are compared with the average LMP for commercial grades T22, T23, T24, and T91 in Figs. 11 and 12. The plot in Fig. 11 shows that Grade A is stronger than T23 and T91 to approximately 1100°F. At higher temperatures, creep-rupture strength of Grade A is similar to that of T23. The plot in Fig. 12 shows that Grade B is stronger than T23 for the entire test temperature range used in the LMP for this plot. Grade B is also stronger than T91 for LMP that corresponds to a temperature of approximately 1150°F. The lower strength of Grade B at temperatures higher than 1150°F is potentially related to its poor oxidation because of its 3Cr as opposed to 9Cr in T91.

WELDING

Initial welding trials on the experimental heats of Grades A and B have shown that both grades are weldable by conventional gas-tungsten-arc and submerged arc processes. The welding trials for the 50-ton heats are currently underway.

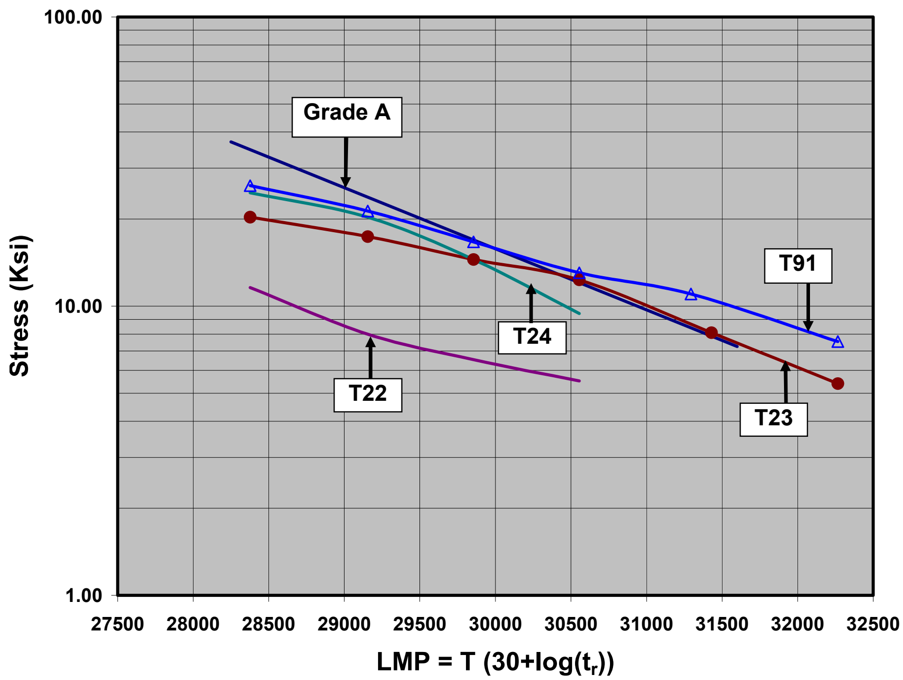


Figure 11: Comparison of stress-to-rupture versus Larsen-Miller parameter of Grade A with commercial alloys T22, T23, T24, and T91.

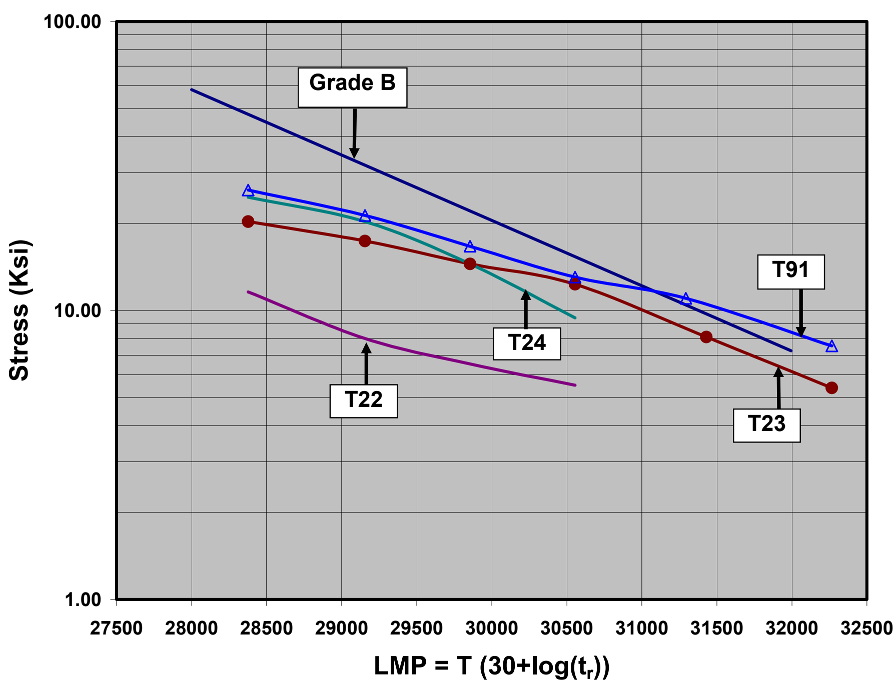


Figure 12: Comparison of stress-to-rupture versus Larsen-Miller parameter of Grade B with commercial alloys T22, T23, T24, and T91.

SUMMARY AND CONCLUSIONS

This paper describes the development of a new class of high-strength Fe-3Cr-W(Mo) ferritic steel. The new steel has two grades, A and B. Grade A is a base Fe-3Cr-W(Mo) composition that is strengthened by optimum additions of C and V. Grade B also contains 0.10 wt % Ta for additional high-temperature creep strength. Both alloys are air hardenble and are recommended for use in the normalized and tempered condition. The best combination of strength and toughness properties are obtained when both grades are austenitized at 2012^{o}F and tempered at 1345^{o}F. Both grades were commercially melted in 50-ton heats by electric furnace melting. The round and slab ingots from the 50-ton heats were forged into billets and rolled into plates by using processing conditions similar to those used for Fe-2.25Cr-1Mo steels. This paper has presented the Charpy impact, tensile, and creep data available to date on both Grades A and B. Tensile and creep data on Grades A and B are compared with the data on the commercially used grades T22, T23, T24, and the modified Fe-9Cr-1Mo Grade 91. The following conclusions are possible from this work:

1. The 40 ft-lb transition temperature for longitudinal orientation is between -30 to -40°F for both Grades A and B melted by electric furnace. For transverse orientation, the 40 ft-lb transition temperature is between 0 and +15°F. The 20-mil (0.02-in.) lateral expansion temperature varies from 0 to -60°F. It is -60°F for Grade A in the longitudinal orientation.
2. The vacuum arc remelting (VAR) of electric-furnace-melted heats showed a significant improvement in Charpy-impact properties of Grade B alloy. For example, the 40 ft-lb transition temperature was lowered by nearly 40°F for both the longitudinal and transverse orientations. Similar lowering in temperature was noted for 20-mil (0.020-in.) lateral expansion values.
3. Tensile properties of both Grades A and B were very similar. The yield and ultimate tensile strength values of both Grades A and B are nearly 25 to 30 ksi higher than the highest strength alloy, T23. This improvement is considered very significant, especially at test temperature of 1200°F.
4. The VAR that resulted in significant improvement in Charpy-impact properties results in lowering the yield and tensile strengths. However, these values are still 15 to 20 ksi higher than Grade T23.
5. The creep-rupture-strength values for 50-ton heats of both Grades A and B match the predicted values based on the experimental size heats.
6. The predicted values of stress-to-rupture versus LMP for Grades A and B were compared with the average LMP for commercial grades T22, T23, T24, and T91. These comparisons showed that Grade A is stronger than T23 and T91 to approximately 1100°F. At higher temperatures, creep-rupture strength of Grade A is similar to that of T23. However, Grade B is stronger than T23 for the entire test temperature range and is also stronger than T91 for temperature of approximately 1150°F.
7. Preliminary data have shown that both Grades A and B are weldable by commonly used methods such as submerged arc and gas tungsten arc.

ACKNOWLEDGMENT

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