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Impact Behavior of Cr–W Steels[1]

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Abstract. Chromium–molybdenum ferritic (martensitic) steels are leading candidates for the structural components for fusion reactors. However, irradiation of steels containing molybdenum or niobium in a fusion environment will produce long-lived radioactive isotopes that will lead to difficult waste disposal problems. To alleviate the waste disposal problem, ferritic steels are being developed that are analogous to conventional Cr–Mo steels, but with molybdenum replaced by tungsten and niobium replaced by tantalum. Experimental steels containing 0.1% C, 2¹/₄ to 12% Cr, 0 to 2% W, 0 or 0.25% V, and 0 or 0.07% Ta were produced. Charpy impact properties were determined. A 5Cr–2W–0.25V steel and a 9Cr–2W–0.25V–0.07Ta steel had the best impact properties. The impact properties of these two steels as well as those of a 9Cr–2W–0.25V and a 12Cr–2W–0.25V steel were as good or better than the properties of similarly heat treated conventional 9Cr–1MoVNb and 12Cr–1MoVW steels.

INTRODUCTION

If conventional steels are used for the first wall and blanket structure of future magnetic fusion reactors, they will become highly radioactive. The complexity of the waste disposal procedure for these radioactive components depends on the time required for the induced radioactivity to decay to safe levels. The more rapid the decay, the simpler is the disposal task. Common alloying elements that result in radioactive isotopes that decay over a long period of time are nickel, molybdenum, nitrogen, copper, and niobium.

Several approaches have been taken to develop ferritic steels that could be more easily disposed of after service in a fusion reactor [1–3]. Ghoniem, Shabaik, and Youssef [1] replaced the molybdenum in 2¹/₄Cr–1Mo steel with 1.5 wt% V. Gelles and Hamilton [2] produced eight steels analogous to commercial Cr–Mo steels with chromium concentrations ranging from 2 to 12%. They also used vanadium in the range 0.5 to 1.5% as the primary substitute for molybdenum, although in two steels 1% W was used [2].

For the alloy development program to be discussed here, it was proposed that fast induced-radioactivity decay (FIRD) versions of present first wall and blanket structural candidate alloys be developed by replacing the non-FIRD alloying elements in the steels presently of interest for fusion reactor components [3]. Ferritic steels now being considered are the following commercial Cr–Mo steels: 2¹/₄Cr–1Mo (2.25%Cr–1%Mo–0.1%C),[2] 9Cr–1MoVNb (9%Cr–1%Mo–0.2%V–0.06%Nb–0.1%C), and 12Cr–1MoVW (12%Cr–1%Mo–0.25%V–0.5%W–0.5%Ni–0.2%C) steels.

Because tungsten behaves like molybdenum in simple steels [4], it was proposed as a replacement for molybdenum [3]. It was suggested that the strengthening function of niobium could be replaced by vanadium, titanium, and especially tantalum, which has characteristics in common with niobium [3]. A series of experimental steels was proposed (Table 1) [3], and heats were obtained. The designation to be used for each of the steels is given in Table 1 (i.e., 2.25 CrV is used to designate the steel with 2.25% C and 0.25% V, 9Cr–2WV for the steel with 9% Cr, 2% W, and 0.25% V, etc.).

Compositions for proposed experimental steels were based on variations of the compositions of 2¹/₄Cr–1Mo, 9Cr–1MoVNb, and 12Cr–1MoVW steels. A range of chromium compositions from ~2¹/₄ to 12% was proposed [3]. An atom-for-atom replacement of molybdenum by tungsten was chosen; this required 2 wt%

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[2]All concentrations are given in weight percent.

Table 1. Proposed Nominal Compositions for Fast Induced-Radioactivity Decay Steel Development Program

	Nominal Chemical Composition[a] (wt%)				
Alloy	Cr	W	V	Ta	C
2¼CrV	2.25		0.25		0.1
2¼Cr–1WV	2.25	1	0.25		0.1
2¼Cr–2W	2.25	2			0.1
2¼Cr–2WV	2.25	2	0.25		0.1
5Cr–2WV	5	2	0.25		0.1
9Cr–2WV	9	2	0.25		0.1
9Cr–2WVTa	9	2	0.25	0.12	0.1
12Cr–2WV	12	2	0.25		0.1

[a]Balance iron.

W, since the atomic weight of tungsten is approximately twice that of molybdenum. A 0.25% V content was used, which is similar to the amount used in the Cr–Mo steels. Experimental alloys with 0, 1, and 2% W were proposed to determine the effect of tungsten, and an alloy with tungsten and no vanadium and one with vanadium and no tungsten were suggested to determine the effect of these elements on properties [3]. Tantalum was added to a 9Cr–2WV steel to get a steel analogous to the 9Cr–1MoVNb steel. A carbon level of 0.1 to 0.15% was proposed for all steels to help ensure weldability. Of the Cr–Mo steels presently in the fusion reactor materials program, only the 12Cr–1MoVW steel has more carbon. That steel contains 0.2% C, which along with 0.5% Ni is used to eliminate delta ferrite in this high chromium alloy.

We have previously reported on the microstructure [5] and tempering and tensile behavior [6] of these experimental steels. In this paper, the impact behavior is presented. For fusion reactor applications, the impact behavior is extremely important, because neutron irradiation is known to increase the ductile–brittle transition temperature (DBTT) of ferritic steels. It is therefore of interest to have a low DBTT before irradiation.

EXPERIMENTAL PROCEDURE

Eight heats of steel[3] similar to those given in Table 1 were prepared by Combustion Engineering, Inc., Chattanooga, Tennessee. Melt compositions are given in Table 2. In addition to the nominal Cr, V, W, C, and Ta desired, the concentrations of other elements, such as Mn, P, Si, etc., were adjusted to levels typical of commercial practice.

All of the heats were air melted and then electroslag remelted (ESR) to obtain about 18 kg of usable material. The ESR ingot was hot rolled to 15.9 mm thick plates that were heat treated and used for making the impact specimens.

Tests were made on normalized and tempered steel.

[3]As a generic designation, the new class of steels will be referred to as Cr–W steels. (The only exception is the 2¼CrV steel, which contains no tungsten.) This follows the procedure used for the Cr–Mo steels, after which these steels are patterned, even though both types of steel may contain other alloying elements.

Table 2. Composition of Fast Induced-Radioactivity Decay (FIRD) Ferritic Steels

	Chemical Composition,[a] wt%							
Element	2¼Cr–¼V Heat 3785	2¼Cr–1W–¼V Heat 3786	2¼Cr–2W Heat 3787	2¼Cr–2W–¼V Heat 3788	5Cr–2W–¼V Heat 3789	9Cr–2W–¼V Heat 3790	9Cr–2W–¼V–Ta Heat 3791	12Cr–2W–¼V Heat 3792
C	0.11	0.10	0.11	0.11	0.13	0.12	0.10	0.10
Mn	0.40	0.34	0.39	0.42	0.47	0.51	0.43	0.46
P	0.015	0.015	0.016	0.016	0.015	0.014	0.015	0.014
S	0.006	0.006	0.005	0.006	0.005	0.005	0.005	0.005
Si	0.17	0.13	0.15	0.20	0.25	0.25	0.23	0.24
Ni	0.01	0.01	<0.01	<0.01				
Cr	2.36	2.30	2.48	2.42	5.00	8.73	8.72	11.49
Mo	0.01	<0.01	<0.01					
V	0.25	0.25	0.009	0.24	0.25	0.24	0.23	0.23
Nb	<0.01	<0.01	<0.01					
Ta	<0.01	<0.01	<0.01				0.075	
Ti	<0.01	<0.01	<0.01					
Co	0.005	0.006	0.008					
Cu	0.02	0.025	0.03					
Al	0.02	0.02	0.02	0.021	0.03	0.03	0.03	0.028
B	<0.001	<0.001	0.001					
W		0.03	1.99	1.98	2.07	2.09	2.09	2.12

[a]Balance iron.

The $2^1/_4$Cr–2W steel was normalized by annealing 1 hr at 900° C and air cooling. The other seven heats were annealed 1 hr at 1050° C and air cooled; the higher temperature was used for these steels to ensure that any vanadium carbide present was dissolved during the austenitization. Two tempering treatments were tested: 1 hr at 700° C and 1 hr at 750° C (the only exception to these tempering temperatures was for the $2^1/_4$Cr–1WV steel, which was tempered 1 hr at 725° C and 1 hr at 750° C).

Impact specimens were made from the 15.9 mm thick plate in accordance with ASTM specification E 23 with dimensions of 10 by 10 by 55 mm; specimens contained a 2 mm deep, 45 deg V-notch with a 0.25 mm root radius. All specimens were taken along the rolling direction with the notch running transverse to the rolling direction (L–T orientation). Each individual Charpy data set was fitted to a hyperbolic tangent function for obtaining the transition temperature and upper shelf energy.

RESULTS

A summary of the data is given in Table 3, where the DBTT and the upper shelf energy (USE) are given for each steel. The DBTT values given in the table were determined at 41 and 68 J levels; lateral expansion measurements were also made.

Impact curves are shown in Figure 1 for the $2^1/_4$Cr steels tempered at 750° C. The $2^1/_4$Cr–2W steel had the lowest DBTT and highest USE. For the vanadium containing $2^1/_4$Cr steels, the steel without tungsten had the highest DBTT, followed by $2^1/_4$Cr–1WV and $2^1/_4$Cr–2WV steels, which were similar. Data scatter was quite large for the $2^1/_4$Cr–1WV steel, and the one high point well removed from the trend of the other data points caused this curve fit to have a lower DBTT than would have been the case if this point had not been included. When tempered at 700° C (Table 3), the $2^1/_4$Cr–2W steel again had the best combination

Table 3. Impact Properties of FIRD Steels

Steel	Tempering Temperature[b] (°C)	Impact Properties[a] TT_{41J} (°C)	TT_{68J} (°C)	TT_{LE} (°C)	USE (J)
$2^1/_4$CrV	700	85	86	85	240
	750	66	69	70	318
$2^1/_4$Cr–1WV	725	52	53	52	220
	750	8	23	38	340
$2^1/_4$Cr-2W	700	24	24	12	260
	750	−41	−30	−31	324
$2^1/_4$Cr–2WV	700	85	110	112	131
	750	31	31	31	265
5Cr–2WV	700	−61	−46	−46	219
	750	−97	−76	−83	259
9Cr–2WV	700	7	26	33	157
	750	−69	−49	−42	217
9Cr–2WVTa	700	−47	−24	−20	181
	750	−95	−78	−82	258
12Cr–2WV	700	11	20	19	168
	750	−13	−2	−24	193
9Cr–1MoVNb	700	56	68	68	161
	750	27	41	41	199
12Cr–1MoVW	700	33	68	64	99
	750	4	29	26	115

[a] TT_{41J} is 41 J (30 ft-lb) transition temperature; TT_{68J} is 68 J (50 ft-lb) transition temperature; TT_{LE} is lateral expansion transition temperature as determined by 0.889 mm expansion; USE is upper shelf energy.

[b] All steels were tempered for 1 hr; before tempering all steels but the $2^1/_4$Cr–2W were normalized at 1050° C; the $2^1/_4$Cr–2W was normalized at 900° C.

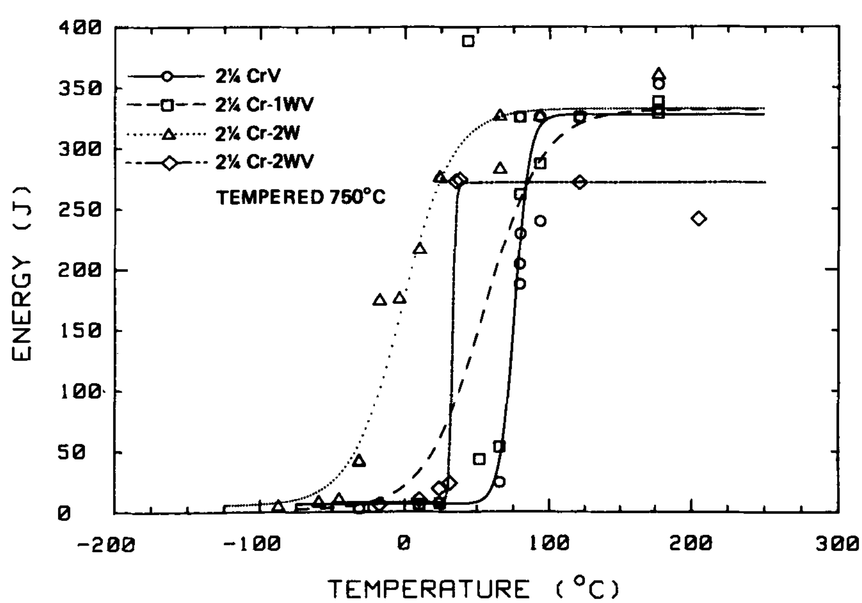

Fig. 1. The Charpy V-notch impact curves for $2^1/_4$CrV, $2^1/_4$Cr–1WV, $2^1/_4$Cr–2W, and $2^1/_4$Cr–2WV steels; all steels were tempered 1 hr at 750° C.

of DBTT and USE. The $2^1/_4$Cr–2WV steel had the worst properties for these tempering conditions. However, the DBTT values of all four steels were considerably above those obtained after tempering at 750° C.

In Figure 2, impact curves for the high chromium steels tempered at 750° C are shown. All of the steels had DBTT values well below room temperature; the 5Cr–2WV and 9Cr–2WVTa had properties that were superior to those of the 9Cr–2WV and 12Cr–2WV steels, although the latter steels had excellent properties after the 750° C temper. After tempering at 700° C, the relative behavior of the different steels remained the same (Table 3), but the DBTT was higher and the USE lower than after tempering at 750° C.

For comparison, Charpy impact tests were conducted on the 9Cr–1MoVNb and 12Cr–1MoVW steels (Table 3). Full-size Charpy specimens were machined from 15.9 mm thick plates that had been austenitized 1 hr at 1050° C, air cooled, and tempered 1 hr at 700° C and 1 hr at 750° C—the identical heat treatments used for the impact specimens of the experimental steels. A tempered martensite microstructure resulted for both of the Cr–Mo steels after such heat treatments.

A comparison of the properties for the Cr–Mo steels and the high chromium Cr–W steels indicated that the toughness of the Cr–W steels exceeded that for the Cr–Mo steels (Table 3). In Figure 3, a comparison is shown after the 750° C temper for the two Cr–Mo steels and their Cr–W analogs, the 9Cr–2WVTa and 12Cr–2WV steels. The 9Cr–2WVTa had the best properties, but the 12Cr–2WV steel also had better properties than those of the 9Cr–1MoVNb and 12Cr–1MoVW steels.

DISCUSSION

Normalized and tempered microstructures of the eight steels tested in this study have been discussed [5]. The $2^1/_4$CrV alloy had 30 to 35% tempered bainite, with the remainder being polygonal or proeutectoid ferrite. For the composition with 1% W—the $2^1/_4$Cr–1WV steel—the microstructure contained ~55% tempered bainite and 45% ferrite. Less polygonal ferrite was observed in the $2^1/_4$Cr–2W and $2^1/_4$Cr–2WV steels: the $2^1/_4$Cr–2W steel was essentially 100% bainite and the $2^1/_4$Cr–2WV steel contained 15 to 20% polygonal ferrite [5].

The 5Cr–2WV, 9Cr–2WV, and 9Cr–2WVTa steels were 100% tempered martensite [5]. However, the 12Cr–2WV steel contained approximately 25% delta ferrite, with the balance being martensite. The only major difference in the martensite of these four steels was that the 9Cr–2WVTa had a much finer prior austenite grain size than the other three steels [5]. The microstructures of the 9Cr–1MoVNb and 12Cr–1MoVW steels to which the Cr–W steels were compared were 100% tempered martensite after normalizing and tempering [7].

For fusion reactor applications, the impact properties are expected to be crucial. When irradiated by neutrons, the DBTT of the 12Cr–1MoVW steel can increase by over 200° C [8,9]. Therefore, it is desirable that any steel used for such applications have as low a DBTT as possible.

When the results for the Cr–W steels were compared against the results for 9Cr–1MoVNb and 12Cr–1MoVW steels for similar heat treatments (Table 3),

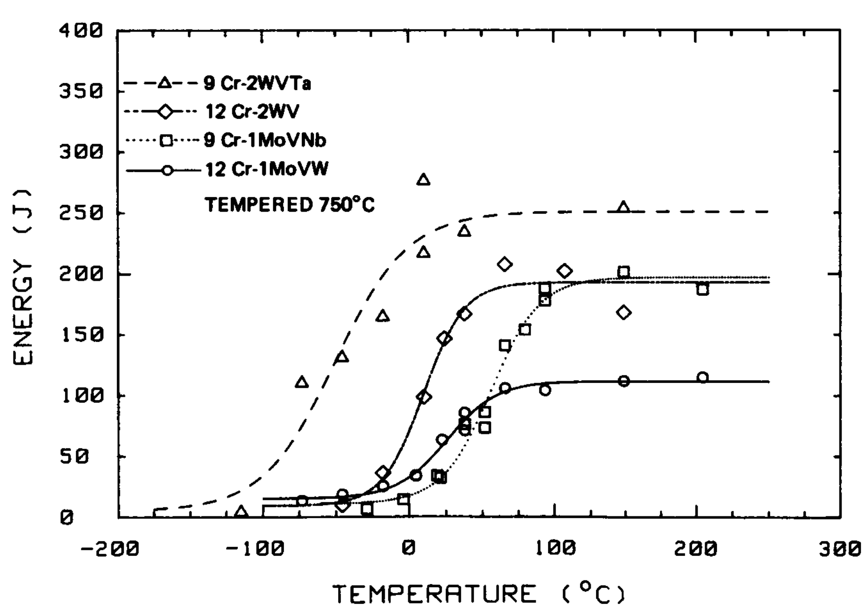

Fig. 2. The Charpy V-notch impact curves for 5Cr–2WV, 9Cr–2WV, 9Cr–2WVTa, and 12Cr–2WV steels; all steels were tempered 1 hr at 750° C.

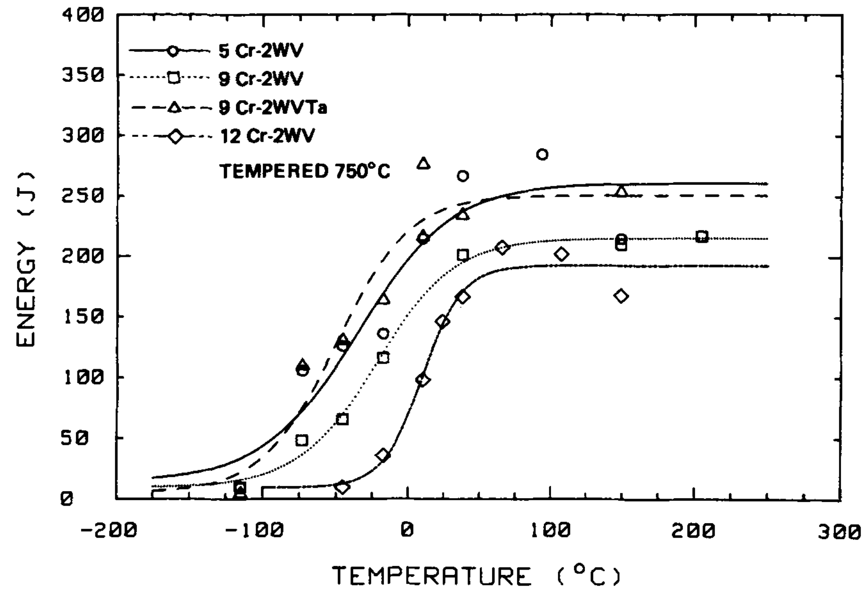

Fig. 3. A comparison of the Charpy V-notch impact curves for 9Cr–2WVTa and 12Cr–2WV steels with the curves for 9Cr–1MoVNb and 12Cr–1MoVW steels; all steels were tempered 1 hr at 750° C.

the properties of the 5Cr–2WV, 9Cr–2WV, 9Cr–2WVTa, and 12Cr–2WV steels were superior to those for 9Cr–1MoVNb and 12Cr–1MoVW steels. However, the results in Table 3 for the Cr–Mo steels are not for these steels heat treated to obtain optimum impact properties. A DBTT of −50° C and a USE of 255 J were obtained for this heat of 9Cr–1MoVNb steel when it was austenitized 1 hr at 1038° C and tempered for 1 hr at 760° C [9]. For the same heat of 12Cr–1MoVW steel austenitized 1 hr at 1050° C and tempered 2.5 hr at 780° C, a DBTT of −2.4° C and a USE of 115 J were obtained [10], which is similar to the values obtained for the 12Cr–2WV steel in the present work, even though the 12Cr–2WV steel contained 25% delta ferrite. For other heats of 12Cr–1MoVW steel, somewhat better values were obtained [10]. It should be noted, however, that heat treatment variations for the Cr–W steels could also lead to an improvement of the properties of these steels.

Investigators have concluded that small amounts of delta ferrite [11,12] cause an increase in the DBTT and a decrease in the USE in 12Cr–1MoVW steel. An increase in the DBTT of about 25° C was observed for a steel containing 1% delta ferrite [11] and an increase of 30 to 50° C was observed when about 5% delta ferrite was present in the microstructure [12]. Although the impact properties of the 12Cr–2WV steel containing 25% delta ferrite were not as good as those of the 5Cr and 9Cr steels that were entirely martensitic (Fig. 2), they were superior to the 9Cr–1MoVNb and 12Cr–1MoVW steels heat treated similarly (Fig. 3), even though the latter two steels were 100% martensite. When the results for the 12Cr–2WV steel are compared with those for the 12Cr–1MoVW, we conclude that it must be more than the delta ferrite in the 12Cr–1MoVW steel that causes the deterioration in properties. This conclusion is supported by impact data on 9Cr–2MoVNb that contained about 20% delta ferrite [13–15], which also had superior properties to those of 12Cr–1MoVW steel. These results plus those of the present study indicate that the inferior properties of the 12Cr–1MoVW steel are not caused by the delta ferrite, but may be due to the higher carbon content of the 12Cr–1MoVW steel (the 12Cr–1MoVW steel contains 0.2% C against ~0.1% C for the 12Cr–2WV steel). Carbon is known to adversely affect impact properties [16]. The higher carbon content has been found to result in large amounts of precipitate [7], including precipitate at martensite–delta ferrite boundaries [12], which could degrade the impact properties.

From these results, it appears that the use of a duplex structure of martensite and delta ferrite should not be ruled out on the basis of impact properties. However, the 12Cr–2WV steel must be ruled out at present because its strength was not as good as the strength of the 9Cr steels and the 2$^1/_4$Cr–2WV steel [6].

Although these steels are still at an early stage of development, the impact properties of the 2$^1/_4$Cr–2WV steel were somewhat disappointing, in view of the excellent tensile properties of this steel [6]. Yield stress and ultimate tensile strength values for this steel were as good or better than those for 9Cr–2WV and 9Cr–2WVTa steels and approached the values for 9Cr–1MoVNb and 12Cr–1MoVW steels [6]. A mixed structure of tempered bainite and polygonal ferrite—the microstructure of the 2$^1/_4$Cr–2WV steel—is known to result in inferior impact behavior compared to a steel with a microstructure made up of a single constituent [17]. This may explain why the $2^1/_4$Cr–2W steel had the best impact behavior of the $2^1/_4$Cr steels (Table 3 and Fig. 2).

The observation that the impact behavior of a bainitic steel is superior to one containing polygonal ferrite means that it should be possible to improve the impact properties of the $2^1/_4$Cr–2WV steel by heat treatment and by increasing the hardenability. By proper alloying, the hardenability of the steel can be increased and the ferrite eliminated. Finally, the type of bainite that forms can also affect the impact properties [18]; the type of bainite, in turn, depends on the hardenability.

SUMMARY AND CONCLUSIONS

By eliminating molybdenum and niobium from steels used for fusion reactor structural components, induced radioactivity will decay faster, which will allow simpler radioactive waste disposal techniques for these reactor components when they are discarded after service. Such fast induced-radioactivity decay (FIRD) ferritic steels are being developed. The steels are patterned on the conventional ferritic steels being considered as candidates for fusion reactor applications—$2^1/_4$Cr–1Mo, 9Cr–1MoVNb, and 12Cr–1MoVW steels. In these steels, tungsten was used as a replacement for molybdenum, and tantalum was substituted for niobium.

To determine the effect of Cr, W, V, and Ta, eight heats of steel were obtained. Alloys containing 2% W (an atom-for-atom replacement of molybdenum in the Cr–Mo steels) and 0.25% V were produced for chromium levels of $2^1/_4$, 5, 9, and 12% (designated $2^1/_4$Cr–2WV, 5Cr–2WV, 9Cr–2WV, and 12Cr–2WV). A 9Cr–2WV steel with 0.07% Ta (9Cr–2WVTa) and $2^1/_4$Cr steels with 0.25% V and 0 and 1% W ($2^1/_4$CrV and $2^1/_4$Cr–1WV) and with 2% W and no vanadium ($2^1/_4$Cr–2W) were also produced. Carbon was maintained at 0.1% for all of the steels.

Impact properties of the 5Cr–2WV, 9Cr–2WV, 9Cr–2WVTa, and 12Cr–2WV steels were superior to those for 9Cr–1MoVNb and 12Cr–1MoVW steels when all steels were given similar heat treatments. The excellent impact properties of the 12Cr–2WV steel occurred despite the 25% delta ferrite in the microstructure. Impact properties of the $2^1/_4$Cr–2WV steel, which had excellent tensile properties relative to the other Cr–W steels, were inferior to those of the high chromium (5–12% Cr) steels. This was attributed to microstructure, and the development of a low chromium FIRD steel with good strength and impact behavior should be possible with further alloying and proper heat treatment.

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