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Effect of rhenium and osmium on mechanical properties of a 9Cr–2W–0.25V–0.07Ta–0.1C steel ☆

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Abstract

The nuclear transmutation of tungsten to rhenium and osmium in a tungsten-containing steel irradiated in a fission or fusion reactor will change the chemical composition of the steel. To determine the possible consequences of such compositional changes on the mechanical properties, tensile and Charpy impact properties were measured on five 9Cr–2W–0.25V–0.07Ta–0.1C steels that contained different amounts of rhenium, osmium, and tungsten. The mechanical properties changes caused by these changes in composition were minor. Observations were also made on the effect of carbon concentration. The effect of carbon on tensile behavior was minor, but there was a large effect on Charpy properties. Several of the steels showed little effect of tempering temperature on the Charpy transition temperature, a behavior that was tentatively attributed to the low silicon and/or manganese concentration of the experimental steels. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Irradiation of the first wall and blanket structure of a fusion power plant by neutrons from the fusion reaction will induce the transmutation of constituent elements of the structural material, which will result in the replacement of a transmuted atom with one solid and one gas (helium or hydrogen) atom in the matrix of the material. This production of solid radioactive transmutants is the impetus for the development of reduced-activation ferritic steels designed to ameliorate the radioactive waste disposal of components of a fusion power plant after its service lifetime [1]. Efforts have been made to determine the effect of the gaseous helium and hydrogen formed this way on the mechanical properties of the material. However, it has generally been assumed that the solid transmutants will have little effect on the mechanical properties, since for most cases only small amounts of such elements are expected to form and only small amounts of the elements of the structural material will be transmuted.

Recently, Greenwood and Garner [2] pointed out that significant amounts of transmutants can be produced when certain materials are irradiated in the fission reactors being used in the United States Department of Energy Fusion Reactor Materials Program. They concluded that the effect is most acute for certain elements irradiated in the High Flux Isotope Reactor (HFIR) [2], because of the thermal neutrons present in the mixed spectrum of this reactor. The HFIR is the principle fission reactor used in the United States Fusion Materials Program. Identified elements of concern included molybdenum, tungsten, vanadium, and rhenium [2].

Tungsten is important because it has been used in the new reduced-activation steels as a replacement for molybdenum [1]. Steels with 9% Cr and 2% W (all compositions are in wt% unless otherwise stated) are the leading candidate reduced-activation steels under consideration for fusion first wall and blanket applications.

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Fig. 1, taken from Greenwood and Garner [2], shows that a considerable portion of the tungsten could be burned out of the steel during irradiation in the Fast Flux Test Facility (FFTF), in HFIR, and in the conceptual fusion power plant STARFIRE. Tungsten transmutes to rhenium [2], and then much of the rhenium transmutes to osmium. This change in composition for a steel with 2% W could significantly affect the tungsten composition of the steel, and thus, it could conceivably affect the mechanical properties. The largest effect occurs for HFIR (Fig. 1). Therefore, if the mechanical properties are affected by the change in composition, the properties could change due to irradiation in a fission reactor, such as HFIR or FFTF [2], or due to irradiation in a fusion power plant.

Tensile and Charpy impact properties were measured on steels of nominal composition Fe–9Cr–2W–0.25V–0.07Ta–0.1C (9Cr–2WVTa) with and without the addition of rhenium and osmium to determine if these elements have a significant effect on the mechanical properties. The 9Cr–2WVTa steel was used as the base because this is a reduced-activation steel with excellent properties in the normalized-and-tempered condition [3–5] and after irradiation [6].

2. Experimental procedure

Small 450-g vacuum arc-melted button heats of 9Cr–2WVTa steel and this composition with various levels of rhenium and osmium were made. Compositions of the experimental steels are given in Table 1.

Rhenium and osmium were added to the basic 9Cr–2WVTa composition with the objective of producing steels with 0.2 Re and 0.2 Os (ReOs-1), 0.1 Re and 0.6 Os (ReOs-2), and a third steel with the latter combination of rhenium and osmium, but with less tungsten to account for the tungsten that is transmuted during irradiation (ReOs-3). The first attempt to produce ReOs-3 resulted in an alloy with twice the desired carbon (ReOs-4), and although this high carbon was beyond that for the 9Cr–2WVTa, the steel was still included in the tests as it provided an opportunity to examine the effect of carbon on the mechanical properties of this type of steel. As a control, a 9Cr–2WVTa steel without any rhenium or osmium additions (ReOs-0) was produced by the same process used to produce the other steels.

Chemical analyses of the heats of steel indicated that the rhenium and osmium values achieved were close to those desired; the Os of the high-Os steels was measured as ≈0.8% instead of the 0.6% desired (Table 1). Further, the objective for ReOs-3 was to reduce the 2% W in proportion to the amount of rhenium and osmium added, resulting in a 1.25% W steel. However, because the tungsten was high in the other steels (closer to 2.25%

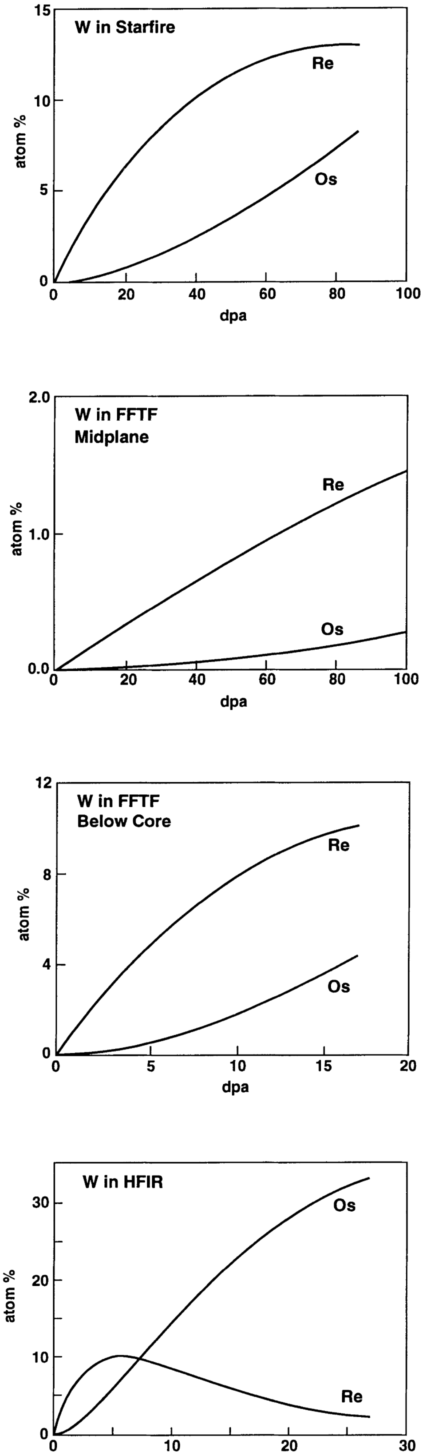

Fig. 1. The calculated transmutation of tungsten to rhenium and osmium in the conceptual fusion reactor STARFIRE, in two positions of the Fast Flux Test Facility (FFTF), and in the High Flux Isotope Reactor (HFIR). Taken from Greenwood and Garner [2].

Table 1
Chemical composition of steels (wt%)[a]

Element	ReOs-0	ReOs-1	ReOs-2	ReOs-3	ReOs-4	18-kg Heat
C	0.081	0.077	0.078	0.060	0.20	0.11
Mn	0.01	0.01	0.01	0.02	0.01	0.44
P	0.007	0.004	0.006	0.012	0.003	0.015
S	0.006	0.005	0.006	0.005	0.007	0.008
Si	0.09	0.20	0.10	0.06	0.01	0.21
Cr	8.96	8.76	8.76	8.72	8.76	8.90
V	0.20	0.21	0.20	0.23	0.21	0.23
Ta	0.06	0.06	0.08	0.06	0.07	0.06
W	2.17	2.29	2.26	1.47	1.58	2.01
Os		0.25	0.79	0.76	0.84	
Re		0.20	0.07	0.11	0.14	
Fe	Balance	Balance	Balance	Balance	Balance	Balance

[a] ReOs-0: 9Cr–2WVTa; ReOs-1; 9Cr–2WVTa–0.2Re–0.2Os–0.1C; ReOs-2: 9Cr–2WVTa–0.1Re–0.8Os–0.1C; ReOs–3: 9Cr–1.5WVTa–0.1Re–0.8Os–0.1C; ReOs-4: 9Cr–1.5WVTa–0.1Re–0.8Os–0.2C; all of these heats were produced a 450-g button melts. The 18-kg heat was a 9Cr–2WVTa steel produced separately.

instead of 2%), ReOs-3 and ReOs-4 contained ≈1.5% W. The five steels will be referred to as 9Cr–2WVTa (ReOs-0), 9Cr–2WVTa–0.2Re–0.2Os (ReOs-1), 9Cr–2WVTa–0.1Re–0.8Os (ReOs-2), 9Cr–1.5WVTa–0.1Re–0.8Os–0.1C (ReOs-3), and 9Cr–1.5WVTa–0.1Re–0.8Os–0.2C (ReOs-4).

The 9Cr–2WVTa was meant to be a reproduction of a larger heat (18 kg) of this composition produced for the original work to develop the reduced-activation steels and for which a range of data have been obtained [3–5]. The small 450-g heat of 9Cr–2WVTa was used as the control for this experiment in order to compare steels made by the same process. The nominal composition of the large heat for Cr, W, V, and Ta, the primary alloying elements, was achieved in the small heat (Table 1). However, the silicon and manganese contents of the 18-kg heat were adjusted to ≈0.2% Si and ≈0.45% Mn [3], which are typical compositions for these elements when such steels are produced by a commercial vendor. The small heats for the present study were made from the individual elements (no manganese or silicon added) and contained less manganese and, in most cases, less silicon: the manganese level was 0.01–0.02%, and silicon varied from 0.01% to 0.2% (Table 1). Carbon concentration was also different: in the small heats where the objective was a heat with 0.1% C, analyses indicated that it varied from 0.06% for ReOs-3 to ≈0.08% for the other three heats, compared to 0.11% in the larger heat. The ReOs-4 was analyzed as containing 0.2% C. For the general discussion of the steels, they will be referred to as containing ≈0.1 and ≈0.2% C.

Half of each 12.7 × 25.4 × 127 mm^3 ingot was hot rolled to a thickness of 6.4 mm and half to a thickness of 0.76 mm. Mechanical properties tests were made on normalized-and-tempered steel. Normalization consisted of austenitizing the steel for 0.5 h at 1050°C in a helium atmosphere, after which it was quickly cooled in flowing helium. Specimens were tested in two tempered conditions: 1 h at 700°C and 1 h at 750°C.

Tensile specimens 44.5-mm long with a reduced gage section of 20.3 × 1.52 × 0.76 mm^3 were machined from the 0.76-mm sheet with gage lengths parallel to the rolling direction. The specimens were heat treated after machining. Tensile tests were conducted over the range room temperature to 600°C in vacuum on a 44-kN Instron universal testing machine at a nominal strain rate of $\approx 4 \times 10^{-4}$ s^{-1}.

One-third-size Charpy specimens 3.3 × 3.3 × 25.4 mm^3 with a 0.51-mm-deep 30° V-notch and a 0.05–0.08-mm-root radius were machined from the normalized 6.4-mm plate along the rolling direction with the notch transverse to the rolling direction. Specimens were tempered after machining. Charpy tests were carried out in a pendulum-type impact machine specially modified to accommodate subsize specimens [7]. The absorbed energy values were fitted with a hyperbolic tangent function to permit the upper-shelf energy (USE) and ductile–brittle transition temperature (DBTT) to be evaluated. The DBTT was determined at the energy midway between the upper- and lower-shelf energies. Note that for these miniature specimens different DBTT and USE values are obtained than for full-size specimens. However, it has been shown that a low transition temperature for miniature specimens translates to a low value for full-size specimens [8–10]. A correlation likewise exists for the USE [8–10].

3. Results

3.1. Metallography and microhardness

The steels were examined by optical microscopy. All of the microstructures were 100% tempered martensite.

There was some variation in the estimated prior-austenite grain size, determined by comparing the microstructure with ASTM Grain Size charts. The three steels with 2% W and different amounts of Re and Os had similar grain sizes (Table 2), while the two steels with 1.5% W had different values: the 1.5% W steel containing ≈0.1% C (ReOs-3) had the largest grain size of all five steels, and the 1.5% W steel with 0.2% C (ReOs-4) had the smallest grain size of the steels.

Hardnesses showed a relatively small variation (Table 2), with the 2% W steel with 0.2% Re and 0.2% Os (ReOs-1) having the lowest hardness. There was less variation among the other steels. The 1.5% W steel containing 0.2% C had the highest hardness.

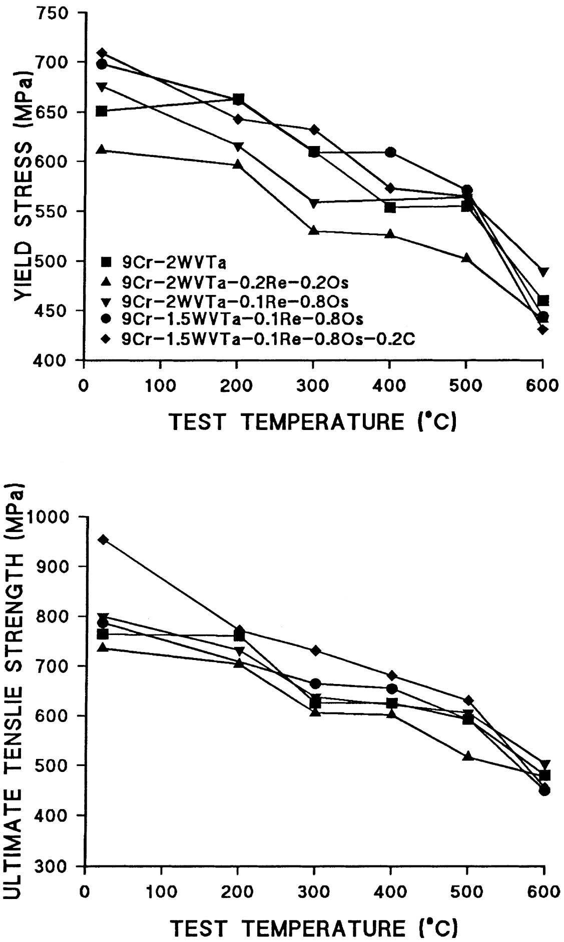

Fig. 2. Yield stress and ultimate tensile strength as a function of test temperature for 9Cr–2WVTa steels containing varying amounts of rhenium and osmium after normalizing and tempering 1 h at 700°C.

3.2. Tensile behavior

There was considerable variation in the strength (Figs. 2 and 4) and ductility (Figs. 3 and 5) among the different heats. The amount of variation for the yield stress (YS) (Figs. 2 and 4) was greatest for the room temperature tests and least at 600°C. Variability was less for the ultimate tensile strength (UTS) of the different steels (Figs. 2 and 4) than for the YS, but again, the variation for the UTS was greatest at the lowest temperatures. At most test temperatures below 600°C, the YS and UTS of the 9Cr–2WVTa–0.2Re–0.2Os steel (ReOs-1) were the lowest. The steels with 1.5% W, 0.8% Os and 0.1% Re with 0.1% C (ReOs-3) and 0.2% C (ReOs-4) were near the strongest of all the steels below 600°C. There was little difference between the YS of those two steels below 600°C, but the UTS of the steel with 0.2% C (ReOs-4) was generally the highest of these two steels as well as of the other steels below 600°C. At 600°C, the YS of the steel with 0.2% C was near the lowest for all the steels.

The variation in ductility – uniform and total elongation – among the steels was also quite wide after both the 700°C (Fig. 3) and 750°C (Fig. 5) tempering treatments (Fig. 5). The relative ductilities of the steels were not always inverse to the strength, as might be expected. For example, the 1.5% W steel with 0.1% C (ReOs-3) generally had the lowest uniform and total elongation, while the steel with 0.2% C (ReOs-4) often had the

Table 2
Microhardness and prior austenitized grain size of steels[a]

Steel[b]	Vickers hardness (average of five readings)	Prior austenite grain size μm (ASTM No.)
ReOs-0	253.8	16 (9)
ReOs-1	235.0	15 (9.25)
ReOs-2	254.6	16 (9)
ReOs-3	246.8	20.5 (8.25)
ReOs-4	262.7	9.5 (10.25)
18-kg Heat	251.3	19 (8.5)

[a] Measurements were made on the steels in the normalized-and-tempered condition.

[b] ReOs-0: 9Cr–2WVTa; ReOs-1; 9Cr–2WVTa–0.2Re–0.2Os–0.1C; ReOs-2: 9Cr–2WVTa–0.1Re–0.8Os–0.1C; ReOs-3: 9Cr–1.5WVTa–0.1Re–0.8Os–0.1C; ReOs-4: 9Cr–1.5WVTa–0.1Re–0.8Os–0.2C; all of these heats were produced as 450-g button melts. The 18-kg heat was a 9Cr–2WVTa steel produced separately.

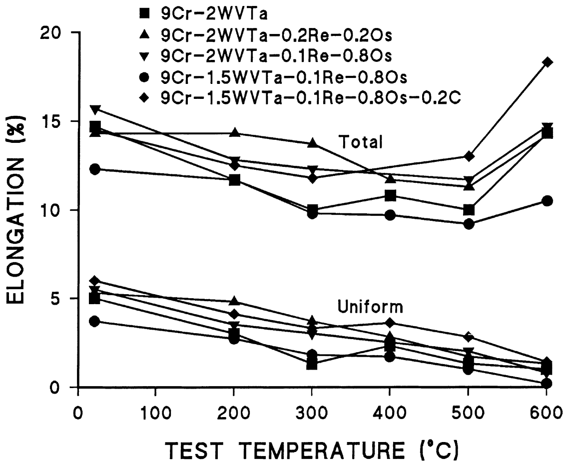

Fig. 3. Uniform and total elongation as a function of test temperature for 9Cr–2WVTa steels containing varying amounts of rhenium and osmium after normalizing and tempering 1 h at 700°C.

highest ductility, even though these were two of the strongest steels. The total elongation of all the steels increased with temperature above 400–500°C, with the largest change occurring for the steel with 0.2% C. The uniform elongation generally decreased continuously with increasing test temperature from room temperature to 600°C.

Yield stress results for the small 450-g heat and the large 18-kg heat of 9Cr–2WVTa steel at room temperature and 600°C are compared in Table 3. The 18-kg heat was substantially stronger than the small heat.

3.3. Charpy impact properties

The ductile–brittle transition temperature (DBTT) and upper-shelf energy (USE) for the steels tempered at 700°C and 750°C are given in Table 4 and Fig. 6; Charpy curves are shown in Figs. 7 and 8 for the steels tempered at 700°C and 750°C, respectively.

There were only small differences in DBTT for all the steels with 0.1% C, and all the DBTTs of these steels were lower than for the steel with 0.2% C (Figs. 6–8). As expected, the USE of all five steels was higher after the 750°C temper than after the 700°C temper (Fig. 6). There was little difference in the USE values for the four steels with 0.1% C, and these were higher than for the steel with 0.2% C.

The lower DBTT after the 750°C temper than after the 700°C temper observed for the 9Cr–2WVTa and the 9Cr–2WVTa–0.1Re–0.8Os–0.1C steels was the expected behavior, since the strength decreases with increasing tempering temperature. What was not expected was the relatively small difference in DBTT for the other three steels after the different tempering treatments. These steels showed essentially no effect of tempering temperature on the DBTT (Table 4 and Fig. 6). For some of the steels (ReOs-3 and ReOs-4), the measured values after tempering at 700°C were actually lower than after tempering at 750°C, but this may occur because there is little difference in the transition region for the different tempering conditions, which would make the steel with the highest USE (the one tempered at 750°C) have the highest DBTT because of the way the DBTT was determined. Note that although little effect of tempering was observed for the three steels, a relatively small number of specimens was tested in the transition region; the error inherent in the measurement of the DBTT is estimated at ±15°C.

The 450-g heat of 9Cr–2WVTa steel used in this experiment had a lower DBTT and a relatively smaller

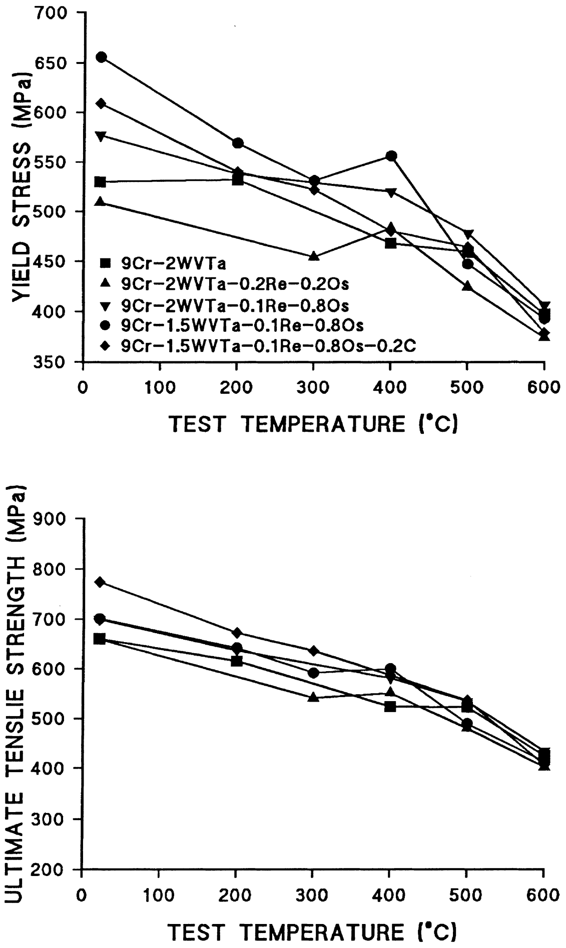

Fig. 4. Yield stress and ultimate tensile strength as a function of test temperature for 9Cr–2WVTa steels containing varying amounts of rhenium and osmium after normalizing and tempering 1 h at 750°C.

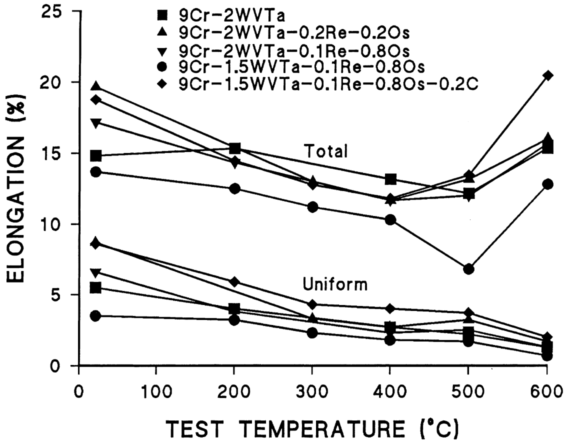

Fig. 5. Uniform and total elongation as a function of test temperature for 9Cr–2WVTa steels containing varying amounts of rhenium and osmium after normalizing and tempering 1 h at 750°C.

difference in DBTT after tempering at 700°C and 750°C than the 18-kg heat tested previously (Table 3). The DBTTs of the large heat after tempering at 700°C and 750°C were −43°C and −88°C, respectively, compared to −103°C and −120°C, respectively, for the small heat. The small heat also had a significantly higher USE in each case (Table 3).

4. Discussion

During irradiation of a tungsten-containing material in a fission test reactor such as the mixed-spectrum HFIR or the fast reactor FFTF, or in a future fusion reactor, tungsten will transmute to rhenium, much of which will subsequently transmute to osmium (Fig. 1) [2]. The objective of these experiments was to determine the possible effects that rhenium and osmium and the substitution of rhenium and osmium for tungsten could have on the mechanical properties of the 9Cr–2WVTa steel. After tungsten is irradiated to ≈25 dpa in HFIR, ≈32% will be transmuted to ≈29% Os and ≈3% Re. For the 2% W in the 9Cr–2WVTa steel, this means ≈0.58% Os and ≈0.06% Re form, thus reducing the tungsten composition by about 0.64%.

Experimental steels containing 0.6% Os and 0.1% Re were proposed for this study. The actual alloys produced contained somewhat more osmium. Additionally, the tungsten was somewhat higher than desired (Table 1). Of course, for neutron-irradiated material, the mechanical properties after irradiation will also be affected by radiation damage, whereas the results obtained here just provide information on the effect of osmium and rhenium on the properties of the 9Cr–2WVTa steel.

Intuitively, no large change in the mechanical properties of 9Cr–2WVTa steel would be expected from the substitution of rhenium and osmium for tungsten. Most

Table 3
A comparison of properties of the 450-g and 18-kg heats of 9Cr–2WVTa steel

Heat size	Tempering temperature	YS (MPa)		UTS (MPa)		Charpy[a]	
		RT	600°C	RT	600°C	TT(°C)	USE (J)
450-g	1 h at 700°C	651	460	764	481	−103	13.7
	1 h at 750°C	530	397	661	425	−120	15.4
18-kg	1 h at 700°C	823	651	942	696	−43	7.5
	1 h at 750°C	645	489	774	526	−88	11.2

[a] Charpy V-notch specimens: 3.3 × 3.3 × 25.4 mm^3, 0.51 mm deep notch.

Table 4
Charpy impact properties of steels[a]

Steel	Tempering temperature	Transition temperature (°C)	Upper-shelf energy (J)
9Cr–2WVTa	1 h at 700°C	−103	13.7
	1 h at 750°C	−120	15.4
9Cr–2WVTa–0.2Re–0.2Os–0.1C	1 h at 700°C	−103	12.7
	1 h at 750°C	−105	14.2
9Cr–2WVTa–0.1Re–0.8Os–0.1C	1 h at 700°C	−102	13.3
	1 h at 750°C	−133	14.3
9Cr–1.5WVTa–0.1Re–0.8Os–0.1C	1 h at 700°C	−114	12.6
	1 h at 750°C	−113	13.8
9Cr–1.5WVTa–0.1Re–0.8Os–0.2C	1 h at 700°C	−84	8.6
	1 h at 750°C	−78	9.4

[a] Charpy V-notch specimens: 3.3 × 3.3 × 25.4 mm^3, 0.51 mm deep notch.

of the tungsten in the 9Cr–2WVTa is present in solid solution with small amounts present in $M_{23}C_6$ and still smaller amounts in the of MC in the steel [11]. Therefore, most of the rhenium and osmium should go into solution, and since there is less than a 4% difference between the atomic radii of the W, Re, and Os atoms [12], relatively little effect on the mechanical properties would be expected.

The objective of testing the two Re–Os alloys with 2% W (9Cr–2WVTa–0.2Re–0.2Os and 9Cr–2WVTa–0.1Re–0.8Os) was to determine the effect of the rhenium and osmium by comparing the results with the 9Cr–2WVTa (Figs. 2–6). The steel with 0.2% Re and 0.2% Os was generally the weakest of the five steels tested. The 9Cr–2WVTa and 9Cr–2WVTa–0.1Re–0.8Os steels had similar strengths and ductility that were more in line with those of the two 1.5% W steels with 0.8% Os and 0.1% Re, one with ≈0.1% C (like the other three steels) and one with 0.2% C.

When the tungsten concentration was reduced from ≈2% to ≈1.5% with no change in carbon, the 1.5% W steel was generally the strongest – at least below 600°C, indicating no adverse effect on strength due to the replacement of tungsten by rhenium and osmium. The stronger 1.5% W steel with ≈0.1% C generally had the lowest uniform and total elongation of the five steels. On the other hand, the 1.5% W steel with ≈0.1% C had a strength similar to the 1.5% W steel with ≈0.2% C, but the steel with 0.2% C was close to having the highest ductility of the five steels. A possible explanation is that for the higher carbon content not all carbides are dissolved during austenitization, which could cause the smaller prior austenite grain size of this steel (Table 2), which may affect ductility. Whether undissolved carbides remained during austenitization needs to be verified by transmission electron microcopy (TEM).

The Charpy properties of the four steels containing 0.1% C were quite similar (Fig. 6), with the only unusual observation being that there was essentially no difference in the DBTT after the 700°C and 750°C tempers for the 9Cr–2WVTa–0.2Re–0.2Os–0.1C and 9Cr–1.5WVTa–0.1Re–0.8Os–0.1C steels. There was also a relatively small difference in DBTT after the two heat treatments for the 9Cr–2WVTa steel. The USE of the steels after the 750°C temper was always greater than after the 700°C temper.

Charpy properties of the steel with 1.5% W and 0.2% C reflected the carbon content, as this steel had the highest DBTT and the lowest USE of all five steels (Fig. 6); this occurred despite the high-carbon steel having the smallest prior austenite grain size and not necessarily always being the strongest of the steels. This was probably due to larger carbides and/or carbide number density in this steel, although that needs to be verified by TEM. The DBTT of the steel with 0.2% C also showed little effect of tempering temperature.

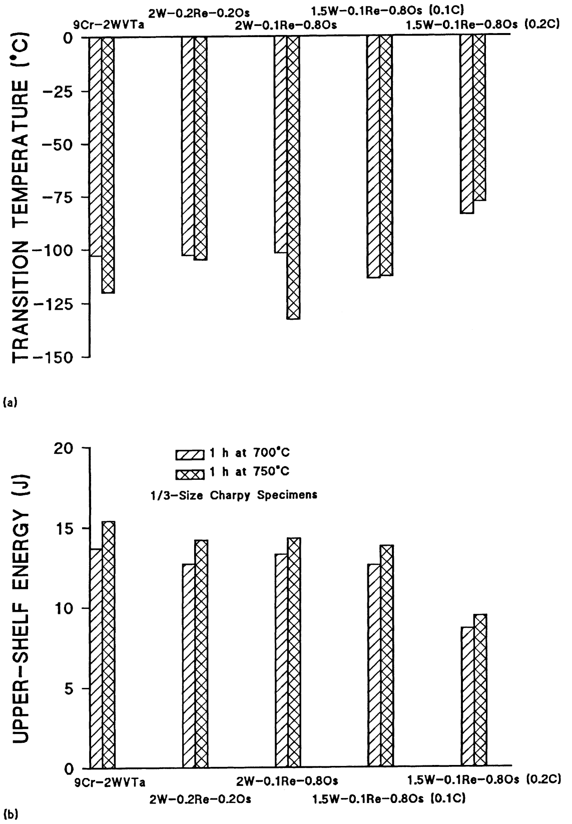

Fig. 6. Transition temperature and upper-shelf energy for 1/3-size Charpy specimens of 9Cr–2WVTa steels containing varying amounts of rhenium and osmium after normalizing and tempering 1 h at 700°C and 1 h at 750°C.

The reason for the apparent lack of effect of tempering temperature on these experimental steels is not known. Experimental error was mentioned in the previous section, but that would seem unlikely to produce a similar unexpected result for three materials with a relatively minor difference for a fourth. In all cases, these steels did have the expected effect of tempering temperature on USE (i.e., the USE was always higher for the higher tempering temperature).

The results of these tests give little indication that the tensile and Charpy properties will be affected significantly by the amounts of rhenium and osmium estimated to form in a 9Cr–2WVTa steel irradiated to ≈25 dpa in HFIR. Likewise, the reduction of tungsten that would accompany the increase in rhenium and osmium also appears to have little effect – at least in the presence of the additional Re and Os. Under the influence of irradiation at temperatures below ≈400°C where irradiation hardening is expected, the effect of the compositional changes would probably be of even less significance.

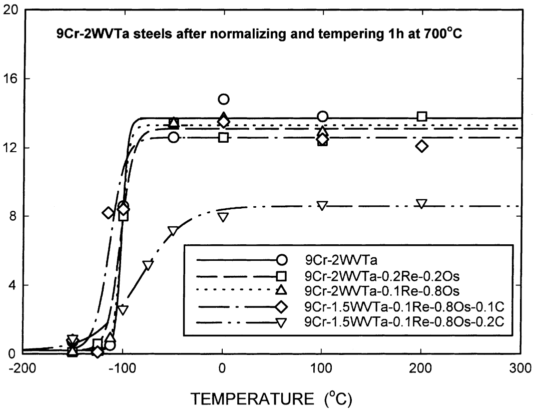

Fig. 7. Charpy curves for 1/3-size specimens of 9Cr–2WVTa steels containing varying amounts of rhenium and osmium after normalizing and tempering 1 h at 700°C.

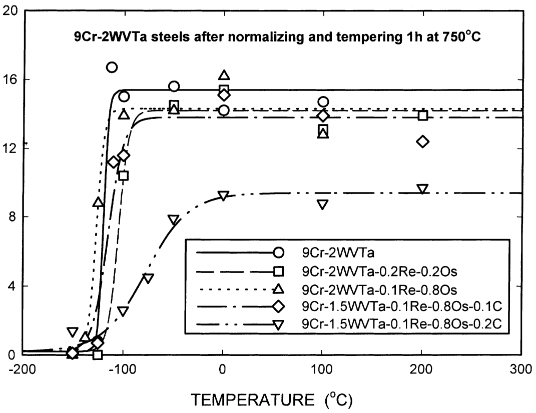

Fig. 8. Charpy curves for 1/3-size specimens of 9Cr–2WVTa steels containing varying amounts of rhenium and osmium after normalizing and tempering 1 h at 750°C.

The largest effect of composition on mechanical properties involved the apparent effect of carbon concentration on the Charpy properties (Figs. 6–8). Although there was relatively little difference in the strength of the 1.5% W steels with ≈0.1 and 0.2% C, there was a substantial difference in the DBTT and USE. Carbon can play a role on the Charpy properties through its effect on the strength and through the amounts, sizes, and morphology of the carbides formed. Since there was relatively little difference in strength for the two steels, the difference in the carbides in the two steels must be the cause, especially since the steel with 0.2% C had a much smaller prior austenite grain size than the steel with ≈0.1% C.

The difference in properties noted between the small (450-g) heat of steel (0.08% C) produced for this experiment and the larger (18-kg) heat (0.11% C) previously studied [3–6] may also be at least partially due to the difference in carbon concentration. As Table 3 indicates, the large heat is stronger and has a higher DBTT and lower USE. These two heats had similar prior austenite grain sizes. Lath size differences could have an effect, but lath size was not determined. Without further experiments, it is not possible to determine if the difference in properties for these two steels is attributable to the carbon, but based on the small difference in the strength of the 1.5% W steels with ≈0.1% C (measured as 0.06%) and ≈0.2% C, there would appear to be other reasons for the difference in strength. There may also to be other reasons for the differences in Charpy properties. That is, the DBTTs of the 1.5% W steels with ≈0.1 and ≈0.2% C after tempering at 700°C were −114°C and −84°C, respectively, and after tempering at 750°C they were −113°C and −78°C, respectively. This compares with the 450-g heat of 9Cr–2WVTa steel that had DBTTs of −103°C and −120°C after tempering at 700°C and 750°C, respectively, compared to the DBTTs of the 18-kg heat of −43°C and −88°C, respectively. The relative difference for the latter steels, especially after the 700°C temper, seems to be somewhat greater than for that attributed to carbon for the 1.5% W steels, especially when it is considered that there is much less difference in carbon for the 450-g and 18-kg heats of 9Cr–2WVTa steels. There is also a smaller change with tempering temperature for the 450-g heat than the 18-kg heat (17°C vs. 45°C).

As pointed out in a previous section, the 9Cr–2WVTa steels also contained different amounts of manganese and silicon; both manganese and silicon are thought to strengthen by solid solution hardening [13]. If this is the case here, then the increased strength and reduced Charpy properties of the large heat might also be partially attributed to the higher silicon and manganese in the 18-kg heat, which contains about 40 times more manganese (0.44 vs. 0.01) and twice as much silicon (0.21 vs. 0.09). Again, further work is required to make a clear determination on the cause for the differences that have been observed. Should manganese be the cause, that could be important because large amounts of manganese are expected to form in such a steel by transmutation in a magnetically confined fusion reactor [14].

When reasons for the observations of little or no change in DBTT with tempering temperature for the steels of this experiment (Table 5) compared to similar steels in previous experiments are considered [5], manganese and silicon concentration differences for the heats of this experiment and heats used previously appear to be the only possible reasons that can be cited. Further work is required to elucidate a relationship to the manganese and silicon composition. If such a relationship exists, it might be possible to exploit it in the development of steels for fusion and other applications.

5. Summary and conclusions

Tensile and Charpy impact properties were determined for the following five steels: 9Cr–2WVTa, 9Cr–2WVTa with additions of ≈0.2% Re and ≈0.2% Os, 9Cr–2WVTa with additions of ≈0.1% Re and ≈0.8% Os, a 9Cr–1.5WVTa with additions of ≈0.1 Re and ≈0.8 Os (all four of these steels contained ≈0.1% C), and a 9Cr–1.5WVTa with additions of ≈0.1 Re, ≈0.8 Os, and ≈0.2% C.

There were only minor variations in the tensile properties due to the addition of the rhenium and osmium to the 9Cr–2WVTa composition or the replacement of the tungsten in that composition by rhenium and osmium. The change in carbon concentration had the major effect on the Charpy impact properties by causing an increase in the transition temperature and a reduction in the USE. For most of the experimental steels, there was little difference in the transition temperature after tempering at 700°C and 750°C, much less than for a heat of 9Cr–2WVTa tested previously. A smaller amount of silicon and manganese in the steels used in the present experiments may be the cause for these differences, although that needs to be verified. The results indicate that no large effect on strength and impact toughness is expected to be caused by the transmutation of tungsten to rhenium and osmium when tungsten-containing steels are irradiated in HFIR.

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