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Substitution of Modified 9 Cr-1 Mo Steel for Austenitic Stainless Steels

V. K. Sikka

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SUBSTITUTION OF MODIFIED 9 Cr-1 Mo STEEL FOR AUSTENITIC STAINLESS STEEL*

V. K. Sikka

ABSTRACT

This report describes the current program to develop a high-strength ferritic-martensitic steel. The alloy is essentially Fe—9% Cr—1% Mo with small additions of V and Nb and is known as modified 9 Cr-1 Mo steel. Its elevated-temperature properties and design allowable stresses match those of type 304 stainless steel for temperatures up to 600°C and exceed those of other ferritic steels by factors of 2 to 3. The improved strength of this alloy permits its use in place of stainless steels for many applications. We expect this substitution to reduce the demand for imported chromium.

INTRODUCTION

Chromium is an essential constituent in alloys used in oil refining, petrochemical plants, conventional and nuclear power plants, tanker trucks, gas turbines, industrial machinery, and all stainless steel applications where high elevated-temperature strength and corrosion resistance are required. Yet our major sources of supply are South Africa and the Soviet Union, and in 1980 we imported 91% of the chromium we required. The United States is currently following a policy of stockpiling critical elements; however, the stockpile of chromium is 180,000 tons short[1] of a stockpile goal of 1.35 million tons. The long-term solution to the critical element (Pt group, Cr, Co, Mn, and Ta) shortage is increased metallurgical research that will lead to the development of alloys that will reduce the need for these strategic materials. The purpose of this paper is to present the status of development of a modified 9 Cr-1 Mo alloy that can be substituted for stainless steels in many applications and, therefore, will reduce the consumption of chromium.

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*Work performed under DOE/RRT AF 15 40 10.3, Task OR-1.7, Advanced Alloy Technology.

BACKGROUND

The 300 series austenitic stainless steels are the most common structural materials for elevated-temperature service. Typically, they contain 18% Cr and 8% Ni, and they provide good air and steam oxidation resistance. However, they do have problems with stress-corrosion cracking in media containing halides. Ferritic steels, on the other hand, contain much less chromium and nickel than do stainless steels and are relatively free from stress-corrosion cracking. They do have less oxidation resistance to air and steam. However, in many applications ferritic steels of the 9 Cr-1 Mo type would be acceptable if they had sufficient elevated-temperature strength. If their strength were improved, ferritic steels would also provide better resistance to thermal stresses because of their lower expansion coefficient and higher thermal conductivity. Most of all, using an alloy of this type instead of stainless steels would produce a substantial saving of chromium. The following section describes the properties of the modified 9 Cr-1 Mo alloy and compares them with those of type 304 stainless steel.

RESULTS AND DISCUSSION

Modified 9 Cr-1 Mo steel is strengthened by small additions of vanadium and niobium. The recommended ranges for various elements are as follows:

C	Mn	Si	P	S
0.08–0.12	0.30–0.50	0.2–0.5	0.02 max	0.01 max

Cr	Ni	Mo	V	Nb	N
8–9	0.2 max	0.85–1.05	0.18–0.25	0.06–0.10	0.03–0.07

The alloy is currently recommended for use in the normalized and tempered condition (1038°C for 1 h, air cool to room temperature, 760°C for 1 h, again air cool to room temperature). However, work in progress shows that the desirable elevated-temperature strength may also be obtained in the isothermally annealed condition (1038°C for 1 h, fast cool to 704°C, hold for 24 h, then air cool to room temperature).

The alloy has been commercially melted by air induction and argon-oxygen deoxidation (AOD) and refined by the electroslag remelting (ESR) process. Ingots have been fabricated into tube, plate, and bar. The fabrication processes used include hot forging, hot rolling, hot extrusion, hot rotary piercing, centrifugal casting followed by cold pilgering, and cold drawing. No problems have been encountered during any of these melting and fabrication procedures.

Specimens from commercial heats have been tensile, creep, Charpy impact, and fatigue tested. Tensile data were used to specify the room-temperature values of 414 MPa (60 ksi) and 586 MPa (85 ksi) for yield and ultimate tensile strength, respectively. The request for inclusion of specifications for this alloy in the ASTM Standards book is currently under review by the appropriate committees.

The average and minimum curves defined by average values and average values minus two standard deviations for yield and ultimate tensile strength of standard and modified 9 Cr-1 Mo alloy are plotted as functions of test temperature in Figs. 1 and 2. Minimum curves for modified 9 Cr-1 Mo based on room-temperature specified values are also plotted in these figures, along with the ASME Code Case N-47 minimum value curves for type 304 stainless steel. These curves show the following:

1. The yield strength of both standard and modified 9 Cr-1 Mo steel is significantly above that of type 304 stainless steel up to 700°C.

2. The ultimate tensile strength of both standard and modified 9 Cr-1 Mo steel is higher than that of type 304 stainless steel for temperatures up to 550°C.

3. The modified alloy shows higher yield and ultimate tensile strength than the standard alloy over the entire temperature range.

The standard 9 Cr-1 Mo data used in Figs. 1 and 2 come from the United Kingdom (U.K.) and are on material in the normalized and tempered condition. In the United States the annealed condition is typical for standard 9 Cr-1 Mo. Data on modified 9 Cr-1 Mo steel are for the normalized and tempered condition described above.

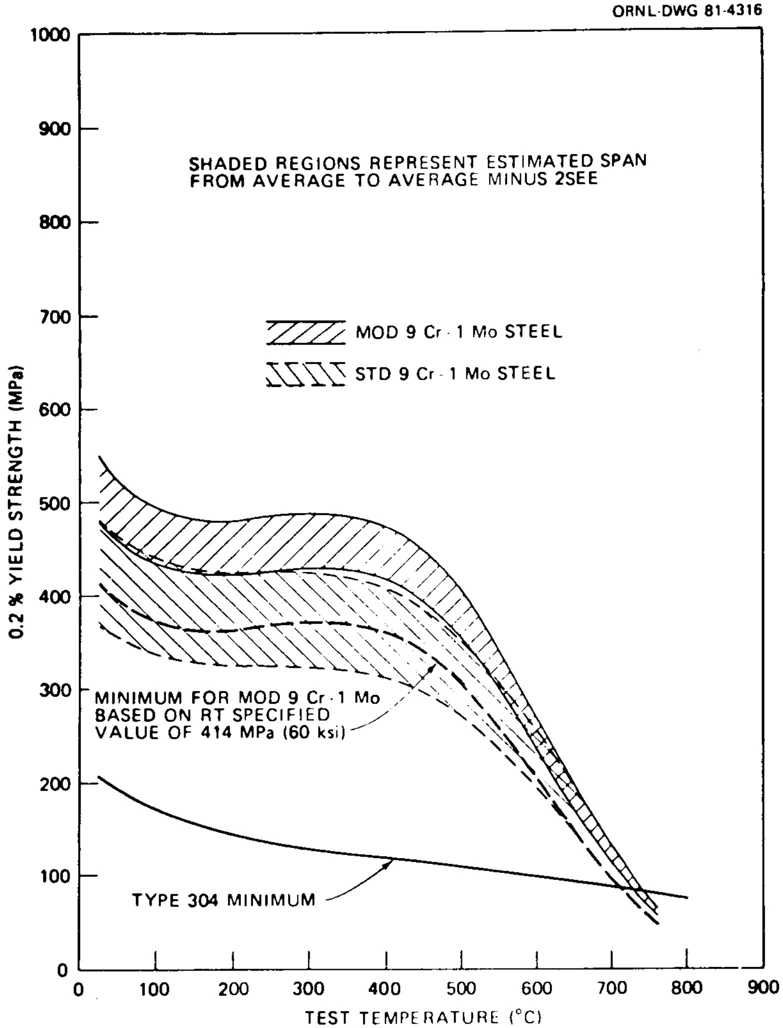

Fig. 1. Comparison of 0.2% yield strength curves for standard and modified 9 Cr-1 Mo and type 304 stainless steel.

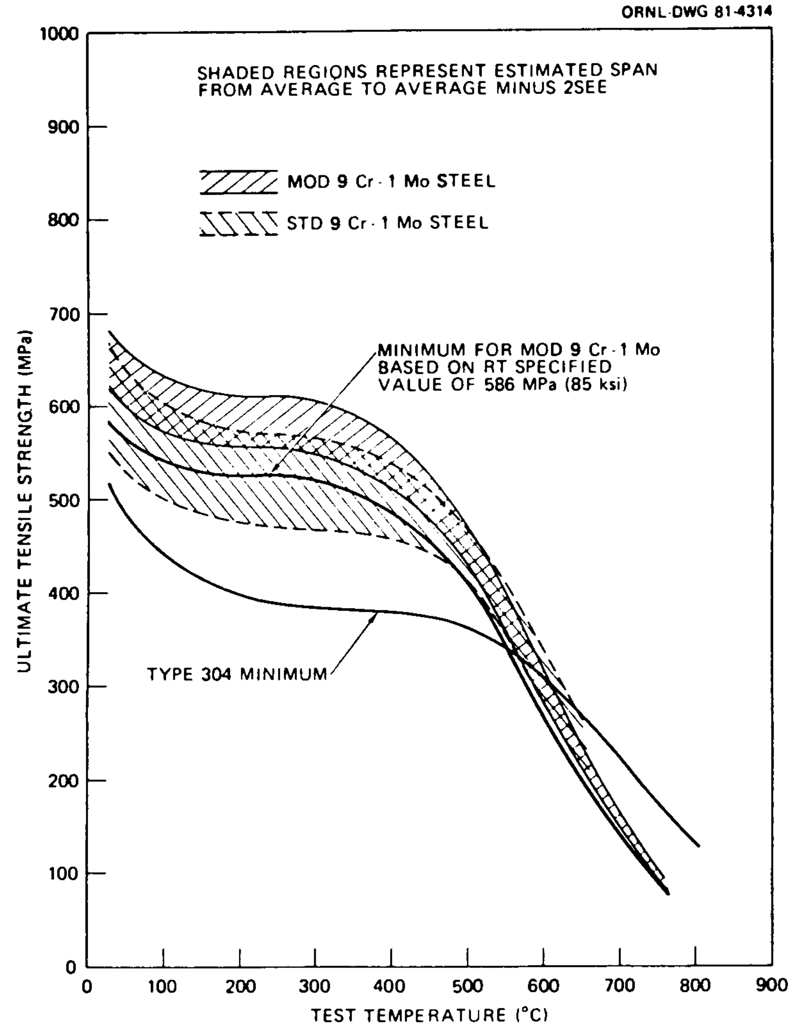

Fig. 2. Comparison of ultimate tensile strength curves for standard and modified 9 Cr-1 Mo and type 304 stainless steel.

Figure 3 illustrates the variation in estimated average 10^4-h rupture strength with temperature for various materials. Shown for comparison are average values for type 304 stainless steel that were used in the analysis[2] to calculate the minimum values now given in Code Case N-47. (This time was chosen because it is the longest time for which verifiable strengths can be calculated for all data sets.) The modified 9 Cr-1 Mo alloy is comparable in creep strength to type 304 stainless steel for temperatures up to about 625°C. Above 625°C it begins to fall below the stainless steel in strength. The 12 Cr-1 Mo-V-W-0.2 C (HT9) maintains a strength comparable to that of stainless steel only up to about 550°C before it drops off. The 2 1/4 Cr-1 Mo and annealed standard 9 Cr-1 Mo are lowest in strength, and the U.K. normalized and tempered standard

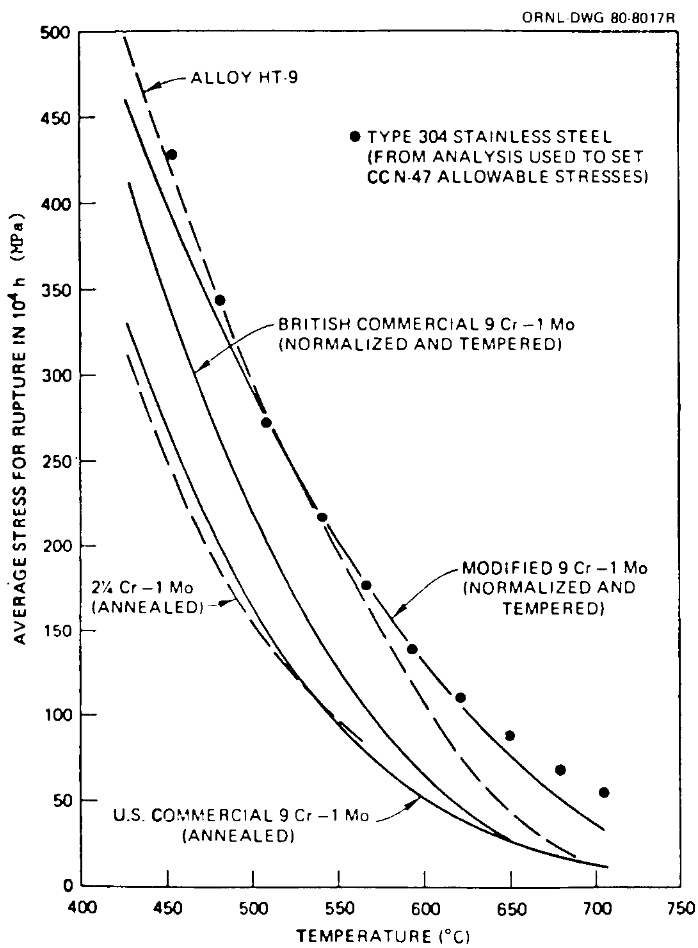

Fig. 3. Variation of 10^4-h creep-rupture strength with temperature for several materials.

9 Cr-1 Mo is intermediate. Above about 675°C, however, all these ferritic steels except modified 9 Cr-1 Mo converge to about the same low strength value. Even as high as 700°C the modified alloy remains intermediate between the stainless steel and the other ferritics.

Fatigue data on modified and standard 9 Cr-1 Mo alloy are compared with the average curve for type 304 stainless steel in Fig. 4. The modified 9 Cr-1 Mo data were obtained in both air and vacuum. This figure shows that the high-cycle fatigue properties of modified 9 Cr-1 Mo are an order of magnitude better than those of type 304 stainless steel. Because of its lower thermal expansion and higher thermal conductivity, the advantage of modified 9 Cr-1 Mo alloy over type 304 stainless steel under thermal fatigue conditions is expected to be even better.

A very important consideration in the use of a given alloy is its design allowable stresses (S_0). For a ferritic steel, S_0 is given as the lowest of the following four stress values at a given temperature:

1. Tensile: one-fourth of the tensile strength at temperature, which is defined as the smaller of (a) the specified minimum tensile strength at room temperature and (b) a value 10% greater than the minimum tensile strength at temperature.

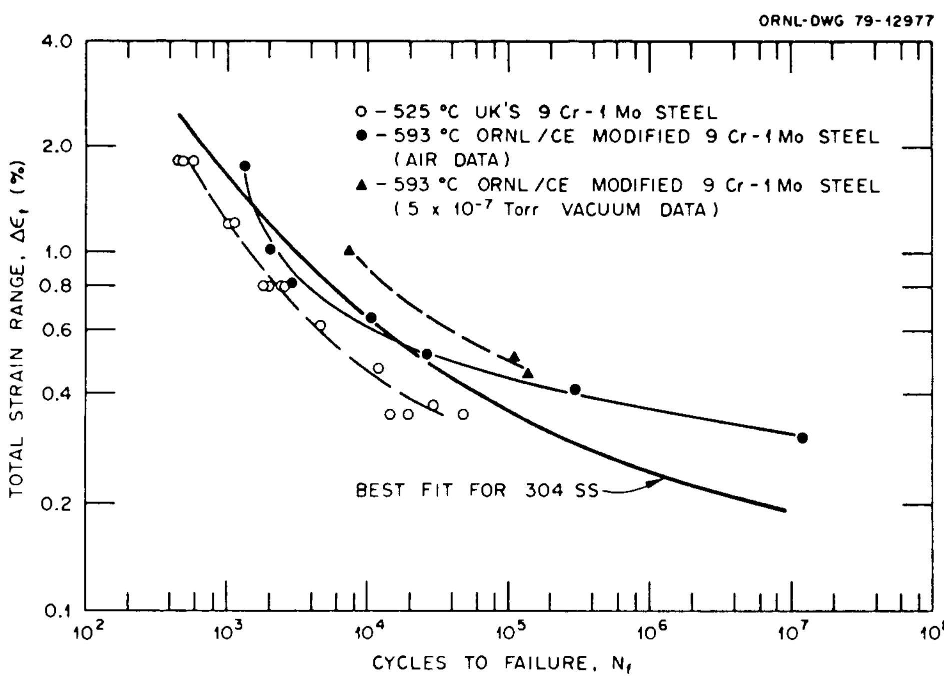

Fig. 4. Comparison of continuous cycling fatigue data on modified 9 Cr-1 Mo steel with standard 9 Cr-1 Mo steel and type 304 stainless steel.

2. Yield: five-eighths of the minimum yield strength at temperature.

3. Rupture: (a) 0.67 of average rupture stress for 10,000 h or (b) 0.8 of minimum rupture stress for 100,000 h.

4. Secondary (or minimum) creep rate: the average secondary creep rate for 0.01% creep per 1000 h (equivalent to 1%/100,000 h).

The estimated allowable stresses based on the criteria listed above are plotted in Fig. 5. This figure includes values for 2 1/4 Cr-1 Mo, standard 9 Cr-1 Mo, and type 304 stainless steel. It shows that modified 9 Cr-1 Mo steel has higher allowable stresses than the other ferritic materials over the entire temperature range from 427 to 704°C. The

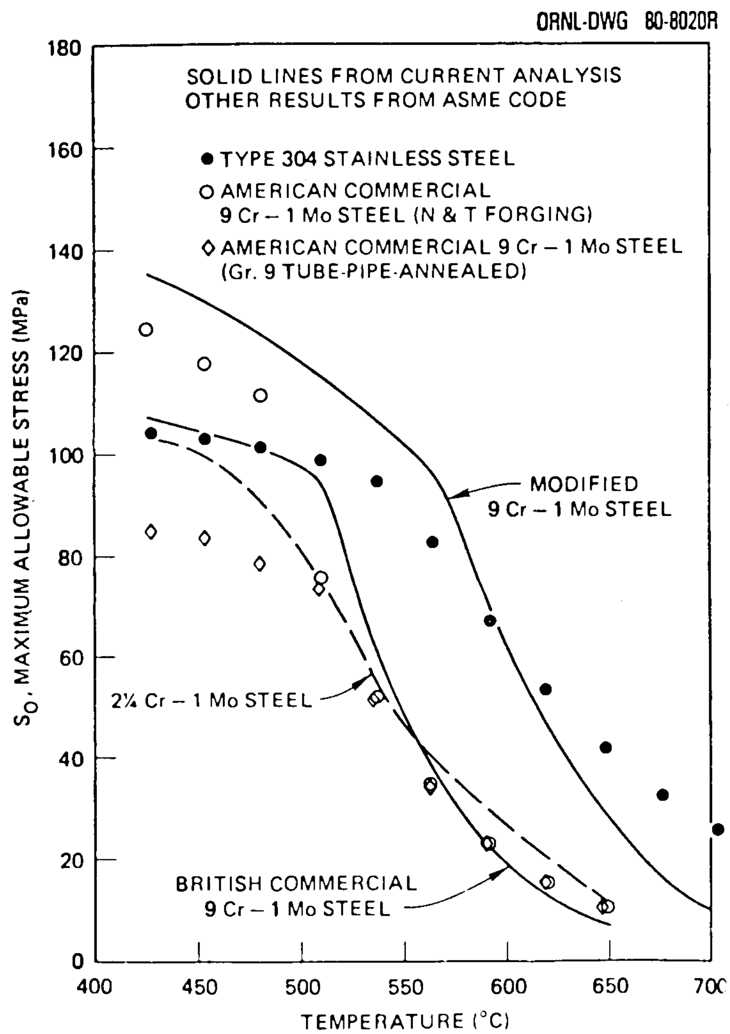

Fig. 5. Variation of estimated design allowable stress intensity, S_0, with temperature for several materials.

modified alloy is also estimated to have allowable stresses equal to or greater than those of type 304 stainless steel to about 600°C. For a given design stress, modified 9 Cr-1 Mo alloy can be used about 75°C higher than other ferritics and thus has an excellent chance of replacing type 304 stainless steel.

To gain commercial experience with modified 9 Cr-1 Mo alloy, we have installed tubes in two conventional utility power plants. At a Tennessee Valley Authority power plant the modified tubes replaced type 321 stainless steel tubes and have operated successfully since May 1980. At a fossil plant of American Electric Power, the modified alloy replaced type 304 stainless steel, and these tubes have been in operation since April 1981.

Work is continuing in the areas of mechanical properties, physical properties, weldability, and thermal aging effects. Initially we expect to obtain approval of modified 9 Cr-1 Mo in Sections I and VIII (for non-nuclear applications) of the ASME Code by 1982 or 1983. The nuclear application of this alloy will require a substantially larger data base and thus ASME Code approval for Section III is not expected until 1985.

SUMMARY

Although chromium is a critical element in many materials applications, over 91% of the chromium used by the United States is imported. To minimize our dependence on foreign sources of supply requires alloys that use less chromium than do present alloys such as stainless steels. This report has outlined the development of a modified 9 Cr-1 Mo alloy, which uses half of the chromium and a trace amount of nickel compared with stainless steel but has elevated-temperature properties matching those of type 304 stainless steel up to 600°C. The design allowable stresses of this alloy are 2 to 3 times those of other ferritic steels in the temperature range from 500 to 700°C. For a given design stress, the modified alloy can be used at 75°C higher than other ferritic alloys that have from 2.2 to 12% Cr. Improved elevated-temperature strength along with excellent physical properties of this modified alloy are expected to make it quite resistant to thermal fatigue.

Data on the modified 9 Cr-1 Mo alloy presented in this report show that there may be many applications where it could replace stainless steel and thereby reduce the need for imported chromium.

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