DEFORMATION BEHAVIOR OF UNALLOYED VANADIUM At 400°C and 500°C -
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OBJECTIVE

The broad objective of this work is to investigate the influence of the interstitial elements on the deformation behavior of BCC alloys.

SUMMARY

The tensile deformation behavior of unalloyed vanadium has been determined at 400°C and 500°C for strain rates in the range 10^{-1}/s to 10^{-5}/s. The occurrence of serrated flow effects in the Lüders extension and work hardening regimes of tensile stress-strain curves is associated with negative strain rate sensitivity of stress parameters.

PROGRESS AND STATUS

Introduction

The deformation behavior of unalloyed vanadium was shown to exhibit dynamic strain aging (DSA) at 200°C and 300°C for strain rates ranging from 10^{-1}/s to 10^{-5}/s [1]. The appearance of serrated yielding (continuous) and jerky flow (discontinuous) in the Lüders strain and work hardening regimes of stress-strain curves and a concomitant negative value in strain rate sensitivity (SRS) for flow stresses was found to be associated with the DSA phenomenon. In addition, the shape, frequency, and magnitude of the serrations and jerky flow depended on temperature, strain, and strain rate. The measured time between load drops for serrations as a function of temperature and strain rate indicated that the DSA effect was due to the migration of interstitial C and O atoms to dislocations below ~300°C. The purpose of this study is to investigate the DSA effect in vanadium at temperatures above 300°C in order to develop a better understanding of the interaction between Ti and interstitial atoms by comparing it with the V-4Cr-4Ti alloy [2-4].

Experimental Procedure

Sheet tensile specimens of the type SS-3 (nominal gage dimensions $0.76 \times 1.52 \times 7.6$ mm) were prepared from unalloyed vanadium (Teledyne Wah-Chang heat no. 820642). A 6.4mm thick plate was cut from the vanadium ingot, hot rolled at ~1050°C to a thickness of 2.5mm (60% reduction) and then cold rolled to 1.5mm (40% reduction). Specimens were electro-discharge machined from the 1.5mm thick plate and annealed at 1000°C for 1 hour in a vacuum of <~3×10^{-7} torr followed by furnace cooling. This procedure resulted in a uniform microstructure consisting of recrystallized grains with an average grain size of 89±5µm. Tensile testing was carried out under a vacuum of ~2×10^{-7} torr using a screw-driven machine. Specimens were held at the test temperature for 20-30 minutes before starting the test. Data were acquired digitally at rates of 20 points per second (pps) for tests conducted at 10^{-1}/s and 10^{-3}/s strain rates and 0.2pps at 10^{-5}/s strain rate.

Results

Data obtained from testing the specimens at 400°C and 500°C with strain rates of 10^{-1}, 10^{-3}, and 10^{-5} are summarized in Table 1. In addition, data from the tests at 200°C and 300°C are also included for comparison. The engineering stress-strain curves for 400°C and 500°C are shown in

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Table 1. Temperature and Strain Rate Dependence of Unalloyed Vanadium Tensile Properties.

Specimen	Test Temp.	Strain Rate	Lower Yield Stress σ_y	Ultimate Tensile Strength σ_u	Stress for 8% Strain σ_s	Luders Strain ε_L	Uniform Strain ε_u	Total Strain ε_t
ID	℃	s^{-1}	MPa			%		
PV46	200	10^{-1}	124	193	172	1.4	29.0	42.8
PV44	200	10^{-3}	105	188	161	0.8	24.1	36.2
PV45	200	10^{-5}	100	194	187	0.8	11.1	17.6
PV41	300	10^{-1}	116	183	174	0.4	14.2	20.6
PV42	300	10^{-3}	115	240	213	0.8	15.2	21.1
PV43	300	10^{-5}	118	297	238	1.4	19.4	27.8
PV47	400	10^{-1}	108	228	194	0.5	19.9	27.5
PV48	400	10^{-3}	111	294	236	0.8	17.1	23.5
PV49	400	10^{-5}	112	318	240	1.0	22.0	29.2
PV50	500	10^{-1}	103	264	211	0	22.2	28.0
PV51	500	10^{-3}	90	280	214	0	21.2	36.9
PV52	500	10^{-5}	95	222	210	0.7	11.7	35.0

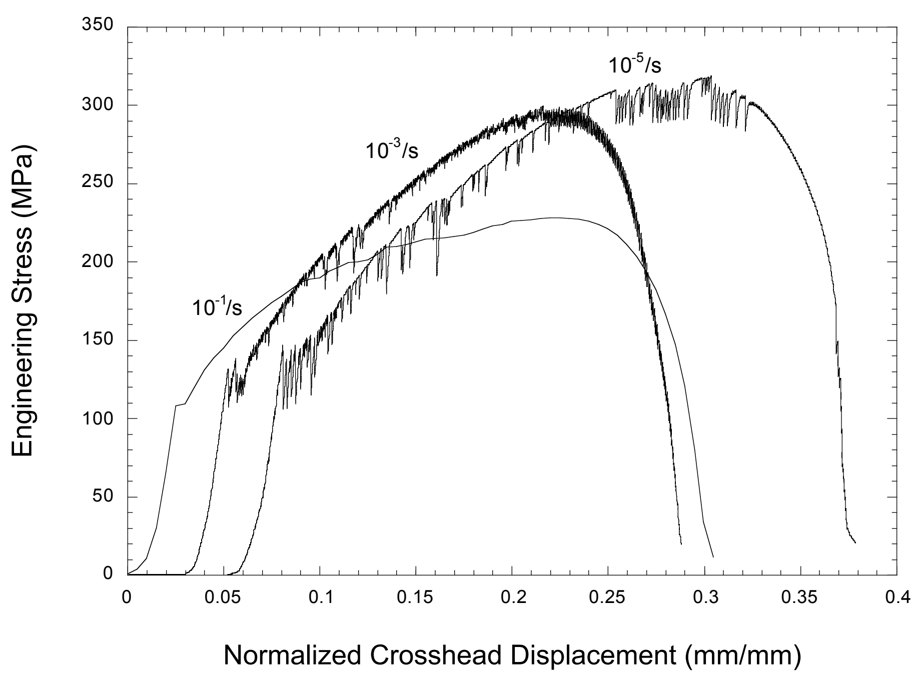

Figure 1. The stress-strain curves for vanadium at 400°C.

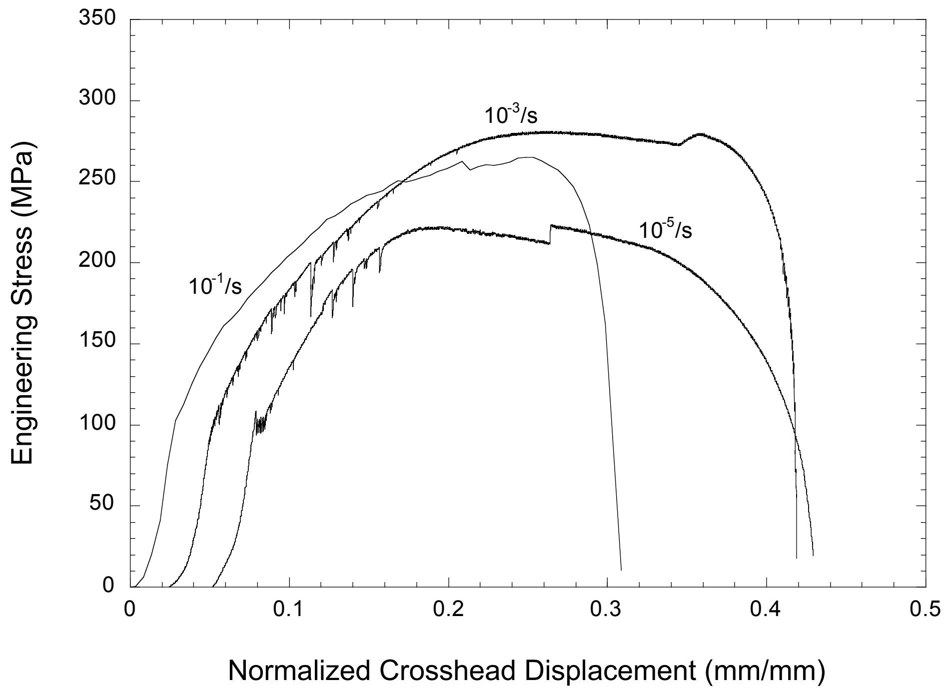

Figure 2. The stress-strain curves for vanadium at 500°C.

Figures 1 and 2, respectively. The curves have been offset along the normalized crosshead displacement axis for comparison of the elastic and Lüders extension regimes. Most of the specimens exhibited Lüders extensions ranging from 0.5 to 1.0%; only specimens tested at 500°C with strain rates of 10^{-1}/s and 10^{-3}/s showed no Lüders extensions. Serrations associated with the Lüders extension are propagated by an average stress which is defined as the lower yield stress, σ_y. Upon completion of the Lüders extension, the deformation proceeds with initially an increase in the work hardening rate on the stress-strain curve that eventually decreases until the ultimate stress, σ_u, is achieved. All of the stress-strain curves exhibited both continuous oscillations (serrated yielding) and discontinuous (jerky flow) behavior in the plastic flow regimes of stress strain curves. The results indicated that both the frequency and magnitude of the serrations changed with temperature, strain, and strain rate. For tests carried out at a rate of 10^{-1}/s, the data acquisition system was not sufficiently rapid to detect load drops associated with the serrations. Therefore, the presence of jerky flow could not be directly ascertained at this strain rate.

The strain-rate dependence was determined for the lower yield stress, σ_y, and for a parameter, σ_s, which is the stress required to produce a strain of 8% after the completion of the Lüders extension. The 8% strain is an arbitrary value selected to represent material in the strain-hardening regime. The strain-rate dependence of these stress parameters for temperatures ranging from 200°C to 500°C are presented in Figures 3 and 4 along with logarithmic curve fits to the data.

The strain rate sensitivity, m, was calculated for σ_y, σ_s, and σ_u at each temperature and are compiled in Table 2. The m values were calculated from:

$$m = \frac{1}{\sigma} \frac{\partial \sigma}{\partial \ln \dot{\varepsilon}} \bigg|_{\varepsilon, T}$$

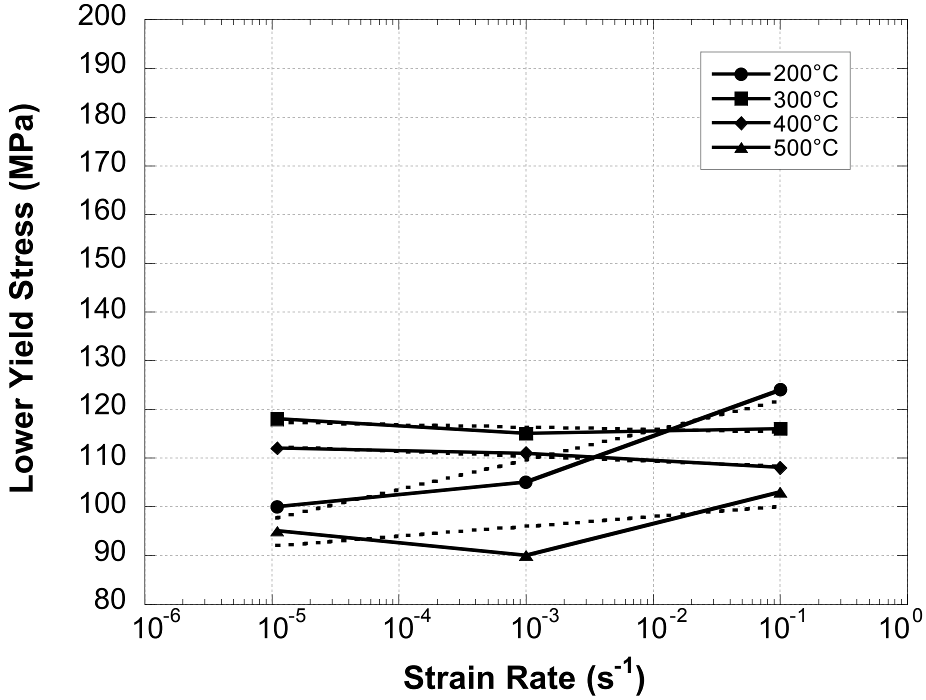

Figure 3. Effect of strain rate on the lower yield strength of vanadium tested at temperatures of 200°C to 500°C.

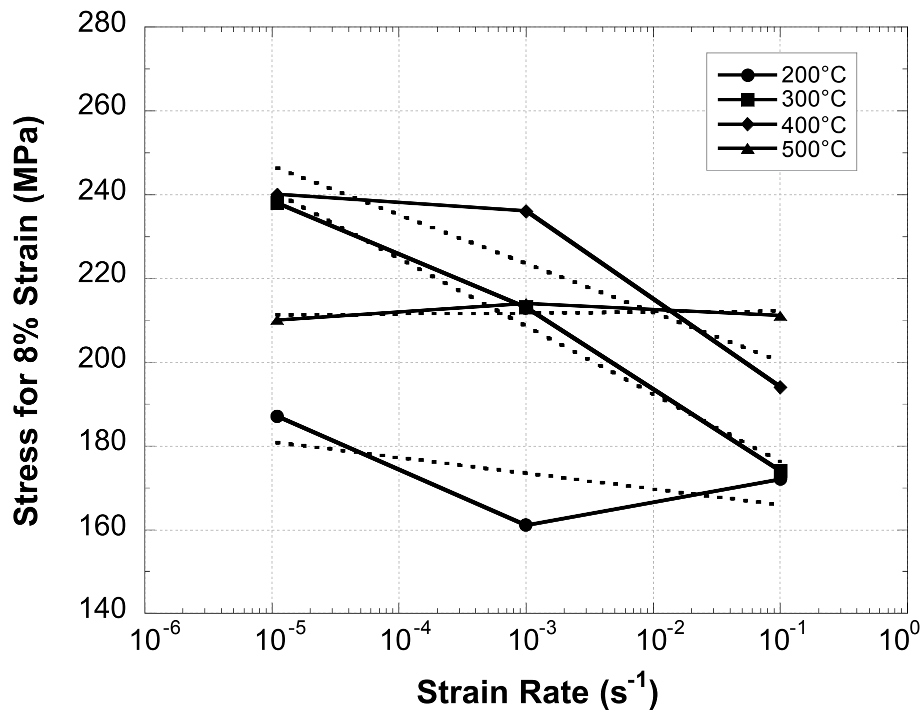

Figure 4. Effect of strain rate on the tensile strength (measured at 8% strain in the strain-hardening regime) of vanadium tested at temperatures of 200°C to 500°C.

where σ is the stress and $\dot{\varepsilon}$ is the strain rate, and are represented by the slope of the logarithmic curve fits shown in Figures 3 and 4. The results indicate that the SRS of σ_y is positive at 200°C, virtually independent of strain rate at 300°C and 400°C, and is slightly positive again at 500°C. The data for σ_y at 500°C actually shows a U-shape dependence with strain rate (Fig. 3). A different behavior in SRS was observed for σ_s and σ_u; both are negative between 200°C and 400°C and slightly positive at 500°C. The maximum magnitude in negative SRS for σ_s and σ_u was found to occur at 300°C.

The appearance of serrations and jerky flow in stress-strain curves at 400°C (Fig. 1) coincided with the negative m values of σ_s and σ_u. At 500°C, serrations and jerky flow are also observed in stress-strain curves but typically occur below 8% strain. This observation correlates with the SRS values measured at 500°C, which is slightly positive at σ_s (m=0.001) and becomes more positive at σ_u (m=0.019). In addition, the frequency and magnitude of the serrations and jerky flow are significantly greater for stress-strain curves at 400°C compared to those at 500°C. It should be mentioned that due to the data acquisition problem described above, serrations and jerky flow were not observed in any stress-strain curves using the 10^{-1}/s strain rate. However, the negative SRS values measured at 300°C [1] and 400°C suggest that serrated yielding is occurring during these tests but detection is limited by the sensitivity of the data acquisition system.

Table 2. Strain rate sensitivity, m, values calculated for several stress parameters of vanadium.

Temperature	Strain Rate Sensitivity (m)		
	Lower Yield Stress (σ_y)	Stress at 8% Strain (σ_s)	Ultimate Stress (σ_u)
200°C	0.024	-0.009	-0.001
300°C	-0.002	-0.034	-0.053
400°C	-0.004	-0.023	-0.037
500°C	0.009	0.001	0.019

Discussion

The results of this study, combined with those previously reported [1] indicate that the phenomenon of dynamic strain aging occurs between 200°C and 500°C. The magnitude of SRS has a maximum negative value at 300°C and remains negative up to 400°C and then diminishes rapidly at higher temperatures. As discussed earlier, the magnitude of the DSA phenomenon decreases in the temperature-strain rate regime where the mobility of the interstitial solutes is sufficiently high for Cottrell atmospheres to migrate along with rapidly moving dislocations.

Examination of the details of the stress-strain curves for vanadium show the existence of two types of discontinuities. The first type consists of high frequency periodic oscillations (serrated yielding) with an approximate saw-tooth pattern; the amplitude varies with temperature and with strain rate in the range 3-8 Mpa. The second type consists of an irregularly spaced series of load drops with magnitudes in the range 8-20Mpa (discontinuous yielding). Further work is in progress to understand the spatio-temporal behavior of these oscillations and to relate their magnitude and frequency to the mobilities of the interstitial solutes.

The results of the testing at 400°C and 500°C lead us to a re-evaluation of our earlier conclusion that alloying with Cr and Ti leads to an increase in the temperature range for DSA of approximately

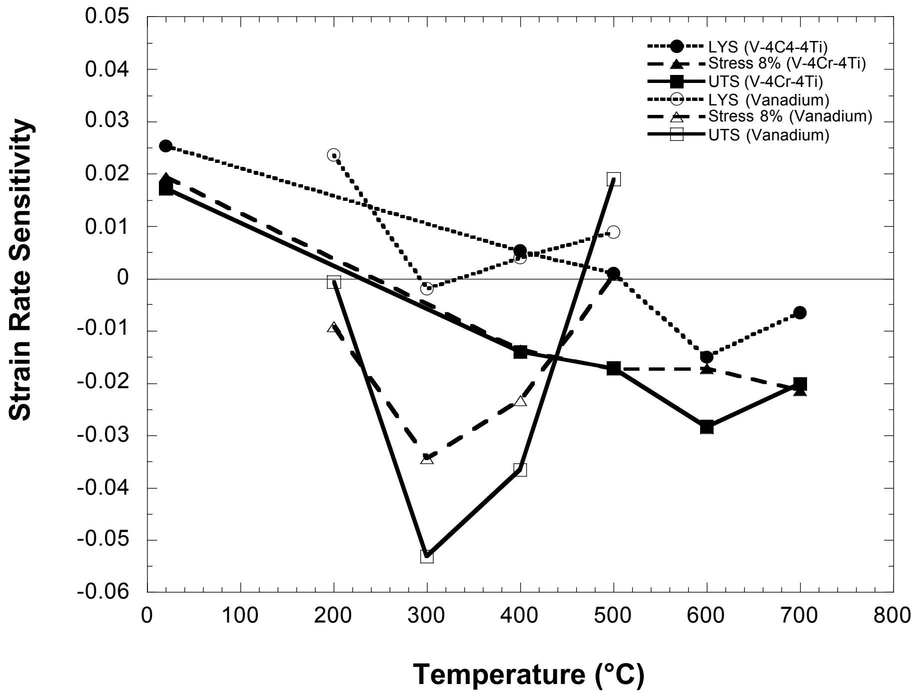

Figure 5. The strain rate sensitivity parameter, m, as a function of temperature for vanadium and V-4Cr-4Ti.

100°C [1]. In Figure 5 the strain rate sensitivity parameter, m, for the three stress parameters is plotted as a function of temperature. These data indicate that the maximum negative value of SRS for vanadium occurs at about 300°C and that as a result of alloying the temperature at which SRS achieves a maximum negative value is increased to around 600°C. In other words, alloying with Ti and Cr increases the temperature range for DSA by about 300°C. This is most probably related to the strong interaction between Ti and the interstitial population and the consequent decrease in interstitial mobility.

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