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Mechanical Properties of a Vanadium Microalloyed Air-cooled Forging Steel with Various Aluminum Additions

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Abstract

The interaction of vanadium, aluminum, and nitrogen was investigated during simulated reheat cycles for forging in a commercial (38MnSiVS5) vanadium microalloyed medium-carbon bar steel with three aluminum levels (0.006, 0.020, and 0.031 wt pct). Laboratory thermal simulations with varied hold temperatures (1100 to 1250 °C) and hold times (5 or 45 min) while maintaining constant heating and cooling rates were used to study the interaction of various components. Tensile testing was used to determine properties after the thermal simulations. The contribution to precipitation strengthening appears to be on the order of 70 to 150 MPa for all conditions tested except for one—the 45 min hold at 1100 °C—where the aluminum reacted with the nitrogen to form AlN and greatly diminished the strength increase from the vanadium precipitates.

Introduction

Significant numbers of hot-forged products are produced using direct-cooled microalloyed (MA) steels. The products are commonly used as a lower-cost alternative to higher alloyed quenched and tempered (QT) steels. The cost savings can be attributed to both a reduction in costly alloying additions and a considerable reduction in post-forging processing. Typical applications of MA forging steels include automotive components such as crankshafts, connecting rods, spindles, and wheel hubs [1].

Microalloyed steels use small additions, often on the order of 0.1 wt pct or less, of alloying elements like vanadium (V), niobium (Nb), or titanium (Ti) to improve mechanical properties through grain size control and precipitation strengthening [1]. In forging steels, these microalloying additions are typically used to modify a medium-carbon (0.30 to 0.50 wt pct) ferrite-pearlite or bainitic steel to improve strength, fatigue resistance, and wear properties [2]. Grain refinement in MA steel is achieved by either solute drag or precipitating microalloy carbides and nitrides out of solution at a high temperature to control austenite grain size (AGS) and morphology during processing [2]. The precipitation strengthening of MA steels can be significant, typically increasing strength by 50 to 200 MPa. This increase in strength is achieved through precipitating very low volume fractions (typically 10^{-4} to 10^{-3}) of very fine (typically <20 nm) incoherent precipitates [3].

The focus of the present paper is on the mechanical properties of a 38MnSiVS5 microalloyed steel, which has undergone a typical reheat cycle prior for forging, and with various aluminum (Al) additions.

Experimental Procedures

A medium-carbon vanadium microalloyed steel—38MnSiVS5 (modified AISI 15V41)—with three separate aluminum additions was studied. Table I gives the composition for the steel. The single heat of steel was continuously cast from a single heat with aluminum additions of 0.006, 0.020, and 0.031 wt. pct being made in the mold by wire feed. A reduction ratio of 4.3:1 was used to roll the billet to a 117.5 mm round bar. The steels are labeled by their aluminum content: 6Al, 20Al, and 31Al.

Table I. Chemical Composition (wt. pct) of the Modified SAE 15V41 Base Steel

C	Mn	Si	Cr	Ni	Mo	V	Al	N	S	P	Cu
0.37	1.36	0.63	0.13	0.08	0.02	0.088	var.	0.0153	0.064	0.010	0.18

Tensile tests were performed on specimens processed for a set of the thermal simulations using a sub-sized round tensile geometry. Tensile blanks (12 mm diameter by 86 mm long) were heat treated using the Gleeble® 1500 thermomechanical simulator.

A two-step heating schedule of 20 °C/s to 750 °C then 4 °C/s to the holding temperature was selected. The change in heating rate at 750 °C is intended to simulate the decreased efficiency of induction heating that occurs above the Curie temperature of ferrite (770 °C).

Five specific combinations of temperature and time were selected for the holding step. The holding temperatures were selected as 1100, 1150, 1200, and 1250 °C. The maximum holding temperature of 1250 °C was determined from the recommended forging temperature for AISI 1541 (1245 °C). The remaining holding temperatures were selected by examining the different amounts of AlN, as determined by the solubility product. Durations of 5 or 45 minutes at the holding temperature were selected to account for both the shorter holding time of induction heating and the longer holding time typical of gas-fired furnaces.

The cooling step consists of two cooling rates: the latter part of the cooling step was modeled after a curve obtained from an industrially processed 76 mm diameter bar. The first cooling step consists of a variable cooling rate from the holding temperature to 750 °C in 360 s. This cooling results in an initial cooling rate that varies from 0.83 to 1.39 °C/s. The cooling rate is then reduced to 0.25 °C/s until the specimen reaches 500 °C, after which the specimens are allowed to freely cool to room temperature (i.e. without program control) between the platens of the Gleeble® 1500.

After the heat treatment, the heat treated blanks were machined into test specimens with a gauge length of 35.6 mm and diameter of 8.9 mm.

All specimens were pulled to failure in quasi-static uniaxial tension at room temperature. The testing was done under displacement control at a crosshead displacement rate of 0.508 mm/min. The geometry of every specimen was measured with a caliper (0.005 mm resolution) to ensure all test specimens were consistent and proper dimensions were used during analysis. Values for 0.2% offset yield strength, ultimate tensile strength, and total elongation were determined based on the load cell and extensometer data. Uniform elongation was determined by use of Considère’s construction [4].

Results and Discussion

Three 12 mm diameter cylinders for each alloy were processed through five selected thermal simulations, machined into sub-sized tensile specimens, and tested at room temperature. Tables II, III, and IV give a summary of the tensile data from the 6Al, 20Al, and 31Al specimens, respectively.

The mean yield strength varied from 650 to 690 MPa for the 6Al, 655 to 686 MPa for the 20Al, and 626 to 682 MPa for the 31Al alloy. The mean ultimate tensile strength ranged from 942 to 990 MPa for the 6Al, 950 to 984 MPa for the 20Al, and 925 to 982 MPa for the 31Al alloy. Both the mean yield strength and the mean ultimate tensile strength had uncertainties that were typically less than 5 pct at the 95 pct confidence level. Uniform elongation was consistent across all conditions at approximately 10 pct. Total elongation and reduction in area varied from condition to condition; however, the large uncertainties make it difficult to reliably assess these trends. The most significant difference observed is between the mean yield strength of the 6Al and 31Al alloys in the 45-1100 and 5-1250. On average, the 6Al has almost 25 MPa higher yield strength than the 31Al in the 45-1100 condition. In the 5-1250 condition, the 6Al has over 10 MPa lower yield strength than the 31Al.

The extent of precipitation strengthening in the five thermal simulations (45-1100, 45-1150, 5-1200, 45 1200, and 5-1250) was evaluated using tensile test data. Figure 1 compares pearlite fraction versus yield strength for the select thermal simulations for all three alloys to data from Gladman *et al.* [5].

Table II. Uniaxial Tensile Testing Data for 6Al Specimens Processed Through Five Select Thermal Simulations. The Mean ± One Standard Deviation is Reported.

Thermal Simulation (min-°C)	Yield Strength (0.2% Offset)	Ultimate Tensile Strength	Uniform Elongation	Total Elongation	Reduction in Area
	MPa (ksi)	MPa (ksi)	pct	pct	pct
45-1100	649.7 ± 9.7	942.7 ± 13.7	10.4 ± 0.2	26.4 ± 1.8	33.7 ± 0.5
45-1150	655.0 ± ---	944 ± ---	10.2 ± ---	25.4 ± ---	30.9 ± ---
5-1200	664.3 ± 9.0	961.3 ± 7.2	10.3 ± 0.2	22.4 ± 1.1	28.0 ± 1.6
45-1200	689.3 ± 12.9	989.7 ± 11.1	9.7 ± 0.4	15.3 ± 4.2	17.4 ± 5.4
5-1250	669.3 ± 3.8	963.7 ± 3.5	10.4 ± 0.3	21.6 ± 1.3	27.2 ± 0.4

Table III. Uniaxial Tensile Testing Data for 20Al Specimens Processed Through Five Select Thermal Simulations. The Mean ± One Standard Deviation is Reported.

Thermal Simulation (min-°C)	Yield Strength (0.2% Offset)	Ultimate Tensile Strength	Uniform Elongation	Total Elongation	Reduction in Area
	MPa (ksi)	MPa (ksi)	pct	pct	pct
45-1100	657.3 ± 10.0	953.3 ± 12.2	10.3 ± 0.1	24.3 ± 1.7	30.5 ± 1.8
45-1150	655.3 ± 2.3	949.7 ± 3.5	10.3 ± 0.3	24.6 ± 0.4	30.6 ± 0.6
5-1200	671.7 ± 7.6	969.7 ± 12.4	10.3 ± 0.2	19.2 ± 1.6	23.6 ± 1.9
45-1200	675.3 ± 1.2	976.7 ± 5.5	9.7 ± 0.2	14.0 ± 2.5	14.9 ± 4.6
5-1250	686.0 ± 9.5	983.7 ± 16.3	9.4 ± 0.8	10.6 ± 2.1	10.5 ± 1.4

Table IV. Uniaxial Tensile Testing Data for 31Al Specimens Processed Through Five Select Thermal Simulations. The Mean ± One Standard Deviation is Reported.

Thermal Simulation (min-°C)	Yield Strength (0.2% Offset)	Ultimate Tensile Strength	Uniform Elongation	Total Elongation	Reduction in Area
	MPa	MPa	pct	pct	pct
45-1100	626.0 ± 3.6	924.7 ± 6.0	10.2 ± 0.2	27.3 ± 0.1	34.9 ± 0.3
45-1150	659.0 ± 8.7	959.3 ± 4.7	10.1 ± 0.2	17.8 ± 4.6	21.5 ± 7.1
5-1200	656.0 ± 9.6	952.7 ± 14.2	10.2 ± 0.3	20.4 ± 4.7	25.5 ± 7.0
45-1200	677.3 ± 7.8	976.3 ± 10.6	9.3 ± 0.5	11.8 ± 1.3	12.9 ± 1.5
5-1250	681.7 ± 5.5	982.0 ± 10.0	9.8 ± 0.4	13.0 ± 0.8	13.2 ± 0.6

The V microalloyed 1100 °C austenitized and air cooled data from Gladman *et al.* has comparable yield strengths as the thermal simulation data, but at higher pearlite fractions. The data from the thermal simulations appear to follow the same increasing trend as the data from the literature, but with an upward shift in yield strength of approximately 200 MPa. This large increase in yield strength as compared to the trend line for the Gladman *et al.* data is slightly deceptive, since the data in Figure 1 are not corrected for alloying or other microstructural effects.

Figure 2 shows the calculated yield strength, using the Gladman equation [5]:

$$\sigma_y(MPa) = f^{1/3}\left[35 + 58.5(wt\ pct\ Mn) + 17.4d^{-1/2}\right] + \left(1 - f^{1/3}\right)\left[178 + 3.85S^{-1/2}\right] + 63.1(wt\ pct\ Si) + 425(wt\ pct\ N_{free})^{1/2} \quad (1)$$

where f is the volume fraction of ferrite, d is the ferrite grain size in mm, and S is the interlamellar spacing in mm.

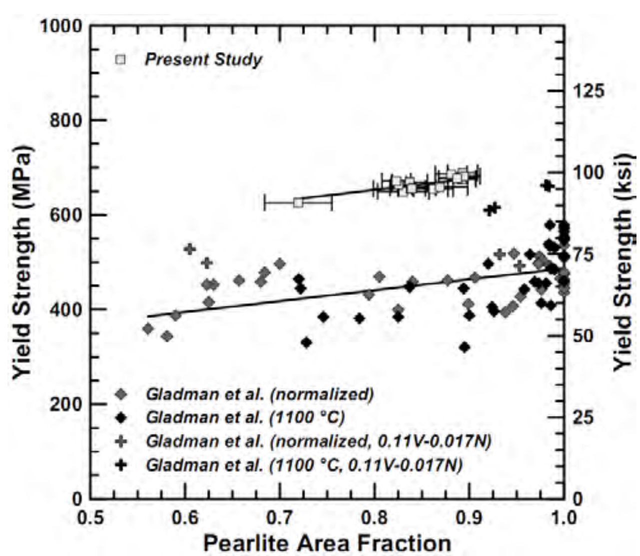

Figure 1. Yield strength as a function of pearlite area fraction for tensile specimens of select thermal simulations, and in the as-received condition for the three alloys in the present study, as well as values from Gladman *et al.* [5].

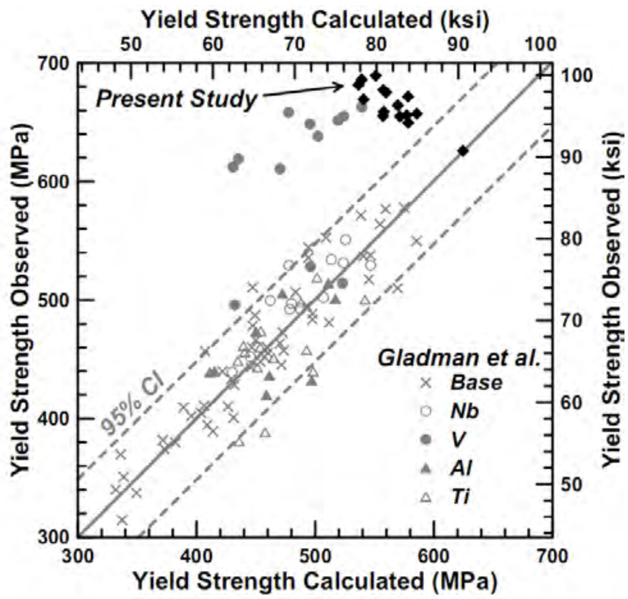

Figure 2. Calculated versus observed values of yield strength from tensile specimens of select thermal simulations for the three alloys in the present study, as well as values from Gladman *et al.* [5].

The thermal simulations show comparable values to data provided by Gladman *et al.* for some V microalloyed steels. The contribution to precipitation strengthening appears to be on the order of 70 to 150 MPa for all conditions tested, except for the 45-1100 thermal simulation for the 31Al alloy. This particular thermal simulation had approximately 10 pct less V precipitated than the 6Al specimen of the same thermal simulation. The decrease is likely due to the reduced number of V(C,N) precipitation, since there was sufficient time for the N to react with the Al to form AlN, and hence reduce the precipitation potential in this alloy.

Summary

Tensile specimens of all Al levels were processed through select thermal simulations and tested. The thermal simulations used were 45 min hold times at 1100, 1150, and 1200 °C, as well as a 5 min hold at 1200 and 1250 °C. When comparing calculated yield strengths (using Equation 1) to observed values, the thermal simulations show comparable values to data from literature for air-cooled medium- and high-carbon V microalloyed steels. The contribution to precipitation strengthening appears to be on the order of 70 to 150 MPa for all conditions tested, except the 45 min hold at 1100 °C thermal simulation for the 31Al alloy based on the calculated versus observed yield strength plot.

Acknowledgements

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