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Vanadium in Cold Rolled HSLA Sheet Steel

David K. MATLOCK[1], Robert J. GLODOWSKI[2], John G. SPEER[1],
Jennifer A. GARRISON[1], Steven W. THOMPSON[1]
(1. Advanced Steel Processing and Products Research Center, Colorado School of Mines, USA;
2. Stratcor Performance Materials, USA)

Abstract: In comparison to other microalloying elements, vanadium has received less attention as a primary alloying addition to cold rolled and annealed sheet steels. However, with changes in steelmaking, alloying, and solid-state processing practices over the years, it is worthwhile to examine the contributions of vanadium in cold rolled products. In this paper the principles of vanadium precipitation applicable to typical thermal processing windows for cold rolled sheet steels are reviewed along with results from a recent study on the combined effects of V and Al in a thin slab cast product.

Key words: vanadium microalloying; testing

1 Introduction

Microalloyed steels, and specifically those alloyed with vanadium, continue to see increased use in a variety of applications, and due to advances in processing technologies, opportunities exist for continued expansion in the use of these steels. In hot rolled high strength products vanadium has been used for many years, often in combination with other microalloying additions such as niobium or titanium. Vanadium can provide important contributions via both precipitation strengthening and ferrite grain refinement (due to austenite conditioning during thermomechanical processing). The focus of this paper, however, is on vanadium in cold rolled sheet steels, and in particular on products produced via the thin-slab compact strip production (CSP) process. This process involves near net shape casting (≅ 50 mm slab) and hot direct rolling (HDR) to streamline the steelmaking process. Some metallurgical characteristics of this process are as follows: (1) there is no γ-α-γ phase change prior to soaking; (2) the soaking temperature is lower than in conventional hot strip mills (1150 °C vs. 1300 °C); and (3) all hot-rolling is accomplished in the finishing stands (i.e. there are no roughing reductions).

For any microalloying addition to be used most effectively, it must be dissolved during processing, and then precipitation must be controlled at a lower temperature. Therefore, understanding precipitate solubility is critical to the design of processing histories for microalloyed steels. Solubility considerations indicate that where higher microalloying additions are desired, vanadium plays a key role because of its greater solubility. VC solubility is much greater than TiC or NbC, and VC is usually soluble during reheating to any austenitic rolling temperatures for carbon levels typical of sheet steel products. As a consequence, VC is not usually considered an important microalloy precipitate in austenite. While VN is less soluble than VC, the levels of nitrogen are low enough that VN solubility is also typically not of concern during reheating. Reheat temperature before rolling is usually not an important variable in the context of optimizing vanadium levels based on solubility, and so vanadium has attracted special interest for processes with low reheating temperatures.

While vanadium is used extensively in hot-rolled HSLA products, it is not as widely used in cold-rolled HSLA sheet products. The conventional view held in the technical literature is that strengthening by vanadium is somewhat less efficient in comparison to other microalloying species, when comparing the relative behavior of the hot-rolled and cold-rolled conditions. The reason that vanadium is less effective in cold-rolled, compared to hot-rolled products, is that the strengthening precipitates, such as vanadium carbide, are believed to coarsen more readily during annealing, than other precipitates such as niobium carbide[2]. The increased coarsening rate of vanadium

Biography: David K. Matlock (1946), Male, Doctor, Professor; **E-Mail:** dmatlock@mines.edu

carbide is considered to arise because of its greater solubility. Coarsening increases the particle size, and reduces the strengthening contribution, so the microalloying contribution can be diminished during the annealing process.

Figure 1, adapted from the work of Pradhan[2], shows the combined effect of annealing condition and microalloy addition on the yield strength of cold rolled 0.06%C Al-killed steels containing Mn/Si/P with 0.004%N in the Nb steel and 0.011%N in the V steel. When compared to a plain-carbon steel, both Nb and V provide strengthening in the hot-rolled condition (not shown here), and after complete recrystallization under both continuous and batch annealing simulated heat treatments. The strength is reduced during annealing of both series of steels (due primarily to microalloy carbonitride coarsening). The strengthening increment due to vanadium in these steels is somewhat less than is achieved by equivalent Nb additions, and vanadium-containing precipitates are considered to be somewhat less resistant to coarsening[2]. These factors may have led to the somewhat limited use of vanadium in cold-rolled HSLA sheet steels. However, it is now common to enhance the nitrogen levels in hot-rolled vanadium microalloyed steels to maximize the strengthening effect of the vanadium addition. The effect of this nitrogen enhancement on the coarsening of nitrogen rich V(C,N) precipitates during annealing has not been well identified.

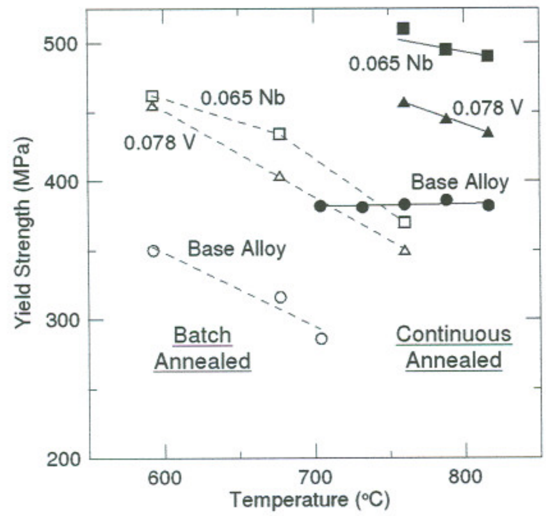


Fig. 1 The effects of simulated continuous (CA: 1 min) and batch (BA: 12 hrs) annealing on the yield strength of cold rolled 0.06% C Al-killed steels (adapted from [2]).

In this paper, the potential for precipitation strengthening in HSLA steels is further examined by considering vanadium-containing HSLA sheet with nitrogen enhancement produced by thin-slab casting (CSP or compact strip production) and the potential additional effects of aluminum additions on the amount of nitrogen available to efficiently participate in the precipitation process.

2 Experimental Approach

Competition between Al and V for nitrogen in CSP sheet products was investigated on material sampled from the outer wraps of two V-added low-carbon CSP coils with the compositions shown in Table 1. The coils were nominally identical, except that one was much lower in aluminum. Samples were laboratory cold rolled and heat treated to simulate production processing. The samples were evaluated with standard tensile testing, light, and electron microscopy techniques. Details of the experimental procedures are summarized elsewhere[3,4].

Table 1 Experimental CSP steel compositions (wt. %) (with ≅ 0.013P, 0.003S, 0.02Si in each steel).

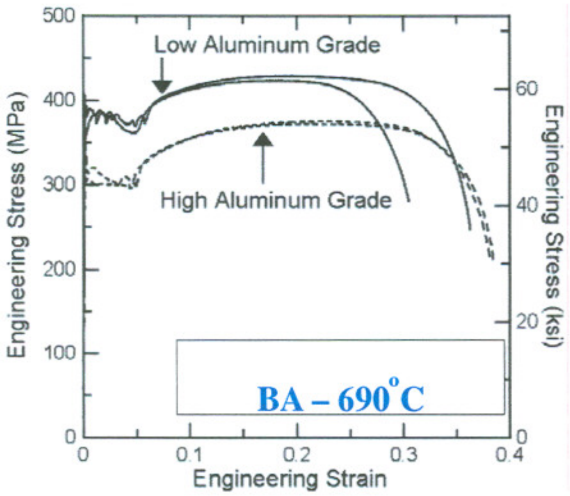
Steel	C	Mn	V	Al	N
Low Al	0.047	0.475	0.04	0.016	0.0117
High Al	0.045	0.461	0.035	0.047	0.0138

3 Results and Discussion

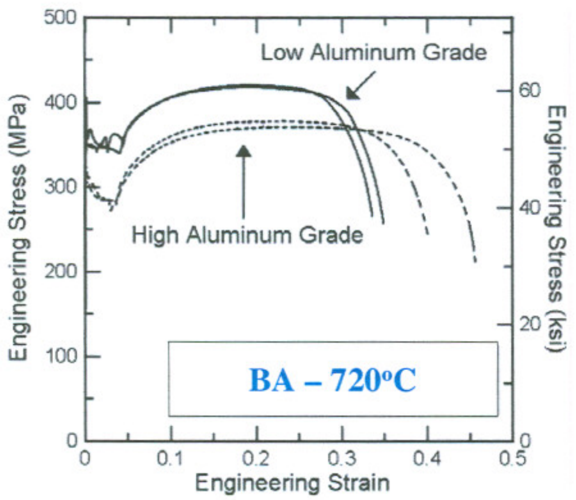
The hot-band yield strength was higher in the low-Al steel and tempering treatments also increased the strength relative to the as-rolled condition, due to secondary hardening[3]. This behavior is indicative of incomplete V(C,N) precipitation in the hot-band, at least in the outer wrap locations used in this study.

Figure 2 shows the effects of batch annealing on the stress strain behavior of the two aluminum steels. The results are similar at both annealing temperatures. The low-Al steel exhibits higher strength than the high-Al steel. The grain sizes of the two steels are not substantially different, indicating that the strength difference is likely related to precipitation effects. Presumably, AlN formation in the high-Al steel consumes nitrogen, which is then unavailable to create an efficient V(C,N) dispersion.

Figure 3 shows stress-strain curves for the two steels

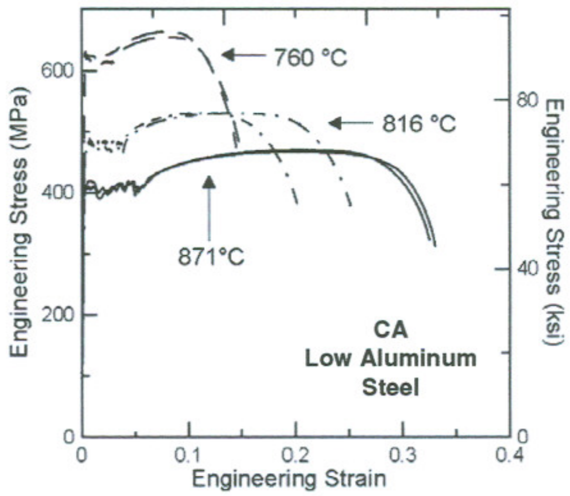


(a)

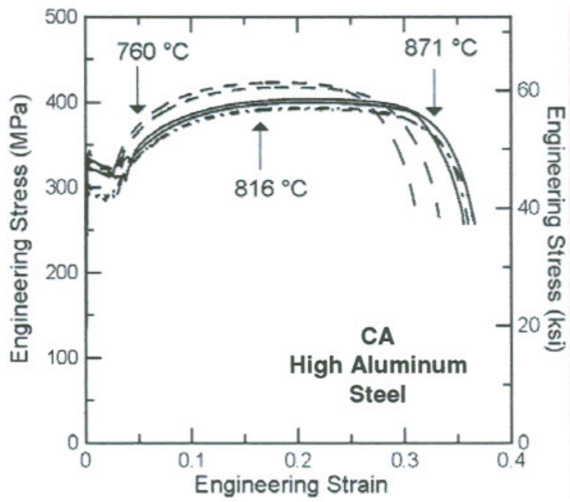


(b)

Fig 2 Stress strain behavior of batch annealed steels processed (a) 690 °C; (b) 720 °C (duplicate samples shown for each test condition).



(a)



(b)

Fig 3 Stress strain behavior of steels continuously annealed at the indicated temperatures: (a) low Al steel; (b) high Al steel (duplicate samples shown for each test condition).

at three different continuous annealing temperatures. The properties in the high-Al steel are not greatly influenced by temperature (Fig. 3b), and suggest complete recrystallization in each instance. In the low-Al steel (Fig. 3a), the higher strength and lower ductility at low annealing temperatures is indicative of incomplete recrystallization, presumably due to greater boundary pinning effects of the V(C,N) precipitate dispersions that form in this steel, in comparison to AlN and VC in the high-Al steel. As in the hot-band and batch annealed conditions, the low-Al steel exhibits higher strength after continuous annealing. The strength difference between the two steels approaches 100 MPa when the steels are compared in the fully recrystallized condition. Light optical metallography confirmed that the high-Al steel recrystallized at all of the continuous annealing temperatures, while the low-Al steel was fully recrystallized only at the highest temperature of 871 °C[3].

Electron microscopy was conducted to examine the precipitate distributions directly, and thereby understand more clearly the controlling mechanisms. Both thin foils and carbon extraction replicas were examined, and energy dispersive x-ray microanalysis (EDS) of small particles was conducted to characterize particle compositions. The thin-foil results presented here focus on the two steels after continuous annealing at 871 °C. Recall that the high-Al steel clearly influenced properties and recrystallization behavior, presumably due to AlN formation influencing the V(C,N) precipitation behavior.

Figure 4 (low-Al steel) shows the presence of vanadium (as identified by the inserted x-ray spectra) in the particles #6 and #7 identified in the figure. Similar observations were made for the other particles highlighted in the figure. In contrast, Figure 5 (high-Al steel) shows the presence of aluminum (see inserted x-ray spectra) in particle #4 identified in the TEM image. Also suggested by a comparison of Figs. 4 and 5 is that the average particle size is finer in the low aluminum steel in comparison to the high aluminum steel, leading to the observed retardation in recrystallization response and higher strength in the low aluminum steel.

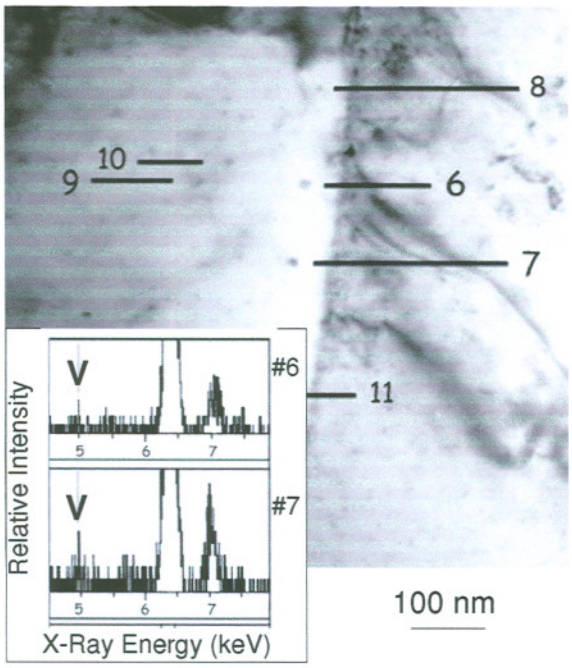


Fig 4 Transmission electron micrograph of the low aluminum steel with superimposed x-ray spectra for particles #6 and #7 showing the presence of vanadium in each particle.

An analysis[3] was conducted to estimate the level of precipitation strengthening in the two steels in various conditions. Figure 6 shows the results of the strengthening analysis for the two steels. The greater strengthening contribution in the low-Al steel is apparent in all conditions, particularly after annealing, reflecting the enhanced V(C,N) coarsening resistance. The two sets of values shown for the as-rolled hot-band reflect uncertainty in the solute nitrogen level in this condition. Nitrogen is assumed to be fully combined as AlN or V(C,N) after annealing. Calculated precipitation strengthening increments are not shown for the low-Al steel after continuous annealing at low temperatures, where recrystallization was incomplete. Interestingly, the precipitation strengthening increment in the cold rolled low-Al steel was greater than in the as-rolled hot-band. This behavior is different than has been reported previously, and may reflect incomplete precipitation in the outer wraps of the hot-rolled coil provided for this study.

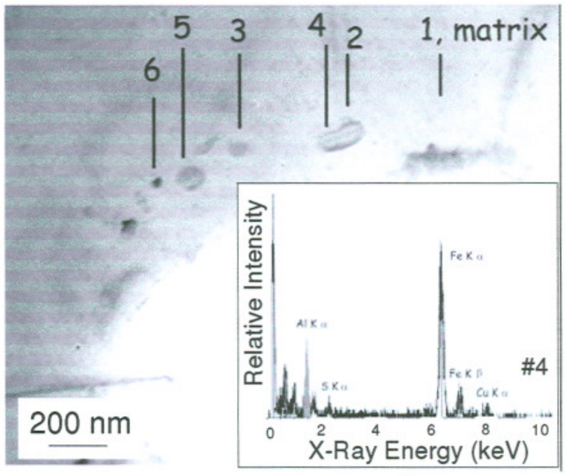


Fig 5 Transmission electron micrograph of the high aluminum steel with superimposed x-ray spectra for particle #4 showing the presence of aluminum.

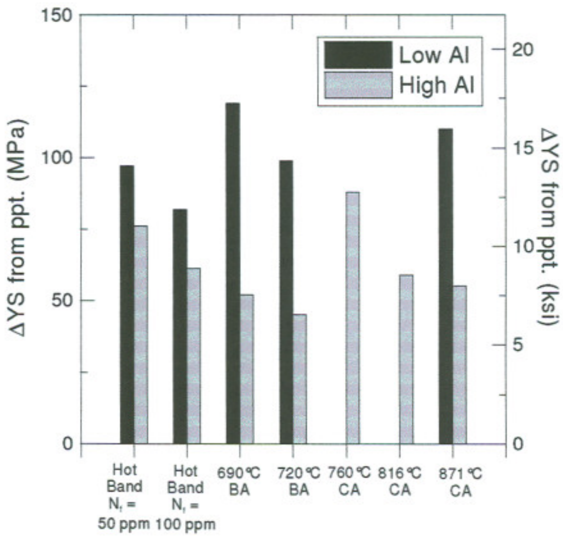


Fig. 6 Predictions of the increment of strength due to precipitation for the indicated conditions[3].

4 Summary

Precipitate coarsening during annealing has limited the application of vanadium in high strength cold-rolled sheet. The results presented here show important influences of aluminum in V-containing HSLA sheet produced via the CSP (thin slab casting and direct rolling) process. Aluminum competes with vanadium for the available nitrogen, and lower Al levels were found to result in higher strength in the hot-band, and in the batch and continuous annealed conditions after cold-rolling. The recrystallization temperature in the continuous annealed steels was also shown to increase in the low-Al steel. AlN was prominent in the high-Al steel, while finer V(C,N) was the dominant precipitate in the low-Al steel. The effectiveness of vanadium as a strengthener in cold-rolled HSLA products should be examined further in steels where sufficient nitrogen is available to enhance the coarsening resistance of the microalloy precipitates.

References:

[1] Gladman T, The Physical Metallurgy of Microalloyed Steels, London, The Institute of Materials, 1997.

[2] Pradhan R, Rapid Annealing of Cold-Rolled Rephosphorized Steels Containing Si, Cb, and V, in The Metallurgy of Continuous Annealed Sheet Steel, TMS, 1982, 203-27.

[3] Garrison J A, Aluminum Nitride Precipitation Behavior in Thin Slab Material, M.S. Thesis, Colorado School of Mines, Golden, Colorado, 2005.

[4] Garrison J A, *et al.*, Aluminum Nitride Precipitation Behavior in Thin Slab Material, AISTech 2005 Proceedings, AIST, Warrendale, PA, 2005, 107-16.