Microalloyed Forging Steels

C.J. Van Tyne, D.K. Matlock, and J.G. Speer
Advanced Steel Processing and Products Research Center
Colorado School of Mines
Golden, CO 80401 USA

ABSTRACT

Microalloyed forging steels offer the forge shop opportunities to produce steels with specific properties, which may be optimized for a specific application. For example, automotive components are continually being refined to produce vehicles that have both improved fuel efficiency and performance. To achieve these goals, lighter-weight vehicles with better engines, power trains, and suspensions are required. To meet these needs, forged microalloyed steels are increasingly used in a variety of components, including crankshafts, connecting rods, suspension systems, spindles, and driveline components. This increased use of microalloyed forging steels is due to the improvements in properties and performance that are obtainable with these steels. Depending on the application and alloy, microalloyed forging steels are used as direct-cooled components (i.e. parts that are control-cooled from the forging temperature) or as heat-treated parts for applications that require post-forging heat treatments such as induction hardening or carburizing. Careful application of fundamental microalloying principles may allow the forge shop to "add value" to their product by using the forging process as a form of controlled thermomechanical processing that enhances the microstructure and properties of forged components.

This paper reviews microalloying strategies for forging steels utilized in both the as-forged and heat treated conditions. The principal microalloying elements involved are vanadium and/or niobium, and the specific selection depends on carbon content, processing conditions, and application requirements. Vanadium contributes primarily through precipitation strengthening or resistance to softening during tempering; and niobium contributes through grain refinement or control of transformation kinetics, and sometimes through precipitation strengthening. Examples are presented of work at the Advanced Steel Processing and Products Research Center, an Industry-University Cooperative Research Center at Colorado School of Mines. One example shows the effectiveness of relatively high niobium levels for suppressing austenite grain growth and improving bending fatigue performance, enabling increased carburizing temperatures and productivity for forged gear applications. Another example shows the benefits of a vanadium microalloyed machinable steel for automotive rear spindles. The steel has not only increased strength and good machinability, but also increased toughness when coupled with the appropriate forging process.

Introduction

Microalloyed bar and forging steels have been developed over the past several years and are increasingly employed, particularly in high performance applications in the transportation sector. Common applications include a variety of engine, transmission, suspension, and driveline components [1-9] such as gears, springs, crankshafts, connecting rods, axles, spindles, etc. In most cases, these applications use microalloy precipitation for strengthening and/or grain refinement. The fundamentals of the precipitation and/or grain refinement are reviewed briefly. Differences encountered among the various applications stem from their different service requirements, which drive the use of different steel compositions and base microstructures (ferrite/pearlite, bainite, or martensite).

Fundamentals of Microalloyed Bar and Forging Steels

Microalloyed bar and forging steels employ small additions of niobium (columbium), vanadium, and/or titanium to improve the microstructure and properties, or to enable alternative processing routes. The property improvements can be considerable, especially when one considers that the microalloying additions are less than several hundredths of one weight percent. While solute effects of these microalloys can occasionally be important, these elements usually form carbides, nitrides, or carbonitrides, and contribute by restricting [5,9] the movement of either dislocations or interfaces, i.e. through precipitation strengthening or grain refinement. Both of these mechanisms are enhanced by fine particle sizes, so the design and implementation of microalloyed bar and forging steels involves tailoring the composition and processing to employ the requisite precipitation mechanisms under appropriate composition and processing constraints.

The critical processing and composition constraints relate most prominently to the carbon content and processing temperatures, which strongly influence the dissolution and precipitation behavior of the controlling microalloy element. Carbon can range from lower carbon steel forgings to high-carbon martensitic steels employed in surface hardened gears; while intermediate carbon levels are used in other components (e.g. springs, shafts, etc.) where a balance between strength and toughness is needed. From a processing standpoint, steels employed in the as-rolled or as-forged condition are reheated and then deformed at elevated temperature prior to transformation during cooling, while heat-treated steels are austenitized at somewhat lower temperatures before cooling to create the final microstructure. The reheating temperature, in combination with the steel composition, controls the extent of microalloy dissolution, and consequently, the amount of microalloy addition available for subsequent precipitation. Fundamental solubility relationships control these behaviors. Precipitate dissolution and precipitation behaviors in microalloyed steels have been reviewed extensively elsewhere [10] and will not be developed in detail here, but it should be recognized that the solubility of a precipitating compound such as NbC, V(C,N) or TiN is influenced by both the microalloy and interstitial concentrations and that there are substantial differences in the behavior of different species. For example, TiN is very stable, usually precipitates at high temperatures in the austenite regime, and resists subsequent coarsening. Vanadium carbonitride, V(C,N), is much less stable, is generally easily dissolved during austenitizing, and precipitates at lower temperature. Niobium has intermediate solubility and may be employed as either a solute or precipitate in austenite (to influence the austenite thermomechanical processing response), or as a fine strengthening precipitate in ferrite. TiN is often avoided in forged components because TiN is very hard, and stable particles that form at high temperature may be detrimental to machinability or toughness and usually contribute little to strength.

As-forged steels employ intermediate to high reheat temperatures with moderate carbon levels (e.g. crankshafts) or higher carbon levels for as-forged applications requiring high-fatigue strength. Higher carbon forgings are associated with reduced solubility in combination with lower reheat temperatures, so niobium levels are very limited, while vanadium additions can be more substantial. Thus, vanadium microalloying is predominant in these steels, although growing importance is being placed on dual additions of vanadium with lower levels of niobium. Nitrogen additions are useful to enhance precipitation strengthening in the vanadium applications [11]. At high reheat temperatures, niobium solubility is greater, and significant levels of either niobium or vanadium may be usefully employed, particularly at lower carbon levels where niobium solubility is greater. Niobium offers added potential in as-rolled or as-forged applications for "austenite conditioning" as part of the thermomechanical processing strategy, in which niobium may contribute by precipitating preferentially on the deformed austenite substructure, suppressing austenite recrystallization, thereby refining the final microstructure. Warm working may further enhance properties, and there are opportunities to develop novel thermomechanical strategies to achieve substantial additional microstructural refinement [12,13].

Steels that are heat-treated after forging may employ microalloying for austenite refinement, or for precipitation strengthening of the as-transformed or subsequently tempered microstructure. Here, complete microalloy dissolution at the austenitizing temperature is undesired, and an array of precipitates that is both fine and coarsening-resistant is most helpful to suppress austenite grain growth. Niobium and titanium are therefore most readily applied for this purpose, and their limited solubility at low austenitizing temperatures precludes substantial precipitation strengthening or secondary hardening (or resistance to softening during tempering) in the final microstructure [5]. Vanadium is more soluble at these temperatures, and may be considered as a potential strengthener, even at low austenitzing (or carburizing) temperature or high carbon levels. Again, nitrogen additions may enhance the effects of vanadium, and competition between aluminum and vanadium for the available nitrogen should be considered.

The preceding paragraphs have outlined the essential alloy and process design strategies that may be employed in microalloyed bar and forging steels to control the interactions between chemical composition and processing, and their influences on microstructure and properties that control performance. Matlock and Speer [14] provide more detailed information about microalloying concepts. Selected background and application examples are cited below. Application of these strategies to specific components involves tailoring a particular alloy design to meet the property and processing requirements of the application [2]. These microalloying strategies are increasingly employed to increase strength and performance, or to reduce the number of heat-treating steps while maintaining adequate performance. The use of microalloyed forging grades to replace quench-and-tempered components has been extensively documented and employed in numerous applications.

Microalloying to Maintain Fine Grains During Carburizing

Many forged gears are carburized in order to improve their fatigue strength and wear resistance during service. Conventional gas carburizing treatments are usually performed at relatively low temperatures in the austenite phase field, where austenite coarsening is minimal and/or suppressed adequately by the presence of AlN. New furnace technologies such as low-pressure or plasma carburizing are driving interest in much higher carburizing temperatures, because of their capability to operate at elevated temperatures and their inherently lower productivity. Reduced productivity can be mitigated somewhat by operating at a higher temperature, due to the enhanced mobility of carbon, so long as other detrimental factors such as grain coarsening can be avoided. In carburized gears, austenite grain coarsening has been shown to diminish bending fatigue performance, and microalloying strategies are thus desired to suppress austenite grain growth in carburizing grades at elevated temperature.

Initial efforts by Davidson and co-workers at the Advanced Steel Processing and Products Research Center (ASPPRC) at Colorado School of Mines examined the potential of TiN to pin austenite grain boundaries at elevated temperature [15]. TiN was chosen for evaluation because it is the most stable of the common microalloy precipitates and is well known to suppress austenite grain coarsening at an elevated temperature. Controlled variations of titanium and nitrogen were made and compared to a base 8620 conventional grade steel. Systematic differences in TiN fractions and solute titanium and nitrogen levels (which influence precipitate coarsening kinetics) were observed, along with some suppression of austenite grain coarsening. The contributions of TiN to the existing AlN effects in these steels were relatively small, however, and follow-up work was designed to employ further contributions from NbC. Due to its typically lower precipitation temperature, niobium carbide offers the potential to create a finer precipitate dispersion than TiN, although the particle stability and coarsening resistance are also correspondingly lower.

AlOgab et al. designed a series of Ti-Nb modified 8620 steels to examine niobium contributions and thermomechanical processing influences on austenite grain coarsening during pseudo-carburizing (simulative heat treatments in the absence of the carburizing atmosphere) [16,17]. The steel chemical compositions involved a 0.03Ti addition (approximately stoichiometric with respect to nitrogen), with niobium variations of 0.0, 0.02, 0.06, and approximately 0.1 (wt%). The precipitate dispersions and austenite grain growth behavior were characterized as a function of composition and processing. The niobium-added alloys exhibit substantially finer prior-austenite microstructures at low carburizing temperatures. The beneficial pinning effects of NbC persist to elevated temperature for the higher niobium steels, while abnormal grain growth in the lower niobium steels begins as a consequence of reduced particle fractions. The 0.1 Nb steel offers the potential for suppression of grain growth at temperatures up to about 1050° C, which is substantially higher than is typical for conventional gas carburizing treatments. Such an increase in carburizing temperature could enable productivity increases on the order of 40% [18] due to the increased carbon mobility in austenite (i.e. reduced carburizing time to achieve a given case depth) at elevated temperature.

Because of the promising results of this study, follow up research was conducted by Thompson et al. with the same Ti/Nb modified 8620 steels to confirm the earlier pseudo-carburizing results under processing conditions applicable to commercial low-pressure carburizing at elevated temperatures, and to examine the influence of niobium on the associated bending fatigue properties [19]. Figure 1 shows selected bending fatigue results (applied stress versus cycles to failure), confirming the improved response of the higher niobium steels, due to suppression of abnormal austenite grain growth during carburizing. This series of studies establishes the potential for microalloying to enable elevated temperature heat-treating of bar and forging steels in applications sensitive to austenite grain growth.

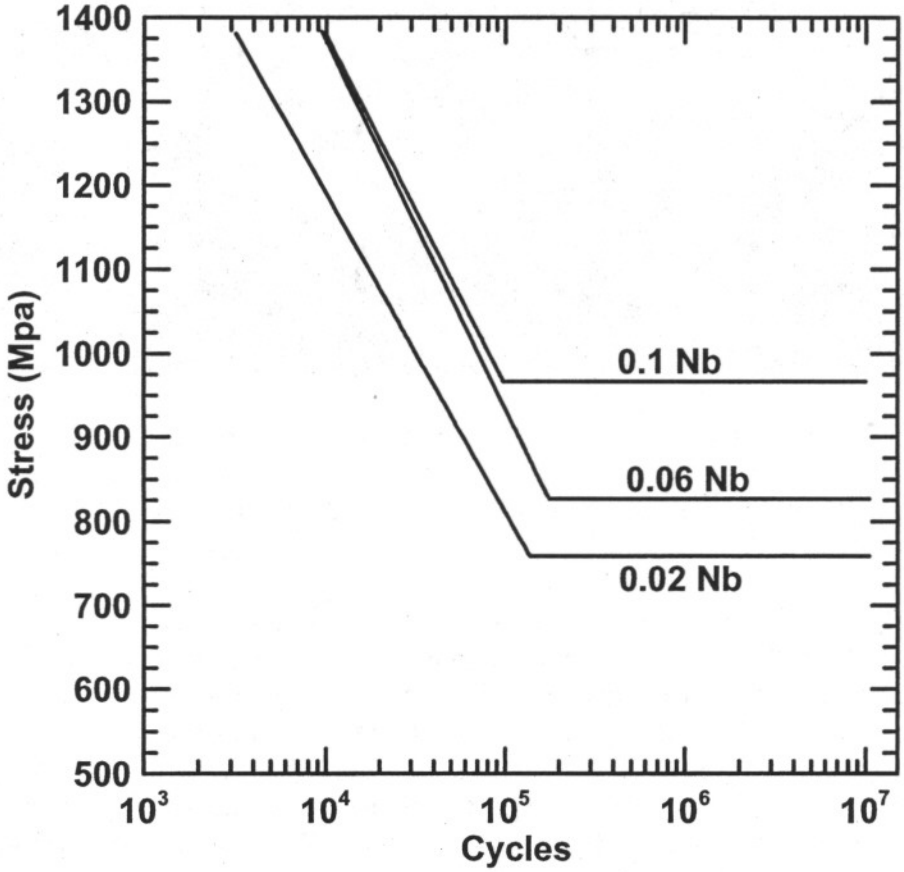

Figure 1 Comparison of experimental bending fatigue S-N curves for Ti/Nb modified 8620 steels with varying niobium additions, showing increased fatigue life and endurance limits with higher niobium additions. Specimens were processed by low-pressure carburizing at1050° C [19].

Forged Automotive Spindle

Other work at the Advanced Steel Processing and Products Research Center by Kirby et al. [20,21] examined the use of vanadium as a microalloy addition to medium carbon steels with higher amounts of sulfur. Five heats of a vanadium microalloyed steel with carbon contents from 0.29% to 0.40% and sulfur contents from 0.031% to 0.110% were forged into automotive spindles and air cooled. Figure 2 shows the forging sequence for the spindle.

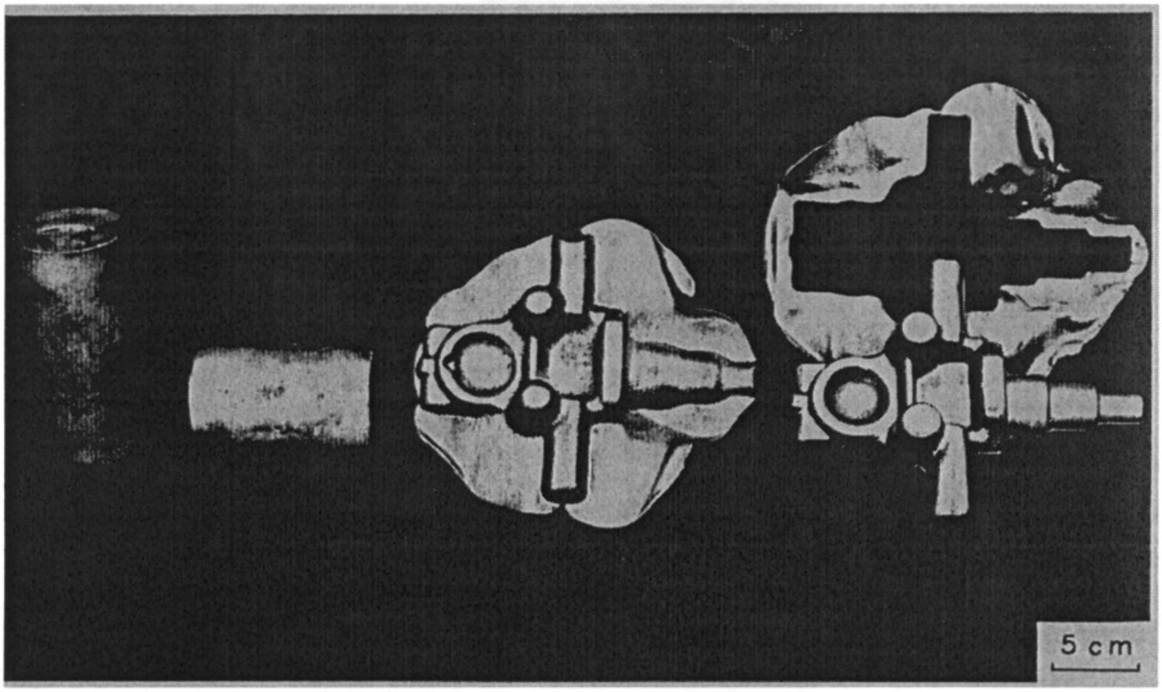

Figure 2 Sequential steps in the forging of the automotive spindle. Shown from left to right are the mult, after a 10% upset to remove the scale, after the blocker where the mult is side struck, and after the finisher with trimmed flash.

The microstructures of the five steels consisted of pearlite and ferrite. The ferrite nucleated both on the prior austenite grain boundaries and intragranularly on the dispersed sulfide inclusions. The room temperature tensile strengths ranged from 820 MPa to 1000 MPa. Charpy V-notch specimens were machined from the spindle at a location where failure would likely occur during service in an automobile. Figure 3 shows the location of the specimens. The room temperature impact values ranged from 13 J to 19 J. The best ductile-to-brittle transition temperatures were associated with steels containing the higher sulfur contents. Bending fatigue specimens were extracted from the spindle at the same location as the Charpy specimens. None of the steels failed in bending fatigue at stress levels below the yield strength. The higher sulfur containing steels also had better machining characteristics.

The improved impact and fatigue properties were attributed to two factors. The first factor is the grain flow in the spindle. The crack propagation direction for both impact and fatigue was perpendicular to the grain flow. Coordination between the forge shop and the end use allowed the favorable grain flow to be located intentionally in the critical performance region of the component. The second factor is the combination of vanadium microalloy additions to the high-sulfur steels. In this case, the vanadium precipitates during cooling on the MnS inclusions providing nucleation sites for intragranular ferrite. The formation of intragranular ferrite decreased the ferrite mean free path, which in ferrite-pearlite steels decreases the ductile-to-brittle transition temperature.

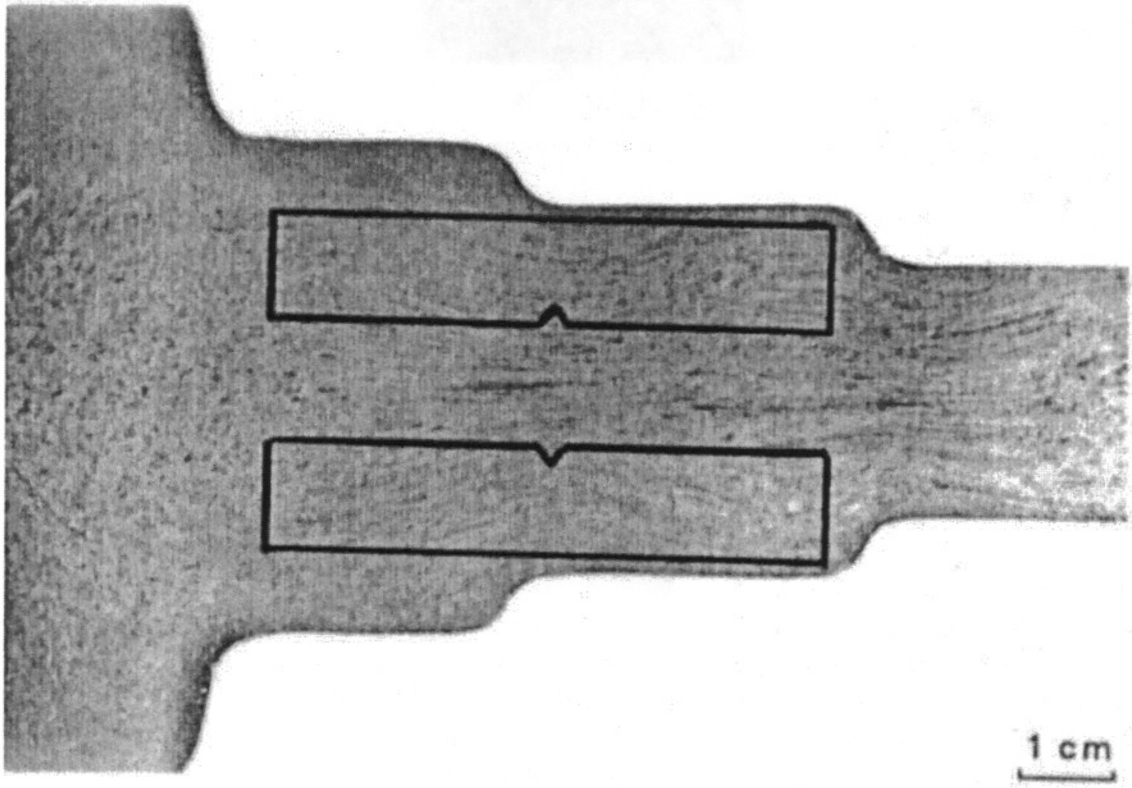

Figure 3 Location of Charpy specimens extracted from spindle. Note that the grain flow in the spindle is perpendicular to the notch.

Summary

Microalloy additions of vanadium and niobium can provide improved properties in forged steel components. The dissolution process of these microalloying elements needs to be understood and controlled during forging and post forging operations. Two specific examples of improved steel properties were presented. The first example was the use of niobium to increase the bending fatigue endurance limit of a carburized component for forged gear applications by controlling austenite grain coarsening, while the second example was the use of vanadium to produce intragranular ferrite in medium-carbon steels to improve the impact properties of an automotive spindle.

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