PROPERTY AND MICROSTRUCTURE VARIATION IN FORGING BAR STEELS

L.M. ROTHLEUTNER¹, A.S. HERING², AND C.J. VAN TYNE³

¹Graduate Research Assistant and FIERF Forging Fellow, Dept. of Metallurgical and Materials Engineering, Colorado School of Mines, Golden, CO 80401 USA
²Assistant Professor, Dept. of Mathematics and Computer Sciences, Colorado School of Mines, Golden, CO 80401 USA
³FIERF Professor, Dept. of Metallurgical and Materials Engineering, Colorado School of Mines, Golden, CO 80401 USA

ABSTRACT

The properties and microstructure of commercial vanadium microalloyed bar steels used in air-cooled forging applications were evaluated. The bar steels were characterized in the hot-rolled condition to gain an understanding of their radial variation in properties, chemistry, and microstructure prior to being reheated for forging. Improved understanding of these variations allows for greater optimization of forging processes and component design. Distinct radial gradients in hardness, chemical composition, phase fraction, and grain size were found. The highest hardness, highest carbon composition, and highest pearlite area fraction were located at the mid-radius of all steels examined.

INTRODUCTION

The complexity of many metallurgical processes frequently results in inconsistent products. Although these inconsistencies are often subtle and fall well within customer specifications, component design can be further optimized with improved understanding of the inherent chemical, microstructure, and property variations of the raw materials. Forgers need to be aware of these variations in chemistry and properties in the raw material when they design their forging sequences, and when analyzing problems that are related to the materials used in their operations. This study examined three variations of a medium-carbon microalloyed steel used as round bar stock for producing forged engine crankshafts. Because the material will be further processed into a critical component in internal combustion engines, failure of the product during use would be catastrophic.

MATERIAL

A medium-carbon vanadium microalloyed steel (SAE 15V41) with three separate aluminum additions were examined. Table 1 provides the nominal composition for the steel. The 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 117.5mm (4-5/8 in) round bar. Hereafter the steels will be designated by their respective aluminum content: 6Al, 20Al, and 31Al.

Table 1 – Chemical Composition (wt. pct) of the Modified SAE 15V41 Base Steel

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Al</th>
<th>N</th>
<th>S</th>
<th>P</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.37</td>
<td>1.36</td>
<td>0.63</td>
<td>0.13</td>
<td>0.08</td>
<td>0.02</td>
<td>0.088</td>
<td>var.</td>
<td>0.0153</td>
<td>0.064</td>
<td>0.010</td>
<td>0.18</td>
</tr>
</tbody>
</table>

EXPERIMENTAL PROCEDURES

Cross-sections of the hot-rolled 6Al, 20Al, and 31Al steels were prepared using a water-cooled abrasive cut-off saw and were wet-sanded smooth using 240 grit silicon carbide sand paper. Two cross-sections of each steel were examined; one was used for chemical analysis while the other was used for hardness testing and metallography. Both the hardness testing and the chemical analysis were done on 5 mm (0.1970 in) intervals across the cross-sections, towards the center of the bar, beginning 4 mm (0.1575 in) from the circumference. Figure 1a and 1b show schematics of the HRC traverses, as well as the chemical analysis traverse conducted. The consistent interval facilitated a direct comparison of the hardness and chemical analysis data.

Chemical compositions were determined from a single traverse while hardness testing was done on 25 traverses (every 15 degrees) for each steel. Chemical analysis was done via inert gas fusion (LECO) for nitrogen and optical emission spectroscopy (OES) for all other elements of interest. A discrepancy was discovered with the procedures used to collect the nitrogen data; therefore, the nitrogen data will not be
presented as part of this analysis. Hardness traverses were done using the Rockwell “C” scale (HRC). Metallography samples were prepared from the cross-sections of each steel which were hardness tested. Samples were taken at the edge, mid-radius, and center positions in the longitudinal and transverse directions. Phase fractions, ferrite grain sizes, and inclusion distributions were determined for all samples. Figure 1 also shows the location of metallography specimens.

RESULTS AND DISCUSSION: HARDNESS

The hardness traverses indicate that a distinct radial hardness gradient is present in all three steels. The hardness is at a minimum near the circumference, rises to a maximum just before the mid-radius, and decreases towards the center. Figure 2 shows polar contour plots for the three steels. The contour plots indicate the gradient characteristics are relatively consistent among the three steels. To verify this observation, the hardness observed at each radial distance were verified to be consistent with a normal distribution, then averaged, and 95 pct confidence intervals were constructed for the mean.

Figure 2 Polar contour plots of hardness as a function of radial distance and angle for (a) 6Al, (b) 20Al, and (c) 31Al steels.

Figure 3 shows the mean hardness and 95 pct confidence intervals as a function of distance from the surface of the bar, as well as both polynomial and locally-weighted scatterplot smoothing (LOESS) regression fits for the aggregated hardness data. The confidence intervals for the three steels at all radial distances overlap, which indicate that at the 95 pct level, there is no statistical difference between the mean hardness of the three at a given distance from the surface. Both polynomial and LOESS regression fits were developed to model the trend observed in the hardness gradient for the grouped hardness (1). A fifth-order polynomial fit was determined to best describe the data based on p-values of coefficients, residual plots, and visual inspection of the fit quality. An adjusted coefficient of determination (adjusted $R^2$) of only 0.5619 was achieved with the fifth-order polynomial, due to the large variation in hardness values observed at a given distance from the surface. Although polynomial regression is commonly used to describe nonlinear patterns in data, a LOESS regression fit is much more robust. The LOESS regression is a locally-weighted polynomial regression fit that
is ideal to use in modeling complex empirical data for which no theoretical model exists. Therefore, a LOESS regression was also used to fit the hardness profile. Both the polynomial and LOESS fits are relatively consistent with each other.

Figure 3 Radial hardness profile in the hot-rolled 6Al, 20Al, and 31Al steels in the transverse direction. Error bars represent the 95 pct confidence interval for the mean. Both fifth-order polynomial and locally weighted scatterplot smoothing (LOESS) fits are plotted for the data.

RESULTS AND DISCUSSION: CHEMICAL COMPOSITION

To better understand the cause for the radial hardness gradient, chemical compositions were taken at the same interval as the hardness testing on a separate cross-section of each steel. Figure 4 shows a paired plot of the combined hardness and chemical analysis data for all three steels. The paired plot is intended as a qualitative method to readily determine relationships between hardness and certain key alloying elements. The lower panel contains scatterplots with LOESS regression fits, the diagonal has histograms for the individual variables, and the upper panel shows the absolute value of the Pearson correlation coefficient along with coefficient significance (e.g. *** denotes a p-value between 0.000 and 0.001). The relatively high correlation coefficient between the chemical data was anticipated since the high sulfur content of the steel promotes MnS inclusions for which nitrogen rich V (C, N) precipitate on at high temperature and provide preferential nucleation sites for ferrite upon cooling (2). However, of all the alloying elements recorded from the OES data, only carbon has a reasonably high correlation with hardness.
Figure 4  A paired plot used to readily identify potential relationship between hardness, carbon (C), manganese (Mn), sulfur (S), and vanadium (V). Hardness was measured on the Rockwell “C” scale while the chemical elements were measured in wt pct. Paired plots with LOESS fitting on the lower half of the plot, histograms for the individual categories of data in the diagonal, and the absolute value of the Pearson correlation coefficient along with coefficient significance in the upper half of the plots. Level of significance is as follows:

0 *** 0.001 ** 0.01 * 0.05 - 0.1 · 1

In order to directly compare hardness to the carbon content of the three steels, a similar analysis is done for carbon as previously presented for hardness. Figure 5 shows the radial carbon profile for the three steels along with appropriate polynomial and LOESS regression fits. Although only a single traverse was done for each steel, the carbon data between the different steels agree very well and show similar profile characteristics, as did the hardness data.
Figure 5  Radial carbon profile in the hot-rolled 6Al, 20Al, and 31Al steels in the transverse direction. Both fifth-order polynomial and LOESS (locally weighted scatterplot smoothing) fits are plotted for the data.

The hardness and carbon data were best represented by fifth-order polynomial fits. Figure 6 shows a comparison plot of the polynomial and LOESS fits for the combined hardness data as well as for the combined carbon data for the three steels. The overall graphical shape of the hardness and carbon data are similar; however, they peak at slightly different locations. This may be a result of the increased variability in the carbon data due to the relatively small number of data points or the different amount of material being sampled between the different testing techniques. The Rockwell “C” hardness scale samples a relatively small area (approximately 1 mm) with a reasonable amount of depth (approximately 0.18 mm for 20 HRC materials) (3). Optical emission spectroscopy samples a relatively large area (approximately 4 mm) with very little sample depth (on the range of 0.01 to 0.05 mm) (4).

Figure 6  Regression fits for both the combined hardness data and the combined carbon data. All data was centered and standardized to allow for comparison of the hardness and carbon fits.
RESULTS AND DISCUSSION: METALLOGRAPHY

Figure 7 shows representative micrographs for the 20Al steel from the edge, mid-radius, and center of the bar in both the longitudinal and transverse directions. All steels examined exhibit similar ferrite-pearlite microstructure with large inclusions, believed to be primarily manganese sulfide (MnS), which are desirable in this steel because of their ability to increase machinability. Grain boundary ferrite as well as a significant amount of intragranular ferrite can be seen at all three locations within the bar. Figure 8 shows the ferrite grain sizes for all steels in the longitudinal and transverse directions. All steels exhibit a continual increase in ferrite grain size from the edge towards the center of the bar in both the longitudinal and transverse directions. This indicates the ferrite grain size may be closely related to cooling rate, since the bar would cool fastest at the edge and more slowly at the center. The steel with the highest aluminum content exhibited the most equiaxed structure at all three locations analyzed in the bar. Figure 9 shows the relationship between the hardness data previously presented and the area fraction of pearlite, in the transverse direction, at each location within the bar. The area fraction of pearlite follows a similar trend as the radial hardness traverses where the mid-radius has the highest hardness and pearlite area fraction while the edge has the lowest hardness and pearlite area fraction. This trend is consistent between all three steels and indicates the pearlite area fraction has a significant impact on the hardness gradient. Figure 10 shows how the carbon content relates to the area fraction of pearlite. Although the carbon content and pearlite fraction trend well with hardness, the non-linear relationship between carbon content and pearlite fraction indicate that carbon content alone is not controlling the fraction of pearlite in the steels examined. Figure 11 shows the inclusion morphology characteristics for all steels. All inclusion data were found to most closely fit a lognormal distribution. Inclusion area and Feret diameter (i.e. maximum caliper) are smallest and most consistent between the longitudinal and transverse directions at the edge of the bar in all steels. Inclusions at all locations in the bar appear to be elongated in the rolling direction. In most instances, this is apparent in the mean aspect ratio as well as the spread of the variance of the mean.

Decreased inclusion size at the edge indicates the bar experienced more deformation during hot rolling at the edge than any other location within the bar. The increased deformation decreased the overall size while increasing the quantity of inclusions. Since MnS inclusions have been shown to inhibit austenite grain growth (5), as well as nucleate ferrite in vanadium microalloyed steels (2), the differences in pearlite fraction may be due to a combination of carbon segregation and inclusion effects.
Figure 7  Representative optical micrographs of the 20Al steel. Micrographs (a), (c), and (e) represent longitudinal samples at the edge, mid-radius, and center of the bar, respectively. Micrographs (b), (d), and (f) represent transverse samples at the edge, mid-radius, and center of the bar, respectively. All micrographs were taken at 100x magnification with a four pct picral etch.
SUMMARY AND CONCLUSIONS

An SAE 15V41 steel used for air-cooled forgings with three variations in aluminum content were analyzed in the hot-rolled condition prior to reheat for forging. Variations in hardness, chemistry, and microstructure were examined, and have resulted in the following observations:

- A distinct radial hardness gradient exists in all three of the steels with the highest hardness close to the mid-radius of the bar. No statistically significant difference
is observed between the hardness gradients of the three steels at the 95 pct confidence level.

- Chemical analysis indicates there is a significant correlation between all elements presented: carbon, manganese, sulfur, and vanadium. Carbon provides the best correlation with hardness out of the elements examined.

- A fifth-order polynomial regression fit best represents the combined hardness data and combined carbon data from all three steels. Comparison of polynomial regression fits and locally weighted scatterplot smoothing (LOESS) fits for the combined hardness data and combined carbon data show similarities in shape; however, their maxima occur at slightly different locations. This difference may be a result of the different volume of material analyzed by the two techniques used to obtain the data or different sample sizes leading to differences in variability of the two curves.

- Pearlite area fraction varies radially in all of the steels. The area fraction of pearlite closely correlates with the observed hardness gradient. The mid-radius of all steels, in the transverse direction, contained the largest area fraction of pearlite at approximately 0.80.

- Ferrite grain size is smallest at the edge and increases towards the center of the bar.

- Inclusion area and Feret diameter are smallest at the edge of the bar. The mean and variance of the aspect ratio indicates that the inclusions are elongated in the rolling direction, and are closest to equiaxed at the edge.

![Figure 10](image-url) 

Figure 10  Pearlite area fraction plotted as a function of carbon content in the transverse direction. Error bars represent the 95 pct confidence interval for the mean.
Figure 11  Average inclusion (a) area, (b) Feret diameter, and (c) aspect ratio at the edge, mid-radius, and center for each steel in the longitudinal (L) and transverse (T) directions. All characteristics were best fit by a lognormal distribution. Error bars indicate one standard deviation from the mean.
REFERENCES


ACKNOWLEDGEMENTS

Support for this work by the Advanced Steel Processing and Products Research Center at the Colorado School of Mines and by FIERF in the form of 2010-2011 FIERF fellowship for L.M. Rothleutner is gratefully acknowledged.