

Effects of Chemical Composition, Heat Treatment, and Microstructure in Splittable Forged Steel Connecting Rods

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ABSTRACT

Fracture split forged steel connecting rods are utilized in many new high performance automotive engines to increase durability. Higher strength levels are needed as the power density increases. Fracture splitting without plastic deformation is necessary for manufacturability. Metallurgical design is a key for achieving the required performance levels. Several medium carbon steels containing 0.07 wt pct P, 0.06 wt pct S and various amounts of Mn, Si, V, and N were produced by vacuum induction melting laboratory heats and hot working the cast ingots into plates. The plates were cooled at varying rates to simulate typical cooling methods after forging. Microstructures were generally ferrite and pearlite as evaluated by light optical and scanning electron microscopy. Mechanical properties were determined by standard tensile tests, high strain rate notched tensile tests, and Charpy V-notch impact tests to assess "splittability". The test results indicate that large prior austenite grain sizes achieved during heating for rolling and increased cooling rates after hot working decreased the fraction of ferrite, leading to higher strength levels. Increased levels of V and N also increased the strength. At higher strength levels the amount of fracture deformation was reduced as measured in the notched tensile test results, and impact transition temperatures were higher. An additional steel containing Cr, Ti, and B resulted in a bainitic microstructure with a higher tensile strength than the ferrite-pearlite microstructures and maintained low levels of plastic deformation in the notched tensile test.

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INTRODUCTION

In the automotive industry there is continued demand to increase strength, endurance, and efficiency of vehicle components, while maintaining minimal weight and cost. The splittable, wrought, forged microalloyed steel connecting rod is one of several relatively new technologies that are advancing [1]. The splittable connecting rod utilizes controlled fracture to split the rod and cap using two notches on the split line 180° from each other (Figure 1). A controlled fracture method provides several advantages including a reduction in machining cost because no milling is required at the contact face. Additionally, a fracture surface rather than a machined surface at the contact face creates an interlock between the rod and cap due to the intimate and unique surface fit and the higher contact area [2, 3]. To optimize the interlocking characteristics of the fracture surface, it is essential that the fracture exhibit the maximum amount of cleavage (minimize local ductile fracture) while simultaneously maintaining excellent mechanical properties during service.

Even with the added manufacturing advantages of these forged rods, strength and machinability still limit further applications. A commonly used alloy in industry for this application is C70, a high (0.7 wt pct) carbon, fully pearlitic steel. The high carbon content of

this steel is reported to decrease machinability and tool life [4]. Furthermore, the maximum reported yield strength of this alloy is 550 MPa, which is adequate for some passenger vehicles, but not for larger vehicles, heavy-duty trucks, or industrial engine applications [2, 5]. These limitations are driving the development of new alloys with increased machinability and higher yield strength.



Figure 1. Example of a fracture split connecting rod with the fracture surface shown in the inset.

A concern with some alloys used in industry is consistent splittability. Current requirements for microalloyed steels used for forged connecting rods specify alloy composition as well as basic mechanical properties such as minimum yield or tensile strength. Input from industrial companies indicated that several alloys with similar reported compositions and tensile strength properties exhibit a wide variation in splitting performance. Ferrite contents ranging from 20 percent to upwards of 70 percent [6] have been observed in industrially produced connecting rods and light optical micrographs of examples are shown in Figure 2. The processing conditions for these connecting rods are unknown.

Splittability presumably depends on microstructural features, including the ferrite fraction, ferrite hardness and grain size in the steel, because these features have the largest impact on fracture mode (brittle/ductile). This behavior is examined further in the current study by varying the chemical compositions and thermomechanical processing parameters.

The purpose of this study was to provide an understanding of the microstructural characteristics and mechanisms that can provide higher strength levels while maintaining or improving splittability. Reducing the carbon content from the 0.7 wt. pct. C in C70 is expected to improve machinability, but also replaces some of the pearlite in the microstructure with lower strength ferrite. The increased ferrite fraction leads to lower yield and tensile strengths and promotes ductile behavior during fracture splitting. Sulfur (0.06 wt. pct.) was incorporated in the design of the test steels as it is commonly added to promote machinability in splittable connecting rods.

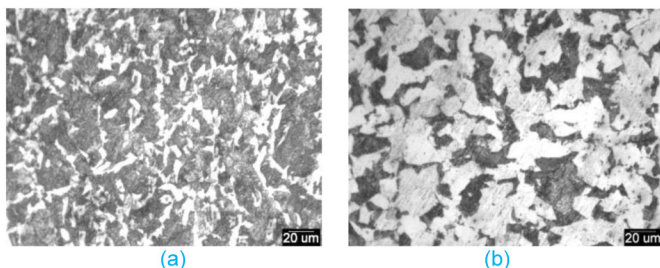


Figure 2. Example microstructures of connecting rods provided for fracture splitting with (a) 20 percent ferrite and (b) 70 percent ferrite [6].

EXPERIMENTAL METHODS

Materials

Eight experimental heats, identified as steels A-H and one commercial steel, C70 were selected for study. The chemical compositions listed as steels A-G in Table 1 were selected to evaluate the effects of carbon, manganese, vanadium, and nitrogen on the microstructure and mechanical properties of steels with ferrite-pearlite microstructures.

Phosphorous was added to all test steels as it is known to strengthen ferrite and reduce fracture ductility. Sulfur was added to levels typically utilized in forged connecting rods to promote machinability. Chromium, titanium and boron were added to steel H to produce an alternative bainitic microstructure. The experimental steels were

melted in a vacuum induction furnace and cast as small (135 mm diameter) ingots. Steel C70 is a commercially produced heat of steel that was continuous cast, and hot rolled to 57 mm diameter bars for manufacturing splittable connecting rods.

Table 1. Chemical compositions (wt. pct.) of vacuum induction melted laboratory steels and reference C70 connecting rod steel.

Steel	C	Mn	Cr	P	S	Si	V	N
A	0.31	1.33	0.19	0.06	0.068	0.75	0.302	0.010
B	0.41	0.96	0.11	0.07	0.054	0.6	0.097	0.0154
C	0.42	1.37	0.21	0.076	0.058	0.86	0.243	0.0198
D	0.38	1.04	na*	0.077	0.063	0.62	0.102	0.0090
E	0.4	1.03	na	0.067	0.066	0.58	0.193	0.0171
F	0.38	1.41	na	0.076	0.061	0.6	0.095	0.0090
G	0.4	1.01	na	0.067	0.058	0.86	0.098	0.0094
H**	0.27	1.31	1.28	0.066	0.041	0.82	0.149	0.0172
C70***	0.69	0.54	0.15	0.014	0.064	0.17	0.037	0.0087

*na = none added

** Also contains 0.07 Ti and 0.002 B

***Commercially produced C70

Thermomechanical Treatments

In producing steel connecting rods, billets (short pieces of hot rolled bars) are heated to temperatures of 1230-1260 °C and hot forged to the final shape in multiple progressive dies. After forging, the connecting rods can be cooled at different rates depending on whether they are dropped into a large container (slow cooling) or cooled as individual parts with fan-forced air on a conveyor. The forged connecting rods may then be supplied directly for further processing or they may be reheated and air cooled (normalized) to provide consistent microstructure and mechanical properties.

In this study, the 30 mm thick plates of steels D, E, F, and G that were hot rolled from the laboratory melted and forged ingots were cut into 13 mm strips. The strips were normalized by reheating as two separate series of tests to high and low temperatures (1200 °C and 900 °C) and cooling at the approximate rate of 1.5 °C/sec in still air [7]. The reference steel C70 was normalized at 950 °C after hot rolling to 30 mm thick plates and cutting into 18 mm thick strips. The cooling rate was the same as the normalized strips from the laboratory steels (1.5 °C/sec) [7].

Steels A, B, C, and H were processed to simulate forging and direct cooling. The laboratory ingots were first forged to 63 mm thick plates. The forged plates were reheated to 1260 °C and hot rolled in seven passes of 6.3 mm reduction in 90° alternating directions to 18 mm thick plates. Following hot rolling, the plates were cooled by four different methods to simulate the range of cooling rates typically observed in hot forging of connecting rods [8]. The methods and cooling rates are summarized in Table 2.

Table 2. Cooling rates after hot rolling to simulate forging.

Cooling Method	Cooling Rate, °C/sec (at 700-650 °C)
Fan Cooled	1.1
Cooled in Furnace set at 400 °C	0.8
Wrap in 1 layer of LyTherm® and cover with sand	0.15
Wrap in 2 layers of LyTherm® and cover with sand	0.05

Test Methods

Metallography

Specimens for light optical metallography were sectioned transverse to the rolling direction, parallel to the orientation of fracture surfaces on mechanical test specimens. The sectioned specimens were mounted in bakelite, polished using diamond to a surface roughness of 1 micron, and etched in 2% nital. The ferrite fractions (percent ferrite) were measured with the manual point count method (ASTM E562). For each sample a grid of 100 points was used and 95% confidence intervals were calculated based on 20 measurements. The ferrite grain diameter was also measured using the intercept method (ASTM E112), and 95% confidence intervals were calculated based on 20 measurements [7, 8].

Prior austenite grain sizes were determined for the normalized conditions by utilizing a separate sample that was immediately quenched from the normalizing temperature and then tempered for 3 hours at 300 °C. A hot saturated aqueous picric acid + HCl solution was used to reveal the prior austenite grain boundaries. The prior austenite grain size was measured by the Heyn lineal intercept procedure (ASTM E112) and 95% confidence intervals were calculated [7].

Mechanical Tests

Standard tensile tests, notched tensile tests, and Charpy V-notch (CVN) impact tests were conducted for all steels [7,8]. The test specimens were all oriented parallel to the direction of major elongation during forging and rolling the ingots into plates. All fracture surfaces after testing were transverse to the rolling direction to simulate the fracture direction during splitting of connecting rods. Standard tensile test specimens were prepared and tested according to ASTM E8, utilizing a 51 mm gauge length and a strain rate of 0.015 s^{-1} . CVN impact tests were conducted according to ASTM E23 on an impact machine with a 195 J capacity at various temperatures to establish ductile and brittle fracture behavior. The hammer velocity at initiation of fracture was 5500 mm/s. The impact transition temperature was selected as the temperature at which 20 Joules of energy was absorbed during fracture. The lateral expansion at the un-notched side of the fracture was measured for CVN specimens fractured at 20 °C and recorded as an indication of the amount of deformation that might occur during fracture splitting of connecting rods.

The notched tensile test specimens, designed to simulate the notch configuration in split connecting rods, were tested at 20 °C on a high strain rate servo-hydraulic tensile test machine at displacement rates equivalent to fracture speeds imposed during commercial connecting rod splitting. The specimen design is shown schematically in Figure 3

and the test is described in detail in a previous publication [9]. The testing speed for this study was selected as a cross-head speed of 250 mm/s, mid-range of the typical speeds reported for the fracture splitting process [10]. The reduction in the specimen thickness (dimension “d” in Figure 3) was measured at the fracture location to reflect the amount of deformation that occurred during the fracture process.

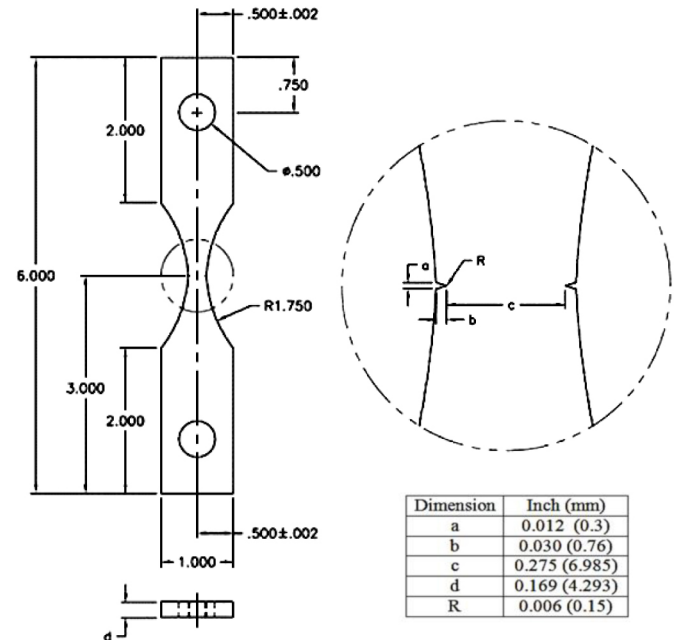


Figure 3. Notched tensile specimen design for high strain rate testing to simulate connecting rod fracture splitting

RESULTS

The results are presented below to show how processing affected the microstructure and how the microstructures affected the strength and splittability characteristics. Specific data for each material and process condition are summarized in the Appendix. The results presented here are summarized from two M. S. Theses at Colorado School of Mines [7,8].

Microstructures

The microstructures of all steels were ferrite and pearlite except the bainitic steel H that is discussed separately. The ferrite fractions are presented here, recognizing that the balance is pearlite. Selected microstructures for steels containing 0.4 wt. pct. carbon and low vanadium (0.1 wt. pct. V) or high vanadium (0.2 wt. pct. V) are illustrated in Figure 4 where the light regions are ferrite and the dark regions are pearlite. Heating to 1200 °C, which is typical of a forging reheating temperature, followed by air cooling results in a very large prior austenite grain size with a small fraction of ferrite grains (Figures 4a, 4b). Most of the ferrite grains nucleated at the prior austenite grain boundaries and some nucleated intragranularly at inclusions. Heating to 1260 °C and hot rolling provided some prior austenite grain size refinement and an increased fraction of ferrite (Figures 4c, 4d). Reheating to 900 °C after rolling produced a much smaller prior austenite grain size and an increased fraction of ferrite (Figures 4e, 4f).