Mass Reduction Opportunities Offered by Powder-Forged Connecting Rods

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ABSTRACT
The advent of direct injection turbocharged engines has increased the need for higher performance connecting rods, able to withstand higher compressive loads in operation. In this respect, the compressive yield strength of the materials used to manufacture connecting rods is of paramount significance as it becomes the most important design factor. Connecting rods are currently designed using mechanical properties obtained at room temperature; however, the operating environment in an engine can have negative effects on their performance, as the strength of most materials declines at higher temperatures. Nevertheless, tests conducted at engine operating temperatures have shown an improvement in mechanical properties of the materials used to manufacture powder-forged connecting rods as a result of copper precipitation strengthening. Scanning and transmission electron microscopy were employed to investigate nano precipitates of copper in the specimens tested at higher temperatures as well as in connecting rods that have been running in engines for appreciable amounts of time. In light of these results, there is an opportunity to reduce the cross section in the I-beam of powder-forged connecting rods by using in design the higher compressive yield strength values obtained at engine operating temperatures, thus resulting in mass savings.

KEY WORDS
Fe-Cu-C alloys, powder forging, connecting rods, mechanical properties, copper precipitation

1 Introduction
Iron-copper-carbon alloys are still the most widely used by the powder-forging (PF) industry to manufacture connecting rods for automotive applications. Carbon, an interstitial solid solution strengthener, and copper, a substitutional solid solution strengthener, rapidly dissolve in iron during sintering, thus strengthening and hardening the iron matrix and producing pearlitic-ferritic microstructures. Furthermore, copper is known to shift the eutectoid carbon level towards pure iron, thus increasing the amount of pearlite in microstructure and, as a result, the strength. In addition, copper is effective in suppressing the growth of new grains formed during the recrystallization that takes place after forging, thus further contributing to strength improvements.

The development of high-strength (HS) materials for mass production powder-forged connecting rods is based mainly on the strengthening mechanisms mentioned above. The optimization of the chemical composition of Fe-Cu-C alloys for optimum performance resulted in higher copper and carbon levels than in the commonly used materials to manufacture connecting rods, namely PF-11C50 and PF-11C60. Among the HS materials, HS170M (3.25 % Cu, 0.64 % as-forged C, 0.32 % MnS, Bal. Fe) has the best performance and is currently used in powder-forged connecting rods assembled in several turbocharged engines by the automotive industry.

In addition to the strengthening mechanisms mentioned above, copper, which has a relatively high solubility in iron at high temperatures but displays a continuously decreasing solubility at lower temperatures, can further contribute to performance improvements in Fe-Cu-C alloys through second phase precipitation strengthening. The relatively high amount of copper in HS170M results in a saturated solid solution at sintering temperature levels, which, in combination with the highly deformed structure produced after forging, can contribute to defect-induced copper precipitation under the joint effect of temperature and strain, thus providing additional strengthening.

It has been shown that, despite the fact that the performance of most materials declines at higher temperatures, mechanical properties of HS170M are higher at 393 K (120 °C) than at room temperature (RT). Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) investigations clearly proved the presence of abundant nano copper precipitates in the specimens submitted to tensile testing at 393 K. In addition, similar copper precipitates were observed in connecting rods that were submitted to lengthy dyno tests.
These results can be important if implemented in design. Currently, connecting rods are designed using mechanical properties obtained from tests conducted at room temperature. However, if mechanical properties obtained at engine operating temperature levels are used in design, steel-forged connecting rods should have a larger cross-sectional area, while powder-forged connecting rods should have a leaner cross-sectional area in the I-beam, thus resulting in mass reductions.

The goal of this work was to collect more test data obtained at engine operating temperature levels from some of the most widely used materials to manufacture connecting rods through powder forging and through wrought steel forging, and make them available to design engineers. In addition, further measurements were completed regarding the size of copper precipitates, their volume fraction, etc.

2 Experimental Procedures

In the case of a diesel engine, a temperature of 125 °C (398 K) was measured in the small end of a connecting rod\(^4\). Thus, it was assumed that the temperature of a connecting rod in the minimum cross section of the I-beam, which represents the most highly stressed area in the component, can range between 373 K (100 °C) and 423 K (150 °C), depending on engine type and operating conditions.

Extensive tensile and compressive yield strength (CYS) tests were conducted in accordance with ASTM standards\(^5\) at 393 K and 423 K on specimens machined from connecting rods manufactured with HS170M and two micro alloyed wrought steels, 36MnVS4 (0.36 % C, 0.73 % Si, 1.02 % Mn, 0.15 % Cr, 0.11 % Ni, 0.075 % S, 0.27 % V, Bal. Fe) and 46MnVS6 (0.46 % C, 0.55 % Si, 1.04 % Mn, 0.26 % Cr, 0.11 % Ni, 0.052 % S, 0.28 % V, Bal. Fe). In addition, some tensile and compressive yield strength tests conducted at 393 K were interrupted at stress levels similar to the ones sustained in operation by a connecting rod, without resulting in specimen failure. Both tensile testing and compressive yield strength testing were conducted at Westmoreland Mechanical Testing and Research Inc., Youngstown, PA, U.S.A. using a Thermcraft furnace chamber (soaking time 30 min). The size and volume fraction of precipitates were evaluated with the help of SEM and TEM at the Center for Characterization and Microscopy of Materials (CM)\(^2\) of École Polytechnique de Montréal, Canada.

3 Results and Discussion

Several specimens were submitted to tensile testing at RT: more than thirty for HS170M, seventeen for 36MnVS4, and eight for 46MnVS6. In addition, several specimens were submitted to tensile testing at 393 K and 423 K, respectively: ten and twenty for HS170M, nine and four for 36MnVS4, and six and six 46MnVS6. The mean results obtained from tensile testing conducted at RT, 393 K, and 423 K on the three materials mentioned above are summarized in Fig. 1.

In addition, several specimens were submitted to compressive yield strength testing at RT: more than thirty for HS170M, four for 36MnVS4, and four for 46MnVS6. In addition, ten specimens were submitted to compressive yield strength testing at 393 K for HS170M, while ten specimens for HS170M, ten for 36MnVS4, and four for 46MnVS6 were submitted to compressive yield strength testing at 423 K. The mean results obtained from compressive yield strength testing conducted at RT, 393 K, and 423 K on the three materials mentioned above are summarized in Fig. 2.

Table 1 summarizes a relative comparison of tensile and compressive properties at engine operating temperatures versus tensile and compressive properties at RT for the three materials under review. For example, the yield strength (YS) for HS170M is higher at 393 K and 423 K by 5.2 % and 1.0 %, respectively. On the contrary, tensile properties of micro alloyed steels decline at engine temperature levels. For example, in the case of 36MnVS4, the YS is lower at 393 K and 423 K by 10.4 % and 16.7 %, respectively, while in the case of 46MnVS6, the YS is lower at 393 K and 423 K by 8.9 % and 8.5 %, respectively.
If CYS is considered, in the case of HS170M it is higher by 7.3 % at both temperature levels of 393 K and 423 K. In the case of 36MnVS4 and 46MnVS6, the CYS is lower at 423 K by 9.7 % and 10.8 %, respectively.

Besides the tensile and compressive yield strength tests shown above, additional testing at 393 K was conducted on specimens machined from connecting rods manufactured with HS170M employing typical tensile and compressive engine loads, well below the yield point of the material, without taking the specimens to failure. Small sections were cut from the intact specimens after these tests were suspended and submitted to SEM investigation. Fig. 3 illustrates Cu precipitates observed on these sections (Fig. 3a), where for comparison purposes, a snapshot of Cu precipitates observed in a specimen machined from connecting rods manufactured with HS170M submitted to tensile testing at 393 K all the way to complete failure is included (Fig. 3b). As shown, very similar precipitates, well visible on cementite lamellae, are observed in both cases.

In addition to the SEM and TEM investigation of copper precipitates presented by Ilia, measurements of size and volume fraction were completed on specimens submitted to tensile testing at room temperature, 393 K, and 423 K (Table 2) as well as on connecting rods that passed dyno testing and aged connecting rods at 423 K for 750 hours (Table 3).

As shown in Table 2, while the volume fraction of copper precipitates measured on specimens tested at 393 K and 423 K is approximately double the volume fraction of copper precipitates measured on specimens tested at RT, the average precipitate size is very similar. The results in Table 3 clearly show that the volume fraction of copper precipitates measured on the connecting rod that passed a 750 hour dyno test is approximately three times higher than the volume fraction measured on the aged connecting rod at a temperature of 423 K for 750 hours. As in the case of specimens, the average precipitate size is very similar in both connecting rods and less than 30 nm.

Micro hardness measurements on sections cut from an as-forged connecting rod, an aged connecting rod at 423 K for 750 hours, and a connecting rod that passed a 750 hour dyno test were taken on Cu-rich ferritic grains using the HV scale (25 gf), Table 4.

As shown, the micro hardness measured on Cu-rich ferritic grains is higher in the aged connecting rod (416 HV), but it is even higher in the case of the connecting rod that passed a 750 hour dyno test.
(434 HV), when compared to the micro hardness measured on Cu-rich ferritic grains of the as-forged connecting rod (327 HV). These measurements indicate that the hardening is more effective when both temperature and stress are applied at the same time.

4 Design Considerations

Compressive yield strength has become a main design factor for connecting rods used in direct injection turbocharged engines or diesel engines, where high compressive loads are applied. In light of the results obtained in this study, the safety factor calculated using the CYS at operating temperatures would actually be higher over the standard safety factor calculated based on RT properties in the case of connecting rods manufactured with HS170M, due to the fact that CYS at 423 K increases by 7.3 % when compared to RT values. On the other hand, in the case of steel-forged connecting rods, the safety factor calculated using CYS at operating temperatures should be reduced by the amount of the decline in CYS at 423 K (10.8 % in the case of 46MnVS6).

A typical minimum safety factor for a connecting rod assembled in a turbocharged gasoline engine calculated using CYS data obtained at RT is 1.2. However, the real safety factor in operation for a powder-forged connecting rod manufactured with HS170M is approximately 1.29 (7.3 % higher), while the real safety factor in the case of a steel-forged connecting rod is 1.07 (10.8 % lower), as illustrated in Fig. 4. As a result, powder-forged connecting rods can be considered as over-designed while steel-forged connecting rods can be considered as under-designed. If the same safety factor of 1.2 can be implemented when using CYS values obtained at 423 K, a leaner powder-forged connecting rod with a smaller cross sectional area can be designed, thus offering mass reductions over a steel-forged connecting rod, which should be designed with a larger cross sectional area.

5 Summary

The effect of Cu precipitation on mechanical properties of Fe-Cu-C alloys used to manufacture powder-forged connecting rods was investigated. The results of mechanical testing conducted at engine operating temperature levels show that the performance of Cu-rich HS materials utilized by the powder-forging industry to manufacture connecting rods increases, while, as expected, the strength of wrought materials decreases. In light of these results, leaner powder-forged connecting rods can be offered to the automotive industry if mechanical properties obtained at operating temperature levels are utilized in design instead of mechanical properties obtained at RT.

References