Torsional Fatigue Performance of Induction Hardened 1045 and 10V45 Steels

Lee Rothleutner, Robert Cryderman, and Chester J. Van Tyne

George S. Ansell Dept. of Metallurgical and Materials Engineering, Colorado School of Mines, Golden, CO 80401 USA
lrothleu@mines.edu

Jody Burke
Gerdau Special Steel North America, Jackson, MI 49201 USA

Abstract

Microalloying of medium carbon bar steels is a common practice for a number of traditional components; however, use of vanadium microalloyed steels is expanding into applications beyond their original designed use as controlled cooled forged and hot rolled products and into heat treated components. As a result, there is uncertainty regarding the influence of vanadium on the properties of heat treated components, specifically the effect of rapid heat treating such as induction hardening. In the current study, the torsional fatigue behavior of hot rolled and scan induction hardened 1045 and 10V45 bars are examined and evaluated at effective case depths of 25, 32, and 44% of the radius. Torsional fatigue tests were conducted at a stress ratio of 0.1 and shear stress amplitudes of 550, 600, and 650 MPa. Cycles to failure are compared to an empirical model, which accounts for case depth as well as carbon content.

Introduction

Induction hardening of medium-carbon steels in the ferrite-pearlite condition is common in applications such as automotive shafts and forgings. The influence of vanadium additions on the microstructure, mechanical properties, and fatigue properties of wrought medium-carbon ferrite-pearlite steels is well documented in literature [1-7]. However, only a few studies have investigated the role of vanadium on induction hardened component microstructures [8-11]. No studies have investigated the direct influence of vanadium on fatigue performance. A fundamental understanding of vanadium’s role in microstructural evolution during induction hardening and its effect on the fatigue performance of medium-carbon steel will allow further optimization of processing and alloy design, potentially improving component performance.

Torsional Fatigue

Three torsional fatigue studies of induction hardened medium-carbon steels were found in literature that provided insight for the current study. Hurd [12] studied both smooth and splined 20 mm diameter induction hardened shafts at case depths of 3, 4, and 7 mm. Although two alloys were used in the study, SAE 1050H and 38B3, only data from the 1050H was discussed in the paper. Hurd found that fatigue failures, for all case depths investigated, were surface initiated at high shear stress amplitudes. In these surface initiated specimens, initiation and early crack growth were observed in Mode III on the order of 1 mm in length and occurred along longitudinal shear planes which were followed by a Mode I, normal stress, crack propagation to failure. The longitudinal crack growth is believed to be a result of linking micro-cracks initiated at inclusions in the crack plane [12]. At low shear stress amplitudes, Hurd observed the lowest case depth condition initiated failure sub-surface at the case-core transition then propagated in a variety of complex growth modes. The second study examined was by Ochi et al. [13, 14]. Ochi et al. studied three plain-carbon steels (0.35, 0.41, and 0.54 wt. % C) and of each alloy, three case depths were examined ranging from 2.1 to 6.8 mm in a 20 mm diameter test specimen. Ochi et al. observed similar results to those found by Hurd in that high shear stress amplitudes resulted in surface initiated failure while low amplitudes initiated failure sub-surface. However, Ochi et al. observed a shift in initiation from surface to sub-surface that was not only a function of case depth but also a function of carbon content. As case depth and shear stress amplitude decreased for a given carbon content, failure initiation shifted from surface to sub-surface. This change is in agreement with the observations made by Hurd [12]. In the third study, Cryderman et al. [15] looked at the influence of continuous cast section size on the torsional fatigue performance of induction hardened SAE 1050. Four slight variations in carbon content were tested (0.52 to 0.56 wt. % C) at a nominal case depth of 4.4 mm in a 12.8 mm diameter test specimen. Although negligible differences between the torsional fatigue performance of the steels were observed, differences in initiation mode were noted. At high shear stress amplitude initiation occurred along longitudinal shear planes, Mode III, while at low strains, or low shear stress amplitudes, initiation occurred due to normal stresses, Mode I. Table 1 shows a summary of the aforementioned torsional fatigue studies regarding carbon contents and effective case depths examined. One important note about the three studies shown in Table 1 regards the stress ratio. Two of the studies did not report the stress ratio of the torsional fatigue data. Nevertheless, a study by Hurd and Irving [16] showed that stress ratio does not play a significant role in torsional fatigue life. Figure 1 shows all 159 observations of torsional fatigue data for the conditions summarized in Table 1. The data span a very broad range of...
cycles to failure, 100 to 3 million cycles, and shear stress amplitude, 400 to 1200 MPa.

Table 1: Induction Hardened Torsional Fatigue Data

<table>
<thead>
<tr>
<th>Reference</th>
<th>C (wt. %)</th>
<th>Normalized Effective Case Depth, t/r</th>
<th>Stress Ratio</th>
</tr>
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<tbody>
<tr>
<td>Hurd [12]</td>
<td>0.50</td>
<td>0.30 / 0.40 / 0.70 NR</td>
<td></td>
</tr>
<tr>
<td>Ochi et al. [13]</td>
<td>0.35</td>
<td>0.21 / 0.34 / 0.48</td>
<td></td>
</tr>
<tr>
<td>Cryderman et al. [15]</td>
<td>0.54</td>
<td>0.37 / 0.52 / 0.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.52</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.54</td>
<td>0.34</td>
<td>0.34</td>
</tr>
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<td>0.56</td>
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<tr>
<td></td>
<td>0.54</td>
<td>0.35</td>
<td>-1</td>
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Table 2: Chemical Composition of Materials in wt. %

<table>
<thead>
<tr>
<th>Steel</th>
<th>C*</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Al</th>
<th>N</th>
<th>S</th>
<th>P</th>
<th>Cu</th>
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<tbody>
<tr>
<td>1045</td>
<td>0.44</td>
<td>0.74</td>
<td>0.23</td>
<td>0.10</td>
<td>0.12</td>
<td>0.03</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>10V45</td>
<td>0.47</td>
<td>0.82</td>
<td>0.28</td>
<td>0.09</td>
<td>0.12</td>
<td>0.03</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>V</td>
<td>Al</td>
<td>N</td>
<td>S</td>
<td>P</td>
<td>Cu</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1045</td>
<td>0.002</td>
<td>0.016</td>
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<td>0.010</td>
<td>0.26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10V45</td>
<td>0.080</td>
<td>0.007</td>
<td>0.0100</td>
<td>0.009</td>
<td>0.007</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* Standard deviation of 0.01 wt. % (n=5) for each steel.

Figure 2 shows representative secondary electron SEM images of the two materials in the hot-rolled condition taken from the mid-radius of the round bar and transverse to the rolling direction. Microstructures are ferrite-pearlite with the 10V45 having markedly smaller ferrite grain size and ferrite fraction. The 1045 has 16.9 ± 2.0% ferrite with a ferrite grain size of 6.4 ± 3.9 µm while the 10V45 has 13.5 ± 1.5% ferrite with a ferrite grain size of 3.3 ± 2.8 µm. These differences in microstructure, as well as the vanadium additions to the 10V45, result in large differences in hardness, 217 ± 5 HV<sub>1kg</sub> for the 1045 and 281 ± 9 HV<sub>1kg</sub> for the 10V45.

Figure 2: Representative secondary electron SEM images of as-hot rolled (a) 1045 and (b) 10V45 steels.

Experimental Procedures

Materials

Two grades of SAE 1045 were produced for this research, one with aluminum additions and one with vanadium additions, designated as 1045 and 10V45 respectively. Both alloys were continuous cast as separate industrial heats and hot rolled to a final diameter of 39.7 mm, giving a reduction ratio of 18.8 to 1. Table 2 shows the nominal chemical composition for both alloys. Sulfur levels are much lower than most commercially produced SAE 1045 heats to reduce, and possibly eliminate, fatigue crack nucleation at inclusions during fatigue testing. Slight differences in chemistry, other than aluminum, vanadium, and nitrogen, are observed between the 1045 and 10V45. The 10V45 has slightly higher carbon, manganese, and silicon levels. As a result, ideal diameter (DI) calculations differ between the two steels, 36.0 mm for the 1045 and 45.5 mm for the 10V45 (39.9 mm without including the vanadium), and will be considered during the analysis of the results [17].
**Induction Hardening**

Hot rolled specimens were scan induction hardened to nominal normalized effective case depths (t/r) of 0.25 (low), 0.32 (medium), and 0.44 (high) using a single turn coil on a 100 kW/200 kHz power supply. The low and high case depth conditions used identical setups with the high case depth simply having a slower scan speed (17.3 mm/s) than the low case depth (22.9 mm/s). To achieve the medium case depth, a pre-heat cycle and quench delay were incorporated into the setup used for the low and high case depth conditions. Figure 4 shows transverse macrographs of 10V45 torsional fatigue specimens at maximum shear stress (minimum diameter) illustrating low, medium, and high case depths. Figure 5 shows representative secondary electron SEM images of the martensitic case microstructure of the 10V45 steel in the low and high case depth conditions. The high case depth condition does appear to have a coarser martensitic structure due to the longer austenitizing time which resulted from the slower scan speed needed to achieve the high case depth.

![Macrographs](image)

**Figure 4:** Macrographs of (a) low (25%), (b) medium (32%), and (c) high (44%) case depths in the 10V45 steel at maximum shear stress location.

![SEM images](image)

**Figure 5:** Representative secondary electron SEM images of the martensitic case microstructure of (a) low case depth and (b) high case depth conditions in 10V45.

Figure 6 shows spline curve fits for radial microhardness data for the low (L), medium (M), and high (H) case depth in the 1045 steel at the specimen minimum diameter. The SAE specification for effective case depth for a 0.45 wt. % C steel is indicated [18]. All three conditions show similar case peak hardness as well as core hardness. Figure 7 shows spline curve fits for radial microhardness data for the low (L), medium (M), and high (H) case depth in the 10V45 steel at the specimen minimum diameter. The medium and high case depths have similar case peak hardness and core hardness while the low case depth shows significantly higher case peak hardness as well as possible over aging at the case/core transition region. The 10V45 conditions showed slightly higher case hardness as well as core hardness as compared to the 1045 conditions. The higher core hardness of the 10V45 is a result of both precipitation strengthening from the vanadium as well as the higher pearlite fraction and smaller ferrite grain size. The higher case hardness of the 10V45 is a result of the slightly higher carbon content in addition to a possible vanadium effect yet to be determined.

![Microhardness curves](image)

**Figure 6:** Spline fits for Vickers microhardness traverses at torsional fatigue specimen minimum diameter (maximum shear stress location) for 1045 steel.

![Microhardness curves](image)

**Figure 7:** Spline fits for Vickers microhardness traverses at torsional fatigue specimen minimum diameter (maximum shear stress location) for 10V45 steel.
Torsional Fatigue

Appropriate stress levels for torsional fatigue testing were determined by establishing an empirical model from the data presented in Table 1 and Figure 1. The following multiple linear regression model was developed

\[
\text{Shear Stress Amplitude (MPa)} = \frac{1115.379}{1 + 16.9815 \log_{10}(N_f)} + 467.975 \times (\text{wt. } \% \text{ C}) + 445.416 \times (t/r)
\]

where \(N_f\) is the number of cycles to failure between \(10^2\) and \(3 \times 10^6\) cycles, wt. \% \(C\) is the carbon content of the steel in wt. \% between 0.35 and 0.56, and \(t/r\) is the normalized effective case depth between 0.21 and 0.68. All variables were found to be significant to the regression above the 99% level. Standardized residuals as well as the predicted output are normally distributed. The adjusted coefficient of determination is 0.8344 for 159 observations used in the model. Figure 8 shows the model graphically with upper and lower 95% confidence limits for the steels in the current study. The upper bound was calculated using the highest carbon content and effective case depth condition, 10V45(H), while the lower bound was calculated using the lowest carbon content and effective case depth condition, 1045(L).

The model was developed to assist in determining test stresses that would provide failures between \(10^2\) and \(10^6\) cycles. As a result, the following three shear stress amplitudes were selected: 550, 600, and 650 MPa. Five specimens of each condition were tested at each shear stress amplitude. A positive stress ratio of 0.1 was used to preserve the fracture surfaces since it has been previously shown that stress ratio has no effect on torsional fatigue performance.

Results and Discussion

Torsional Fatigue Failure Origin

A total of 90 specimens were tested with 79 having a surface failure origin and 11 having a sub-surface failure origin. Of the 90 failures only 8 initiated failure outside the 95% maximum shear stress region, 2 were surface and 6 were sub-surface initiated. Figure 9 shows example fracture surfaces exhibiting different failure origins and fracture behavior in high case depth specimens tested at 550 MPa. Figure 9a shows Mode I initiation and failure propagation in a 10V45 specimen while Figure 9b exhibits Mode I initiation followed by Mode III then Mode I propagation in 1045. The transition in propagation mode in the 1045 is likely a result of the slightly lower case hardness of the 1045 in general. Figure 9c shows a fracture behavior that is indicative of all observed sub-surface initiated failures. Initiation may be either Mode I or Mode III followed by Mode I propagation into the case and Mode III propagation into the core.

Table 3 shows failure origin for all of the torsional fatigue test as a function of steel and induction hardened case depth. For the low case depth condition failure predominately originated at the surface at all stress levels in both the 1045 and 10V45 steels except for 10V45 tested at 550 MPa. In this condition, 4 of 5 specimens failed sub-surface. In the medium case depth condition all specimens initiated failure at the surface. At the high case depth both steels exhibited a significant mix of both surface and sub-surface initiation at the 550 MPa stress level.

<table>
<thead>
<tr>
<th>Shear Stress Amplitude (MPa)</th>
<th>1045</th>
<th>10V45</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>600</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>550</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

Torsional Fatigue Stress-Life Behavior

Figures 10, 11, and 12 show 1045 and 10V45 stress-life data for the low, medium, and high case depth conditions respectively. Specimens that initiated failure outside the 95% maximum shear stress region are indicated by a separate
symbol on each plot. The 95% confidence limits for the empirical model are superimposed for each condition for comparison. The limits were calculated using the applicable nominal effective case depth along with either 0.43 (lower limit) or 0.48 wt. % C (upper limit).

In the low case depth condition (Figure 10), a noticeable difference in fatigue life was observed at all shear stress amplitudes between the 1045 and 10V45. The 10V45 has significantly longer fatigue lives that more closely align with the empirical model. The low case depth 10V45 was measured to have a higher case hardness than all of the other conditions tested which may be a reasonable explanation for its improved fatigue performance.

In the medium case depth condition (Figure 11), fatigue lives demonstrate very low variability at a given stress level and appear to be independent of vanadium content. Although this condition has both deeper effective and total case depths, the fatigue life is notably worse than the 10V45 low case depth condition. This result is contrary to literature stating total case depth is closely related to fatigue performance [19]. This result suggests the pre-heat cycle and/or the quench delay used in processing the medium case depth condition may have influenced factors such as residual stresses which significantly influence fatigue behavior. In addition, the empirical model over-predicts the fatigue life of the medium case depth condition significantly.

In the high case depth condition (Figure 12), very little difference was observed between the fatigue life of the 1045 and 10V45 steels. At 600 and 650 MPa the fatigue data of the two steels overlay on each other and the empirical model over-predicts the fatigue life of both the 1045 and 10V45. At 550 MPa the 1045 steel appears to have increased variability in fatigue life resulting in the 10V45 having a slightly higher average fatigue life. Although it is unclear for the 1045, the empirical model appears to under-predict the fatigue life of the 10V45 steel at 550 MPa in this condition.

Summary and Conclusions

The torsional fatigue performance of three induction hardened effective case depths of commercially produced 1045 and 10V45 were compared. Effective case depths of 25, 32, and 44% were produced using a single coil scan-hardening system. Five specimens per condition were fatigue tested in torsion at shear stress amplitudes of 550, 600, and 650 MPa. An empirical model was developed from literature data to determine test stress levels as well as for comparison. The most significant observations from the current study are as follows.

- The low case depth 10V45 condition exhibited
  1. Significantly higher case hardness than any other condition.
  2. Superior fatigue performance compared to the 1045 low case depth condition as well as all medium case depth conditions.
  3. Most closely fitting the empirical model of any condition.
• The medium case depth condition demonstrated nearly identical fatigue performance and very low variability in fatigue data at all stress levels for both the 1045 and 10V45.

• The high case depth condition exhibited very similar fatigue performance between the 1045 and 10V45 at all stress levels.

Acknowledgments

Support for this work by the Advanced Steel Processing and Products Research Center at the Colorado School of Mines, Inductoheat Inc. of Madison Heights, MI, Fluxtrol Inc. of Auburn Hills, MI, and Gerdau Specialty Steels North America is gratefully acknowledged.

References