HIGH-STRENGTH STEEL PROCESSING VARIABLES THAT AFFECT FATIGUE

Jay J. Pengra and George G. Wald

ABSTRACT

Fatigue characteristics of high-strength steels are highly dependent on final surface condition. For this reason, valid alloy comparison of fatigue behavior must be based on closely controlled specimen preparation and test. Two high-strength low-alloy steels, 300M and 4340, were evaluated using both spectrum and constant amplitude fatigue loading. Conventionally oil quenched and tempered high-strength steel specimens were notched by two machining methods, lathe turning and crush-form grinding. The ability of shot peening, using both standard and hard shot, to normalize any differences in fatigue characteristics of high strength steel alloys was evaluated.

The fatigue performance of 300M was found to be closer to that of 4340 than anticipated from published handbook data. At stress concentrations of $K_t = 2.0$ and below, the fatigue performance of 300M was superior to 4340; while at a higher stress concentration of $K_t = 3.0$, 4340 had slightly longer life than 300M. A notched, $K_t = 1.9$, specimen was developed that could be adequately shot peened. Testing showed shot peening with standard shot more consistently improved fatigue characteristics than did peening with hard shot. Shot peening did not normalize fatigue difference attributed to variances in final machine surface quality. Final machining methods were developed that show promise for reducing the fatigue scatter of high-strength steel specimens.

1. INTRODUCTION

Using the constant amplitude fatigue characteristics for 4340 at 260-280 ksi and 300M at 270-300 ksi, as presented in Military Handbook 5, for analysis of fatigue critical parts results in a weight penalty with the use of the higher strength 300M. This data, Figure 1, shows differences in the fatigue characteristics of the two alloys which are attributed to several factors:

1) Product Variances: 4340 data was generated from bar\(^1\) while 300M data was generated from forging stock.\(^2\)

2) Heat Treat Variances: 4340 was oil quenched an tempered while 300M was ausbay quenched an tempered.

3) Specimen Preparation Variances: 4340 was m achined and polished or lathe turned to 10 rms whil 300M was ground and polished to 63rms.

4) Test Variances: Tests performed at different laborato ries.

A two-phase program was developed to directly com pare 4340 and 300M in a realistic manner. The first phase involved spectrum fatigue testing of lathe-turned notched
Figure 1. Comparison of Military Handbook Constant Amplitude Fatigue Data for High Strength 300M and 4340, R = 0.1.

(K_t = 2.0 and 3.0) specimens. Results were closer than anticipated from Military Handbook data but the scatter experienced was large. Phase two attempted to reduce scatter and determine the ability of shot peening to diminish differences in machining effects. For this second phase, lathe turned and crush form ground3 notched (K_t = 1.9) specimens were shot peened with standard and hard shot. It was expected that shot peening would enhance the fatigue characteristics of notched parts and normalize differences in machining effects as it does with partially decarburized surfaces2. It has been shown4 that peening high-strength steel with hard shot produced higher residual compressive stresses to a greater depth than did peening with conventional shot. Since the effect of peening with hard shot on the fatigue characteristics of high-strength steel had not been evaluated, the question remained whether the increased depth of compressive stress would enhance fatigue characteristics due to retarded crack initiation and growth.

2. EXPERIMENTAL PROGRAM

Spectrum Fatigue Testing

Two billets each of CEVM 4340 and 300M (8 to 8.5 inches thick) were used for this effort. Refer to Table I for billet dimensions and chemical compositions.

Longitudinal tensile and fatigue specimens were machined with the fatigue specimens being a minimum of 0.020 oversize to permit post heat-treat clean-up.

The 300M specimens were given a conventional 1725°F normalize, 1625°F austenitize, oil quench and 575°F double temper heat treatment. The 4340 specimens were also given conventional processing with a 1625°F normalize, 1500°F austenitize, oil quench and 450°F double temper. High temperature processing was performed in a salt bath and vertical oil quench was used to reduce warpage.

Tensile tests showed the following average ultimate strengths:

<table>
<thead>
<tr>
<th>Alloy</th>
<th>billet</th>
<th>Ultimate Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>300M</td>
<td>A</td>
<td>283 ksi</td>
</tr>
<tr>
<td>300M</td>
<td>B</td>
<td>287 ksi</td>
</tr>
<tr>
<td>4340</td>
<td>1</td>
<td>274 ksi</td>
</tr>
<tr>
<td>4340</td>
<td>2</td>
<td>266 ksi</td>
</tr>
</tbody>
</table>

The fatigue specimens were machined, to the configuration of Figure 2, with the notch lathe turned with a formed tool.

| TABLE 1.  
Chemical Composition of 300M and 4340 Steel Reforging Billets. |
<table>
<thead>
<tr>
<th>Material</th>
<th>Billet</th>
<th>Size (in.)</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Heat No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>300M</td>
<td>A</td>
<td>8-1/2 x 8-1/2</td>
<td>0.41</td>
<td>0.79</td>
<td>0.008</td>
<td>0.004</td>
<td>1.63</td>
<td>1.74</td>
<td>0.87</td>
<td>0.40</td>
<td>0.08</td>
<td>3810907</td>
<td></td>
</tr>
<tr>
<td>300M</td>
<td>B</td>
<td>8-1/4 x 9</td>
<td>0.43</td>
<td>0.74</td>
<td>0.008</td>
<td>0.002</td>
<td>1.64</td>
<td>0.21</td>
<td>1.74</td>
<td>0.85</td>
<td>0.42</td>
<td>0.08</td>
<td>3831857</td>
</tr>
<tr>
<td>300M</td>
<td>Requirements</td>
<td>0.39-*</td>
<td>0.60</td>
<td>0.015</td>
<td>0.015</td>
<td>1.50</td>
<td>0.35</td>
<td>1.65</td>
<td>0.70</td>
<td>0.30</td>
<td>0.05</td>
<td>0.44</td>
<td>0.90</td>
</tr>
<tr>
<td>4340</td>
<td>1</td>
<td>8 x 10</td>
<td>0.42</td>
<td>0.80</td>
<td>0.006</td>
<td>0.004</td>
<td>0.30</td>
<td>0.12</td>
<td>1.78</td>
<td>0.80</td>
<td>0.26</td>
<td>3953205</td>
<td></td>
</tr>
<tr>
<td>4340</td>
<td>2</td>
<td>8 x 8</td>
<td>0.40</td>
<td>0.80</td>
<td>0.007</td>
<td>0.003</td>
<td>0.27</td>
<td>1.81</td>
<td>0.77</td>
<td>0.25</td>
<td>0.43</td>
<td>0.90</td>
<td>Max</td>
</tr>
<tr>
<td>4340</td>
<td>Requirements</td>
<td>0.38**</td>
<td>0.65</td>
<td>0.010</td>
<td>0.010</td>
<td>0.20</td>
<td>1.65</td>
<td>0.70</td>
<td>0.20</td>
<td>0.43</td>
<td>0.90</td>
<td>Max</td>
<td>Max</td>
</tr>
</tbody>
</table>

* Check Analysis Tolerance ± 0.01
** Check Analysis Tolerance ± 0.02
The objective of the program was to compare the fatigue characteristics of 300M and 4340 under loading conditions that approached service usage history. It was felt this would be better achieved using spectrum testing. A representative portion of a commercial transport main landing gear axial fatigue load stress level and sequence history was selected and used in a random flight spectra program. Fatigue tests were performed in four 10,000-pound servo channels with specimens tested as series pairs. The 4340 and 300M specimens were placed in tandem to assure the same load exposure for each. Specimens were assigned to the test channels randomly with respect to stress concentration and material.

It was desired to ensure that fatigue test specimens failed at approximately 100,000 flights or twice testing days. Preliminary tests showed this objective could be approximated for the $K_t = 2.0$ specimens with fatigue loads 70 percent of the reference loads and 50 percent of the reference loads for the $K_t = 3.0$ specimens. Comparative spectrum tests were then conducted at these levels.

**Constant Amplitude Fatigue Tests**

As a follow-on to the spectrum fatigue effort, a constant amplitude fatigue program was conducted and 4340 (1) and 300M (A) billets were again used. Refer to Table I for chemistry.

To evaluate the effect of standard processing on the notched fatigue characteristics of high-strength steel, it was first necessary to ensure that shot peening could be performed on the specimen notch, as production parts are shot peened prior to plating. Previous efforts on peening notched high-strength steel have shown that specimen configuration and peening procedures are critical in assuring complete coverage of fatigue specimen notches. Peening trials were performed with various specimen configurations. It was determined that 100 percent coverage could be obtained on a 0.060-inch radius grooved specimen with SAE 230 shot of nominal 0.0230-inch diameter. The specimen selected for test had a stress concentration ($K_t$) of 1.9 and is shown in Figure 3.

Longitudinal fatigue and tensile fatigue blanks were taken from the billets and normalized, austenitized, oil quenched and double tempered. Tempers of 450°F and 550°F were used for the 4340 and 300M respectively.

The following were the average tensile strengths obtained:

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Billet</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>300M</td>
<td>A</td>
<td>277 ksi</td>
</tr>
<tr>
<td>4340</td>
<td></td>
<td>263 ksi</td>
</tr>
</tbody>
</table>

The notch in the lathe-turned specimens was generated by a formed tool followed by sanding with 320 then 600 grade silicon carbide paper wrapped around a small diameter wire. The notch of the crush form ground specimens was generated on a Sheffield 187 with a formed WA220N5V20 grinding wheel and Excelene #340A coolant. The grinding wheel was dressed intermittently with a tungsten carbide master roll former producing sharp grains on the working sheel that remove material from the part rather than smearing material, as is sometimes experienced with conventional diamond dressed grinding wheels. The surface appearance of these crush form ground specimens was superior to that obtained on the lathe turned and polished specimens as well as that noted on production ground or turned parts.

Shot peening was performed by air blast with three 3/8-inch nozzles. Nozzle distance to the specimen was 5 to 6.5 inches and air pressure was 60 psi. Specimens were mounted on a fixed cam and rotated in the shot stream for two minutes as shown in Figure 4. To produce uniform coverage, the specimens were inverted and peened for two additional minutes. To assure coverage of the specimen notch radius, by minimizing interference of shot, each specimen was peened for two additional minutes with a single nozzle perpendicular to the notch (nozzle 2 of Figure 4).
The same procedure was used for both peening with standard, MIL-S-851, cast iron shot and hard shot. The standard shot used had a hardness of from Rc 46.4 to 55.0, while the high hardness shot had a Rc hardness of 61.5 to 66.0 with a preponderance of Rc 65.0. An intensity of 0.015 Almen has developed when peening with standard shot and 0.016 Almen intensity was developed with the hard shot. These intensity evaluations were made with horizontally mounted Almen specimens. Due to the geometric constraints of a notch, the intensity of that area would be less than that of the flat Almen specimen.

Fatigue testing was performed in three 20,000-pound servo channels at a frequency of 6 Hz and a stress ratio \( R \) of 0.1.

Crush form ground nonpeened 300M and 4340 fatigue specimens were tested at various maximum stresses to produce standard S-N curves. From these data maximum stress levels of 130 ksi and 106 ksi were selected for comparison of material and fabrication variables. It was hoped these stress levels would produce anticipated fatigue lives of 10,000 and 100,000 cycles, which would assist in the comparison of high-load versus long-life fatigue characteristics.

Some test specimens failed in the thread grip area which could have been avoided by increasing the thread diameter and rolling the threads.

3. TEST RESULTS AND DISCUSSION

Spectrum Fatigue Tests

Heat-to-heat comparison of the 4340 and 300M billets could not be effectively performed due to the small number of fatigue data points. For comparing the spectrum performance of the two alloys the geometric mean, \( \bar{x} \), was used.

\[
\bar{x} = \text{antilog} \left( \frac{1}{n} \sum_{i=1}^{n} \log x_i \right)
\]

A summary of all specimens tested at 50 percent and 70 percent reference spectrum loads is presented in Figure 5. The results on the \( K_t = 2.0 \) specimens, showing 300M to have a longer spectrum fatigue life than 4340, were reversed for the \( K_t = 3.0 \) condition. This fatigue superiority of 4340 at \( K_t = 3.0 \) agrees with Military Handbook data but performance of the two alloys was much closer than anticipated.

The high degree of fatigue data scatter pointed out a need for a fabrication method that produces fatigue specimens of more uniform quality.

The reversal of spectrum fatigue performance of 4340 and 300M at stress concentrations of 3 is attributed to possible greater sensitivity of the higher strength material to machining variables, as noted with the higher scatter for 300M, and greater sensitivity of the higher strength material to fatigue crack initiation at higher stress concentrations. In addition, the surface quality of sharper notched 300M specimens was noted as being poorer than that of the 4340 \( K_t = 3.0 \) specimens.

Constant Amplitude Fatigue Testing

Test results were grouped by specimen alloy and fabrication method and the geometric mean, Eq. (1), was calculated for comparative purposes. Included in these calculations were data generated on three specimens that failed out of the test area but would not lower the geometric means as these specimens had the longest lives of their group. Each group consisted of from 4 to 6 specimens.

Comparing the fatigue performance of the lathe turned specimens to that of the crush form ground specimens, is graphically presented in Figure 6, we see the crush form ground specimens were far superior. In fact, the differences in machine surface quality far outweighed any differences in the fatigue characteristics of the two alloys tested. The lathe turned data should be considered as more typical.
The improvement of fatigue characteristics by shot peening smooth sections in steel parts is well known. As shown in Figures 8 and 9, fatigue improvements can be realized from shot peening notched high-strength steel provided adequate peening procedures are used. The minimum life of all specimen groups tested, including lathe turned and crush form ground at both stress levels tested, was increased by shot peening.

Figure 6. Constant Amplitude Axial Fatigue Test Results of Lathe Turned and Crush Ground 4340 and 300M Steel Reforging Stock.

of production conditions but should not be considered as conservative. These specimens were lightly polished, which is not normal production practice, and random parts of poorer quality could be anticipated from standard production machining.

Figure 7 shows in bar graph form the minimum, maximum and logarithmic geometric mean of the lathe turned and crush form ground specimens. This again shows the superior performance of the crush form ground specimens, which is attributed to the higher quality surface generated by crush form grinding.

Figure 8. Summary of Fatigue Data Showing Effect of Shot Peening on Endurance of 4340 and 300M at Maximum Stress of 130 KSI, $R = 0.1$, $K_t = 1.9$.

Peening also reduced the data scatter for all cases except the 4340 lathe turned condition tested at 106 ksi. The reduction of scatter is attributed to improvement of surface condition of poorer quality specimens with peening while not realizing this same increment of improvement with peening of higher surface quality specimens. Although the geometric mean of all groups of specimens tested was not improved, the large improvement in minimum life and reduction in scatter permits more confidence in the shot peened data and the position that fatigue improvements can be realized from shot peening notched high-strength steel.

Shot peening improved the fatigue characteristics of both 4340 and 300M, and for both machining methods. However, differences in fatigue characteristics between
machining methods were not overcome by shot peening. This agrees with previous results reported by Bush and Lowe where they demonstrated that fatigue of shot peened smooth 260-280 ksi 4340 specimens were also dependent on prior machining practices specifically polishing versus grinding. There are three primary reasons for differences in fatigue characteristics attributed to metal removal methods.

1. Differences in surface residual stresses
2. Differences in microscopic surface roughness
3. Differences in surface material deformation

Shot peening may overcome differences in residual stresses as it induces surface residual stresses but it does not appear to overcome differences in the micro surface quality or deformation state introduced by the differences in prior machining methods.

Under the conditions tested, the use of high hardness shot during peening did not improve the fatigue performance over that of specimens peened with standard shot. This data is summarized in Figure 10. Although the high hardness shot may induce higher surface compression stresses to a greater depth, once coverage of peening is attained, machining residual stresses are overcome and other factors, such as surface material deformation determine the life of the part.

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The fatigue characteristics of 300M are slightly superior to those of 4340 at stress concentrations below K,t = 2.0. This is true for both the peened and the nonpeened conditions.

2. At a stress concentration of K,t = 3, lathe turned 4340 appears to have a slightly longer mean spectrum life than 300M. This is attributed to greater sensitivity of the higher strength 300M to fatigue crack initiation at higher stress concentrations and its greater susceptibility to damage during normal machining.

3. Machining practice differences outweigh any differences in fatigue performance attributed to 300M or 4340 alloy selection.

4. Shot peening with complete coverage enhances the fatigue characteristics of notched high-strength steel but does not remove effects that prior machining practices may have on these characteristics.

5. The use of high hardness shot during shot peening of notched high-strength steel does not consistently improve fatigue characteristics compared to shot peening with standard shot at normal intensities.

Recommendations

1. Update Military Handbook 5 to incorporate recently published high-strength steel fatigue data in addition to the constant amplitude data summarized in this report. More emphasis should be placed on data that closely typifies manufacturing surface conditions.

2. To enhance fatigue characteristics of circular grooves in high-strength steel parts and reduce machining variables during fatigue testing, specify these areas to be final machined by crush form grinding.

3. To ensure that the critical condition of complete coverage is obtained during shot peening of fatigue critical parts, require that the peening techniques for these parts be approved by Materials and Process Engineering Peening Specialist.

REFERENCES


3. Western Machinery and Steel World, “Crush Form Grinding Cylindrical Parts”, 6-70.

4. E. Launchner, Northrup, WESTEC Presentation, 3-74.


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