A STRAIN RATE SENSITIVITY INVESTIGATION OF AEROSPACE STEEL GEAR TEETH VIA INSTRUMENTED IMPACT TESTING

A Thesis in

Mechanical Engineering

by

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Master of Science

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ABSTRACT

The purpose of this research was to investigate the performance of carburized gear teeth made from three aerospace steels at high strain rates and evaluate any potential strain rate sensitivity. Most materials are strain rate sensitive, meaning their strength varies with rate of load application. Instrumented impact testing was performed at five strain rates with carburized gears made from 9310 VIM-VAR, X53 and Vasco X-2M. Load and position data was recorded during the impact event and used for various comparison techniques, including linear deviation point (LDP) strain, peak load, absorbed energy to LDP and absorbed energy to peak load. Metallurgical properties of each material were evaluated and post test fracture analysis was completed. Test results indicate a potential for poor performance at very high strain rates with Vasco X-2M.
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<th>Page</th>
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</thead>
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</tr>
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<td>43</td>
</tr>
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</table>
ACKNOWLEDGMENTS

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Chapter 1

Introduction

In recent years, the use of HHH (high hot hardness) steels in the manufacture of high performance gearing applications has been on the rise. The ever increasing demand for greater power densities at high temperatures, specifically in the rotorcraft industry, has forced this transition. Many of these materials have been evaluated through countless fatigue testing programs and have been found superior to “the old standard” material, 9310 steel. However, a very important performance characteristic may have been overlooked. The resistance to impact loading, fracture toughness and the strain rate sensitivity of high hot hardness and 9310 steels have not been compared. The scope of this research is to examine these properties through instrumented impact testing.

Typical test methods do not account for the possibility of the occasional collision, drop, blow or other overload that may happen in a real-world application. Impact testing evaluates the high loading rate behavior of a component. For many materials, the act of processing them into finished components directly affects their impact performance characteristics. Standard impact test methods such as Charpy, Izod and Gardner are important tools for raw material research and quality control, but they provide little value to engineers seeking to understand how their finished components perform in real-world impact situations (Instron Corporation, 2006).
High performance gears are manufactured from steels that are heat treated, usually case carburized, to have a very hard outer layer (case). Below the case is the much softer, very tough core. Due to these complex, almost composite-like characteristics of gear teeth; it becomes very important to perform testing with actual gears, not generic specimens. Also, the geometry of the gear tooth is very unique and is not accurately simulated by Izod or Charpy (notched or un-notched) tests. These tests usually start with a notch and/or seeded fault (manufactured or fatigue initiated crack) and then measure the materials resistance to the propagation of the crack. This is not an accurate representation of the generous radius and irregularities contained within the root fillet region of a gear.

It is widely documented that most materials are strain rate sensitive, meaning they behave differently based upon the rate of load application. Figure 1 illustrates the typical response of mild steel to increasing strain rates (ASME Handbook, 1953). This trend of increasing strength with increasing strain rate is known as positive strain rate sensitivity. The opposite condition or worst case scenario for a gear tooth would be negative strain rate sensitivity. The ASTM standard for Notched Bar Impact Testing of Metallic Materials states that as the speed of deformation increases, the shear strength increases and the likelihood of brittle fracture increases. It goes on to say that the velocity of straining has a similar effect to reducing the temperature. Below the ductile to brittle transition temperature cleavage fractures may occur and there may be an extremely sharp drop in absorbed energy (American Society for Testing and Materials, 2007).
An instrumented drop tower test apparatus located at The Gear Research Institute at the Pennsylvania State University - Applied Research Lab was used for this effort. A schematic of the test setup is given in Figure 1.2. The fixture is precisely aligned below the drop weight, holding the gear stationary for the impact event. Rotation is prevented by the reaction support. Proper impact loading will result in a bending stress failure of the loaded tooth.

Figure 1.1 – Strain rate effect on properties of mild steel (ASME Handbook, 1953).
Figure 1.2 – Impact loading schematic of gear tooth.

The impact tester contains a piezoelectric force transducer and a linear variable differential transformer (LVDT). By recording the force and position signals generated during the impact, the bending stress, strain, strain rate and absorbed energy can be calculated.

Research Objective

This research focuses on varying the rate at which the impact load is applied to the gear tooth. The impact failure characteristics of three gear steels were to be examined for the possibility of negative strain rate sensitivity behavior. They are Vasco X-2M
(VascoJet 2000), X-53 (AMS 6308) and 9310 (AMS 6265). The general chemical composition specifications for each alloy are given in Table 1.1.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>W</th>
<th>Cu</th>
<th>V</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>9310 min.</td>
<td>0.07</td>
<td>0.40</td>
<td>--</td>
<td>1.00</td>
<td>2.95</td>
<td>0.08</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>AMS 6265</td>
</tr>
<tr>
<td>max.</td>
<td>0.13</td>
<td>0.70</td>
<td>--</td>
<td>1.45</td>
<td>3.55</td>
<td>0.15</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Vasco X-2M</td>
<td>0.14</td>
<td>0.30</td>
<td>0.90</td>
<td>5.00</td>
<td>--</td>
<td>1.40</td>
<td>1.35</td>
<td>--</td>
<td>0.45</td>
<td>Nominal(Teledyne Vasco)</td>
</tr>
<tr>
<td>X-53 min.</td>
<td>0.07</td>
<td>0.25</td>
<td>0.60</td>
<td>0.75</td>
<td>1.60</td>
<td>3.00</td>
<td>--</td>
<td>1.80</td>
<td>0.05</td>
<td>AMS 6308</td>
</tr>
<tr>
<td>max.</td>
<td>0.13</td>
<td>0.50</td>
<td>1.20</td>
<td>1.25</td>
<td>2.40</td>
<td>3.50</td>
<td>--</td>
<td>2.30</td>
<td>0.15</td>
<td>S_{max}=0.01%, P_{max}=0.015%</td>
</tr>
</tbody>
</table>

Table 1.1 – General alloy composition specifications (given in weight percent).

**Impact of Research**

Due to the ever increasing demand for vehicles and aircraft to carry more, travel faster and farther, and be quieter and more efficient, new high performance steels can be very attractive to the design engineer. A more complete understanding of the strain rate sensitivity of gear materials is vital to the design of drivetrain components with increased performance. Without a full performance characterization of a material and/or component under all possible service conditions, consequences could potentially be catastrophic.
Chapter 2

Literature Review

Impact Energy Absorption

S. B. Russell stated in 1898 that if the stress on a body changes from zero up to the ultimate strength of the body, the energy absorbed is a measure of the ultimate resilience or toughness of the body. The actual measurement of a body’s toughness is quite difficult to perform. The load must be increased gradually and the deflection measured and recorded with its corresponding load (Russell, 2000). Due to the problems associated with the accurate measurement of the load and position during an impact, other methods for energy comparisons have been derived.

The Charpy Notched Bar (CNB) impact resistance test has become the most widely used test method for the determination of a material’s resistance to an impact loading. Un-notched Charpy testing is also used, but usually only for very brittle materials. The standardized test specimen in the Charpy test is impacted with a weighted pendulum dropped from a fixed height. After complete specimen fracture, the distance that the pendulum continues to travel is recorded. This post fracture distance is correlated to absorbed energy and comparisons based upon it can be made. However, accurate absorbed energy values cannot be easily obtained. The ASTM standard for the Charpy notched bar impact test states that the test design is complicated by complex energy loss mechanisms within the machine and the specimen. Therefore, there is no
absolute standard to which the measured values can be compared (American Society for Testing and Materials, 2007). Due to the large amount of unpredictable energy loss present in the Charpy test accurate energy absorption must be determined by other means such as actual load and displacement measurement methods.

The instrumented test differs from the standard test by the addition of a force transducer and either the calculation or measurement of displacement during the impact. The Instrumented Charpy test is widely used for developing dynamic plane strain fracture toughness data ($K_{IC}$). $K_{IC}$ is a measurement of crack extension resistance at the onset of crack extension. Values of $K_{IC}$ are calculated based upon the force and displacement records for each test according to ASTM standard E99-08 (American Society for Testing and Materials, 2008). Static $K_{IC}$ is calculated in a similar manner; however values are often determined by cyclic loading of samples at a much lower rate.

Available Fracture Toughness and Impact Property Data

Three different methods of evaluating dynamic fracture toughness for the desired steels are given in Table 2.1. The Instrumented Charpy method was reported (Diesburg, 1982) at two carbon levels for each material and specimens were pre-cracked before testing. All three alloys had higher fracture toughness at the lower carbon concentration. The short rod (Cutler, 1983) and Terra Tek (DiRusso, 1986) methods were conducted without carburization, representing the core properties of a gear. All sources claimed valid $K_{IC}$ data. Based upon the differences in the short rod and Terra Tek values, it appears that test method greatly influences the test results. In summary, the 9310 has
higher fracture toughness than Vasco X-2M and X-53 without carburization. However, when carburized as found in gear applications, X-53 has the best fracture toughness.

Impact fracture strengths are reported in Table 2.2 for 9310 only. This testing was developed on a simulated gear specimen (Diesburg, 1982). While not particularly useful because data was not available for Vasco X-2M and X-53, the difference in result for the two variations of 9310 strongly reinforces the need to test a condition (both geometrically and metallurgically) as close to the production part as possible.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Fracture Toughness, $K_{IC} - KSI(IN)^{1/2}$ at 70°F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charpy Pre-cracked Method</td>
</tr>
<tr>
<td>9310</td>
<td>38 (0.50% C)</td>
</tr>
<tr>
<td>Vasco X-2M</td>
<td>41 (0.50% C)</td>
</tr>
<tr>
<td>X-53</td>
<td>44 (0.50% C)</td>
</tr>
</tbody>
</table>

Table 2.1 – Fracture toughness data comparison.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Impact Fracture Stress (KSI) at 70°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>9310</td>
<td>590 – carburized and tempered</td>
</tr>
<tr>
<td></td>
<td>485 – identical to above except chilled to -115°F before temper</td>
</tr>
<tr>
<td>Vasco X-2M</td>
<td>Not Available</td>
</tr>
<tr>
<td>X-53</td>
<td>Not Available</td>
</tr>
</tbody>
</table>

Table 2.2 – Impact Strength data comparison.
Impact Data Collection and Interpretation

Figure 2.1 shows the typical load versus deflection data recorded for a gear tooth impact event. The load trace shows load increasing linearly with deflection up to 13,000 lb, then increasing at a slower rate until tooth breakage at 20,000 lb. This result is typical for many materials and is possibly related to the onset of plastic flow prior to fracture. Based on this, the stress corresponding to the change in slope of the load deflection trace corresponds to the ultimate (in the case of crack formation or yield if local plastic flow occurs) bending strength of the material at the critical point in the case. Maximum load, or energy required to break the tooth, represents the strength of the core rather than the strength of the case (McPherson, 2005).

Figure 2.1 – Load deflection trace from single tooth impact test (McPherson, 2005).
Describing the physical events that lead to the loading record shown in Figure 2.1 is a complicated multi-step process. Due to the force of the impact load, the tooth is broken off. Further examination of this seemingly simple event reveals several connected events. The first of which is crack initiation (possibly preceded by localized plastic flow), which occurs at a flaw of some sort along the tooth flank in the root fillet region (area of highest bending stress). After this point origin forms, the crack expands rapidly through the case hardened area toward the core and the edges of the tooth. At this point the crack is expanding very quickly due to the relatively hard and brittle case properties. As the crack progresses into and through the much tougher core material, the loading rate begins to decrease until the eventual complete removal of the tooth.

Diesburg reported that while using a modified Brugger test in slow bending a pre-peak loading event was detectable. He described a “pop-in” which he termed “overload critical”. This was theorized to be a pre-fracture flow (yielding) of the material in the highly stressed region or the initiation of a crack in the case region of the test specimen. Attempts to measure this critical overload fracture stress have revealed that this property is strain rate sensitive as shown in Figure 2.2 (Diesburg D. E., 1984).
Potential Problems with Dynamic Data Collection at High Strain Rates

The nature of an impact event between two metal objects causes each object to vibrate or ring violently. This ringing can make the acquisition of accurate force data very difficult. High rate force measurements are typically done with piezoelectric (quartz) load cells. The high sensitivity and fast response of these cells makes them very susceptible to the ringing and elastic waves generated during the impact event (Boyce, 2009). A typical Charpy test data trace with ringing present is shown in Figure 2.3 (Bohme, 1992).
Many attempts have been made to eliminate the ringing without affecting the accuracy of the data acquired. Most published research concentrates on the method of passive damping by adding an absorbing material at varying locations in the test setup. Rubber, soft metals and leather are commonly used damping materials. Results seem to vary widely. All damping materials have the undesirable characteristic of absorbing some of the impact energy. The exact amount of energy absorbed is very difficult to predict and is the most likely source for increased data scatter when passive damping methods are used.
Material Chemistry

The gears for this effort were machined from bar stock provided by Timken - Latrobe Steel Company (9310 VIM-VAR) and Carpenter Technology Corporation (X53 and Vasco X-2M). Specific heat and chemistry data is given in Appendix A, Table A-1.

Heat Treatment

All three materials were heat treated by gas carburizing. Gas carburizing is a typical mass production carburizing process. An endothermic natural gas atmosphere is used to introduce carbon into the surface of the part. By varying the carbon potential and atmosphere exposure times, the carbon gradient diffused into the material can be closely controlled. The 9310 VIM-VAR and X53 gears were heat treated by Bell Helicopter. The Vasco X-2M gears were heat treated by Litton Precision Gear (now Northstar Aerospace, Inc.). Specific heat treatment recipes for each material are given in Appendix B, Table B-1.

Micro-Hardness

Hardness gradients were obtained by sectioning tested teeth. Mounting, polishing and micro-hardness testing was conducted for each material. Vickers hardness indents
were made with a 500 gram load and gradients were made near and parallel to the crack path. Vickers measurements were converted to the Rockwell C scale by the measurement apparatus. Table 3.1 summarizes the hardness information and Figures 3.1 through 3.3 give full hardness gradients for each material tested.

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface Hardness (HRC)</th>
<th>Depth to HRC 50 (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9310 VIM-VAR</td>
<td>62.0</td>
<td>0.038</td>
</tr>
<tr>
<td>X53</td>
<td>60.6</td>
<td>0.044</td>
</tr>
<tr>
<td>Vasco X-2M</td>
<td>63.2</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Table 3.1 – Specimen hardness summary.

Micro-Structure

The metallographic specimens were then etched with a 3% nitric acid solution. The etchant exposure time was different for each material. The 9310 VIM-VAR reacted most quickly and X53 was similar. The Vasco X-2M sample took significantly longer to bring out the microstructure. Micrographs showing the case and core structures for each material are given in Figures 3.4 through 3.9.
Figure 3.1 – Microhardness gradient of 9310 VIM-VAR specimen.
Figure 3.2 – Microhardness gradient of X53 specimen.
Figure 3.3 – Microhardness gradient of Vasco X-2M specimen.
Figure 3.4 – Case microstructure of 9310 VIM-VAR specimen.

Figure 3.5 – Core microstructure of 9310 VIM-VAR specimen.
Figure 3.6 – Case microstructure of X53 specimen.

Figure 3.7 – Core microstructure of X53 specimen.
Figure 3.8 – Case microstructure of Vasco X-2M specimen.

Figure 3.9 – Core microstructure of Vasco X-2M specimen.
Chapter 4

Impact Testing and Analysis Methodology

Impact Testing Components

The impact testing apparatus utilized for this effort is shown in Figure 4.1. A specimen gear is shown in the fixture at the moment of impact by the drop weight. The load cell and LVDT are also visible. A rubber band is used to maintain contact between the support tup and the reaction tooth until the loading tup and drop weight make contact with the test tooth. This prevents an impact from occurring on the reaction tooth and minimizes the probability of any reaction tooth failures. Test specimen geometry details are given in Figure 4.2.

Figure 4.1 – Specimen gear and test apparatus at the moment of impact.
Figure 4.2 – Impact gear test specimen.
Test Parameters

The velocity of the drop weight at the moment of impact is directly proportional to the strain rate of the gear tooth. The velocity at impact, assuming a frictionless free fall, is given by Equation 4.1, where g is the acceleration of gravity (386.4 inches/second²). A rough approximation of strain rate can be made by dividing the impact velocity by two for the specimen geometry used here. This has been determined empirically from historical data is only valid for the exact conditions used here.

\[ Impact\ Velocity = \sqrt{2 * g * drop\ height} \]  
Equation 4.1

The drop height is infinitely variable up to 36 inches and is accurate and precise to 1/16th of an inch. Five drop heights were selected for testing. The minimum is 3 inches and the maximum is 36 inches. The maximum height is limited by the depth of the hole in the floor for the LVDT guide rod.

The drop weight assembly weighs 133 pounds in the fully unloaded condition. Additional weight was added to the assembly as required to ensure sufficient energy be present to induce fracture in all tests at each height. The minimum weight required was determined experimentally with setup tests with each alloy. A full test matrix is given in Table 4.1 and summarizes this discussion.
<table>
<thead>
<tr>
<th>Drop Height (inches)</th>
<th>Weight (pounds)</th>
<th>Impact Velocity (inches/second)</th>
<th>Approximate Strain Rate (in./in./sec)</th>
<th>Number of Tests with each Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>741</td>
<td>48</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>333</td>
<td>68</td>
<td>34</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>203</td>
<td>96</td>
<td>48</td>
<td>3</td>
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<td>24</td>
<td>133</td>
<td>136</td>
<td>68</td>
<td>3</td>
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<tr>
<td>36</td>
<td>133</td>
<td>167</td>
<td>84</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4.1 – Test Matrix

Data Acquisition and Interpretation

Force and position data is acquired in the time domain during the impact event. Data is sampled at 5 MHz or 1 data point every 2x10⁻⁷ seconds. A time domain data example is shown in Figure 4.3. Force versus position is then plotted as illustrated in Figure 4.4 and is then used for analysis. This data is of particular interest because the area under the force versus position curve is the kinetic energy absorbed during the impact event according to Equation 4.2, as taken from the Work-Energy theorem.

\[ \text{Work} = \int_{l}^{f} F \cdot ds \]  \hspace{1cm} \text{Equation 4.2}

The limits of the integral are arbitrary initial and final positions of the body, F is the instantaneous force and ds describes the infinitesimal displacement. The theorem concludes that the work done on a body by the resultant force acting on it is equal to the change in the kinetic energy of the body (Serway, 1992). The energies absorbed to the linear deviation point (LDP) and to peak load (fracture) can then be used for impact performance comparisons.
Figure 4.3 – Time domain force and position data traces of impact event.
Figure 4.4 – Load versus position data for an impact event.
Recent arguments have been made that the energy absorbed to peak load is of no use to the gear design engineer. The energy to the LDP is of greater value because this is theorized to be the beginning of plastic flow or case crack initiation. At this point the gear has failed and will no longer operate properly. Historically, peak load information has been reported for gear tooth impact testing. For this reason, both will be investigated here and the relationship between them and how they are influenced by strain rate will be presented. The energy absorbed to peak load is most certainly the best measure of the total toughness of the gear tooth and could potentially be a measure of how long a gear will continue to carry load before complete fracture.

**Linear Deviation Point (LDP) and Peak Load**

In theory, the determination of the point at which the load versus position curve deviates from linearity should be a simple task. Due to the ringing of the drop weight present in the load signal, this has proven to be a difficult task. A straight line is fit “by eye” to the lower portion of the curve, ignoring the first bump. This bump is present to varying degrees in all data traces at the same time after impact. Due to the non-linearity of the signal above the LDP, analytical attempts to filter out the natural frequency have been unsuccessful. This is explained further in the next chapter. A curve is fit to the top portion of the data to complete the approximate filtering as shown in Figure 4.5. It is recognized that this method contains some uncertainty and is a strong argument against the use of the LDP method of data comparison. Peak load determination is self explanatory and is also reflected in Figure 4.5.
Figure 4.5 – Peak load and LDP locations.
Strain and Strain Rate

Bending stress was first calculated based upon the gear geometry and load application point. Identical test geometry has been used from many Gear Research Institute single tooth bending fatigue test programs. The stress conversion factor of 19.2 ksi/pound of applied load has previously been verified both analytically and experimentally. The bending stress ($\sigma$) was calculated to LDP and peak load based upon Equation 4.3.

$$\sigma = 19.2 \times \text{Load} \quad \text{Equation 4.3}$$

Strain ($\varepsilon$) was then determined at each condition according to Hooke’s law, Equation 4.4.

$$\varepsilon = \frac{\sigma}{E} \quad \text{Equation 4.4}$$

E is the modulus of elasticity of steel and is taken to be 30 million psi. The time from the start of load application to LDP is then used to determine strain rate ($\dot{\varepsilon}$) by Equation 4.5.

$$\dot{\varepsilon} = \frac{\varepsilon}{\text{time to LDP or peak load}} \quad \text{Equation 4.5}$$
This strain rate is only representative of the linear (elastic) portion of the curve and is sufficient representation of the instantaneous strain rate at impact by which basis further comparisons will be made. All strain rates throughout this paper should be taken to mean strain rate at impact.

Energy Calculation

The energies absorbed by the gear tooth (area under the load versus position curve) to the LDP and the peak load were calculated by multiplying the instantaneous force by the differential position. These values were then summed to either the LDP and to peak load according to Equation 4.6.

\[
Absorbed\ Energy = \sum_i^f (Force \times \Delta\ Position)
\]

Equation 4.3
Chapter 5

Drop Tower Harmonics

Significant effort was spent attempting to understand the “bump” present in all time domain load signals. The reliability of the LDP determination would be greatly improved if this bump could be minimized or eliminated. Figure 5.1 shows load traces for all drop heights on X53. It is interesting that the bump occurs at the same time after impact for all drop heights. This reinforces the theory that this is a system property most probably related to the fundamental natural frequencies of the drop weight assembly. This bump begins to occur around 0.05 milliseconds after impact and reaches its low point between 0.10 and 0.15 milliseconds. By assuming that this is one period of vibration and inverting these times, approximate frequencies can be obtained. This results in numbers between 6.7 and 20 kHz. The variation present in the three lowest drop heights could be a result of the additional weight necessary to get failures at those heights changing the natural frequency of the system. Attempts at analytical filtering based upon these values were unsuccessful. Partial smoothing of the signal could be obtained but peak load values were inflated to unrealistic levels.

Figure 5.2 contains time domain load traces for another gear tooth impact project. Load values have been removed because the data is proprietary to the project sponsor. All tests were performed with the minimum drop weight of 133 pounds and the time to the bump occurrence is very uniform and virtually identical to the drops at 24 and 36
inches here. This again suggests some sort of time constant property inherent to the drop weight system. It is important to note that the test gear geometry and fixture were very different from those used for this research effort. This eliminates the possibility that the bump is a characteristic of the gear or fixture’s geometry or material. The test gear and fixture were removed and the drop weight was impacted onto a steel block. The time domain load signal showed a similar bump between 0.15 and 0.20 milliseconds, as shown in Figure 5.3.

An accelerometer was placed as various locations on the drop weight and the weight was struck with a steel hammer at the location of impact. A fast fourier transform (FFT) was performed on the accelerometer signal. Results were inconclusive with most data reflecting frequencies around 1.125 and 4.5 kHz. A hammer strike and corresponding FFT are given in Figure 5.4. This was achieved with the accelerometer on the large pin through the drop weight, used for stacking the additional weight plates. The pin was removed and the bump was still present in the load signal.

Attempts were made to calculate the natural frequency of the drop weight assembly with a simplified two mass and one spring system. Results were again not successful, likely due to over simplification. Further modeling could be done accounting for all masses involved, the spring rate of the load cell and the Hertzian contact stiffness between the impact tup and the gear tooth. This model would be a significant undertaking and is outside the scope of this research.

Mechanical damping methods were quite successful in eliminating the bump in the load signal. Materials such as rubber, soft metals and leather were placed in varying
locations in the system with hopes of eliminating the unwanted vibration. A $\frac{1}{4}$ inch thick piece of leather placed under the impact tup gave the best results, see Figure 5.5. Unfortunately, the energy absorbed by the leather was very hard to predict and not repeatable from test to test. Results of LDP strain versus strain rate had a high amount of scatter and trends were not discernable. Due to the uncertainty involved, this method was also abandoned.
Figure 5.1 – Load traces for all drop heights showing “bump” at similar time.
Figure 5.2 – Load traces at different drop heights from another project.
Figure 5.3 – Time domain load trace of drop weight impacted on steel block.

Figure 5.4 – Time domain accelerometer signal of hammer blow and frequency domain FFT.
Figure 5.5 – Time domain load trace with leather under impact tup.
Chapter 6
Test Results

All tests were conducted at room temperature (60°F-70°F). The load and position versus time and load versus position curves for all tests are shown in Appendix C, Figures C-1 through C-112. Numerical results are tabulated in Tables 6.1, 6.2 and 6.3 for 9310 VIM-VAR, X53 and Vasco X-2M, respectively.

Several trends can be clearly observed upon analysis of test data. As expected, the strain to LDP increases with increasing strain rate as shown in Figure 6.1. This indicates positive strain rate sensitivity of the case. All test results follow the expected trend except test number 46. Test 46 is discussed in detail in the next section. Figure 6.2 summarizes the energy absorption to LDP with varying strain rates. A similar trend, although with more scatter at all strain rates, is observed. The low side scatter is thought to be a direct result of problems with alignment between the LVDT barrel and core. This is evident by examination of the time domain position and load versus position plots for the offending data; contained in Appendix C. The low side scatter band tests have an apparent lag in the position data caused by the LVDT core contacting the barrel upon entry. Based upon LDP strain and absorbed energy to LDP, X53 appears to have a slight advantage. Due to the scatter present and limited amount of test data further rankings are not reliable.
Peak load versus strain rate is shown in Figure 6.3. There is a slight increase in peak load with increasing strain rate for X53. While Vasco X-2M exhibits a more significant trend in the positive direction with increasing strain rate. 9310 VIM-VAR remains fairly constant within the range of strain rates tested. Again, test 46 is an outlier. Peak load is reported instead of strain at peak load because beyond the LDP the deformation is plastic and Hooke’s law no longer applies. The materials can be ranked from highest to lowest based upon peak load, with X53 highest, 9310 VIM-VAR and Vasco X-2M the lowest.

The energy absorbed to peak load with changing strain rate is summarized in Figure 6.4. The trend of increasing absorbed energy with increasing strain rate is expected and indicates that the core of all materials behave with positive strain rate sensitivity. Material rankings based upon peak load are identical to energy absorbed to peak load. The scatter present in the absorbed energy data is again a result of the misalignment of the LVDT components. The misalignment affects are more apparent in the LDP energy absorption data due to the inaccuracy occurring at or before the time of impact. As loading occurs and the LVDT core is forced into the proper location, the measurement data becomes valid.

Finally, Figure 6.5 shows how the relationship between the LDP and peak load changes with strain rate variation. The movement of the LDP toward peak load as strain rate is increased is also expected. In some cases for Vasco X2-M the ratio was 1.0, meaning there was no LDP before fracture occurred.
Test 46

Test 46 was conducted with Vasco X-2M gear specimen S/N 001, tooth number 12. This test exhibited highly negative strain rate sensitive behavior as shown by Figures 6.1 through 6.3. This was anticipated based upon historical data for this material and was the principal reason for this research. However, eleven additional tests were conducted under identical conditions and the result could not be duplicated. Unfortunately, further tests could not be conducted due to the lack of additional Vasco X-2M test specimens.
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<th>Test Number</th>
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<th>Strain At Impact</th>
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Note:  Height is specified in inches.  Loads are specified in pounds.  Energies are specified in inch-pounds.  Strain in specified in inches/inch.  Strain rate is specified in inches/inch/second.

Table 6.1 – Data summary for all tests with 9310 VIM-VAR.
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<th>LDP Energy</th>
<th>Peak Load</th>
<th>Peak Load Energy</th>
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Note: Height is specified in inches. Loads are specified in pounds. Energies are specified in inch-pounds. Strain in specified in inches/inch. Strain rate is specified in inches/inch/second.

Table 6.2 – Data summary for all tests with X53.
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<td>0.88</td>
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<td>31,054</td>
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Note: See Table 5.2 for description of units.

Table 6.3 – Data summary for all tests with Vasco X-2M.
Figure 6.1 – Strain to LDP versus strain rate at impact.
Impact Testing Summary: Energy to LDP versus Strain Rate at Impact

Figure 6.2 – Energy absorbed to LDP versus strain rate at impact.
Figure 6.3 – Peak load versus strain rate at impact.
Figure 6.4 – Energy absorbed to peak load versus strain rate at impact.
Figure 6.5 – LDP/Peak load ratio versus strain rate at impact.
Chapter 7
Fractography

The result of the impact test is the complete removal of the tooth from the gear. Due to the path of the drop weight and impact tup, the fracture surface of most teeth is damaged as it breaks off. Images of representative fracture surfaces for each material at the lowest and highest strain rates are shown in Figures 7.1 through 7.6. Note that both 9310 VIM-VAR and X53 have large areas torn out of the tooth. This is indicative of higher toughness or ductility of the core material. The Vasco X-2M fracture surfaces are contained within a very uniform plane, meaning lower toughness or brittle behavior. This brittle hypothesis is reinforced by the examination of the load traces in Appendix C, showing the sharp decrease in load after fracture for the Vasco X-2M samples at all strain rates. The diagonal step evident in Figure 7.6 is indicative of multiple fracture origins and was characteristic of X53 and Vasco X-2M at high strain rates. The steps form as multiple crack paths intersect.

Figure 7.1 – Fracture surface of 9310 VIM-VAR gear tooth at lowest strain rate.
Figure 7.2 – Fracture surface of 9310 VIM-VAR gear tooth at highest strain rate.

Figure 7.3 – Fracture surface of X53 gear tooth at lowest strain rate.

Figure 7.4 – Fracture surface of X53 gear tooth at highest strain rate.
Due to the damage present on most gear tooth specimens, post test fracture analysis was conducted on the gear side of the fracture surface. This required sectioning the fracture surface region from the gear. Specimens were then prepared by ultrasonic cleaning in detergent, followed by ultrasonic cleaning in ethanol. The samples were then viewed in a scanning electron microscope (SEM).
Fracture Analysis – 9310 VIM-VAR

Figures 7.7 and 7.8 show the fracture origin of Test 3, a low strain rate test with 9310 VIM-VAR. The origin is well defined and slightly sub-surface, which is representative of others with this alloy at low strain rates. There is a small flat region at the center of the origin area. This is intra-granular (trans-granular) fracture, a brittle cleavage fracture across the grains. As crack propagation slows, the increase in surface texture is indicative of inter-granular fracture, a more ductile fracture along grain boundaries. Energy Dispersive Spectroscopy (EDS) analysis was performed at and away from the fracture origin. The EDS results are given in Figures 7.9 and 7.10. High levels of manganese and sulfur were found at the origin, leading to the probability of a manganese sulfide inclusion being present. This is undesirable, but not uncommon.

Figure 7.7 – Fracture origin of Test 3, 9310 VIM-VAR at lowest strain rate.
Figure 7.8 – Fracture origin of Test 3, 9310 VIM-VAR at lowest strain rate.

Figure 7.9 – EDS analysis at fracture origin of Test 3, 9310 VIM-VAR at lowest strain rate.
Figure 7.10 – EDS analysis of bulk material, 9310 VIM-VAR.

Figure 7.11 shows the fracture origin of Test 16, 9310 VIM-VAR at the highest strain rate. The appearance is virtually identical to lower strain rates with the same material. The only difference evident is an increase in size of the intra-granular (brittle) fracture region. Figure 7.12 shows the EDS analysis of the white nodule in the center of the origin reveals low levels of sulfur. This non-metallic inclusion could be responsible for the fracture originating in this location.
Figure 7.11 – Fracture origin of Test 16, 9310 VIM-VAR at highest strain rate.

Figure 7.12 – EDS analysis of inclusion at origin of Test 16, 9310 VIM-VAR.
Fracture Analysis – X53

Figures 7.13 and 7.14 show the fracture origin of Test 14, a low strain rate test with X53. As with 9310 VIM-VAR this origin is also slightly sub-surface, which is again representative of others X53 samples at low strain rates. The X53 origins do not show the same large ultra flat regions as 9310 VIM-VAR. Upon closer examination, see Figure 7.15, very small planar brittle fracture regions can be identified. EDS analysis was performed at many locations around the origin and results were similar to the bulk material result shown in Figure 7.16.

At the highest strain rate, all X53 samples showed multiple fracture origin sites on multiple planes, as shown in Figure 7.17 through 7.19. EDS analysis showed no difference between origin areas and bulk X53 material.

![Fracture origin of Test 14, X53 at lowest strain rate.](image)

Figure 7.13 – Fracture origin of Test 14, X53 at lowest strain rate.
Figure 7.14 – Fracture origin of Test 14, X53 at lowest strain rate.

Figure 7.15 – Fracture origin of Test 14, X53 at lowest strain rate, showing brittle fracture region.
Figure 7.16 – EDS analysis of bulk material, X53.

Figure 7.17 – One of multiple fracture origins of Test 32, X53 at highest strain rate.
Figure 7.18 – Additional fracture origin of Test 32, X53 at highest strain rate.

Figure 7.19 – Fracture origin at edge break of root fillet of Test 32, X53 at highest strain rate.
Fracture Analysis – Vasco X-2M

Fracture origins on Vasco X-2M specimens were typically not as well defined. The majority of specimens had multiple origins even at the lowest of strain rates. This is a definite difference when compared to the other alloys. Figures 7.20 through 7.22 show multiple fracture origin sites from Test 35 (lowest strain rate). Figures 7.23 and 7.24 show fracture origins at each edge of the fracture surface from Test 49 (highest strain rate). Repeated edge origins are often indicative of test specimen or fixture misalignment. Fracture originating at opposite edges of the same sample is normally a rare occurrence, but was observed on multiple Vasco X-2M specimens. Test fixture, specimen and impact tup alignment was verified before, during and after testing.

EDS analysis was performed at many locations around each origin site and no difference was found from EDS of bulk Vasco X-2M (Figure 7.23).
Figure 7.20 – One of multiple fracture origins of Test 35, Vasco X-2M at lowest strain rate.

Figure 7.21 – Additional fracture origin of Test 35, Vasco X-2M at lowest strain rate.
Figure 7.22 – View of fracture origin of Test 35 showing brittle fracture region.

Figure 7.23 – EDS analysis of bulk material, Vasco X-2M.
Figure 7.24 – Fracture origin at left edge of Test 49, Vasco X-2M at highest strain rate.

Figure 7.25 – Fracture origin at right edge of Test 49, Vasco X-2M at highest strain rate.
Fracture Analysis – Vasco X-2M – Test 46

Test 46 was the only sample to exhibit what appeared to be negative strain rate sensitive behavior. It is one of very few Vasco X-2M samples that appear to have only one well defined fracture origin. Figures 7.26 through 7.29 show various views of the fracture origin. A large less textured area is clearly visible in Figure 7.26 pointing toward the origin. Higher magnification images show no material defects that could explain the poor performance. EDS analysis at the origin was identical to Figure 7.23.

Figure 7.26 – Fracture origin of Test 46, poor performing Vasco X-2M at highest strain rate.
Figure 7.27 – Fracture origin of Test 46, poor performing Vasco X-2M at highest strain rate.

Figure 7.28 – Fracture origin of Test 46, poor performing Vasco X-2M at highest strain rate.
Figure 7.29 – Fracture origin of Test 46, poor performing Vasco X-2M at highest strain rate.
Chapter 8
Research Summary and Future Work

Research Summary

The purpose of this research was to investigate the performance of carburized gear teeth made from three aerospace steels at high strain rates and evaluate any potential negative strain rate sensitive behavior. Instrumented impact testing was performed at five strain rates with each alloy. Load and position data was recorded during the impact event and used for various comparison techniques, including linear deviation point (LDP) strain, peak load, absorbed energy to LDP and absorbed energy to peak load. Metallurgical properties of each material were evaluated and post test fracture analysis was completed.

Conclusions

The following conclusions are made based upon the specific material chemistries, heat treatments, geometry and test conditions utilized for this effort.

1. 9310 VIM-VAR, X53 and Vasco X-2M all exhibited positive strain rate sensitive behavior with the exception of one test with Vasco X-2M at the highest strain rate.
2. Case toughness for all materials was approximately equivalent, based upon LDP strain comparison method.

3. Core toughness for X53 was 7% better than 9310 VIM-VAR. Vasco X-2M had 7% lower core toughness than 9310 VIM-VAR. Both results are based upon peak load comparisons averaged over all strain rates.

4. At strain rates of approximately 80 unit/unit/second and above, the potential for negative strain rate sensitivity behavior exists in carburized gears made with Vasco X-2M.

Future Work

In future studies the comparison of performance at a greater range of strain rates should be considered. The wide face width gear geometry and 36 inches of LVDT travel limited the maximum strain rate that could be examined. By utilizing a gear geometry with a lesser face width or increasing the drop height potential of the test apparatus, testing could be conducted at higher strain rates. This would allow the full characterization of these alloys and possibly confirm the negative strain rate sensitivity behavior of Vasco X-2M suggested by this research.


Boyce, B. L and Dilmore, M. F. (2009). The Dynamic Tensile Behavior of Tough, Ultrahigh-Strength Steels at Strain Rates from 0.0002 s\(^{-1}\) to 200 s\(^{-1}\). *Institutional Journal of Impact Engineering*, 36, 263-271.


APPENDIX A

Material Chemistry
<table>
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<th>Material</th>
<th>Source</th>
<th>Heat</th>
<th>C</th>
<th>Si</th>
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<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>Al</th>
<th>V</th>
<th>W</th>
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<td>E3895</td>
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<td>-</td>
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<td>0.004</td>
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<td>-</td>
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<td>-</td>
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<td>-</td>
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Table A-1 – Material heat and chemistry specifics, as certified by the suppliers.
APPENDIX B

Heat Treatment Recipes
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<th>X53</th>
<th>Vasco X-2M</th>
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<td>Details Not Reported</td>
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</tr>
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<td><strong>Carburize</strong></td>
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<td>1700°F – 9 hours</td>
<td>1700°F – 8.8 hours</td>
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<td>1.16 – 1.19 %C</td>
<td>Proprietary</td>
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<td><strong>Sub-critical anneal</strong></td>
<td>1150°F – 4 hours</td>
<td>1200°F – 4 hours</td>
<td>1250°F – 2.5 hours</td>
</tr>
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<td><strong>Harden</strong></td>
<td>1500°F – 1.5 hours</td>
<td>1675°F – 20 minutes</td>
<td>1500°F – 1 hour</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1850°F – 30 minutes</td>
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<td><strong>Quench</strong></td>
<td>Oil – 5 minutes</td>
<td>130°F Oil</td>
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<td><strong>Freeze</strong></td>
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<td>-120°F – 3 hours</td>
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<tr>
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<td>600°F – 2 hours*</td>
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<td>450°F – 2 hours</td>
<td>600°F – 2 hours</td>
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* Cool to room temp between temper #1 and temper #2.

Table B-1 – Material heat treatment recipes.
APPENDIX C

Test Data
Impact Test 1 - 9310 - 3 Inch Drop - Time Domain

Figure C-1 – Time domain load and position traces for Test 1.
Figure C-2 – Load versus position trace for Test 1.
Figure C-3 – Time domain load and position traces for Test 2.
Figure C-4 – Load versus position trace for Test 2.
Figure C-5 – Time domain load and position traces for Test 3.
Figure C-6 – Load versus position trace for Test 3.
Figure C-7 – Time domain load and position traces for Test 4.
Figure C-8 – Load versus position trace for Test 4.
Figure C-9 – Time domain load and position traces for Test 5.
Figure C-10 – Load versus position trace for Test 5.
Figure C-11 – Time domain load and position traces for Test 6.
Figure C-12 – Load versus position trace for Test 6.
Figure C-13 – Time domain load and position traces for Test 7.
Figure C-14 – Load versus position trace for Test 7.
Figure C-15 – Time domain load and position traces for Test 8.
Figure C-16 – Load versus position trace for Test 8.
Figure C-17 – Time domain load and position traces for Test 9.
Figure C-18 – Load versus position trace for Test 9.
Figure C-19 – Time domain load and position traces for Test 10.
Figure C-20 – Load versus position trace for Test 10.
Figure C-21 – Time domain load and position traces for Test 11.
Figure C-22 – Load versus position trace for Test 11.
Figure C-23 – Time domain load and position traces for Test 12.
Figure C-24 – Load versus position trace for Test 12.
Figure C-25 – Time domain load and position traces for Test 13.
Figure C-26 – Load versus position trace for Test 13.
Figure C-27 – Time domain load and position traces for Test 14.
Figure C-28 – Load versus position trace for Test 14.
Figure C-29 – Time domain load and position traces for Test 15.
Figure C-30 – Load versus position trace for Test 15.
Figure C-31 – Time domain load and position traces for Test 16.
Figure C-32 – Load versus position trace for Test 16.
Impact Test 17 - 9310 - 36 Inch Drop - Time Domain

Figure C-33 – Time domain load and position traces for Test 17.
Figure C-34 – Load versus position trace for Test 17.
Figure C-35 – Time domain load and position traces for Test 18.
Figure C-36 – Load versus position trace for Test 18.
Figure C-37 – Time domain load and position traces for Test 19.
Figure C-38 – Load versus position trace for Test 19.
Figure C-39 – Time domain load and position traces for Test 20.
Figure C-40 – Load versus position trace for Test 20.
Figure C-41 – Time domain load and position traces for Test 21.
Figure C-42 – Load versus position trace for Test 21.
Figure C-43 – Time domain load and position traces for Test 22.
Figure C-44 – Load versus position trace for Test 22.
Figure C-45 – Time domain load and position traces for Test 23.
Figure C-46 – Load versus position trace for Test 23.
Figure C-47 – Time domain load and position traces for Test 24.
Figure C-48 – Load versus position trace for Test 24.
Figure C-49 – Time domain load and position traces for Test 25.
Figure C-50 – Load versus position trace for Test 25.
Figure C-51 – Time domain load and position traces for Test 26.
Figure C-52 – Load versus position trace for Test 26.
Figure C-53 – Time domain load and position traces for Test 27.
Figure C-54 – Load versus position trace for Test 27.
Figure C-55 – Time domain load and position traces for Test 28.
Figure C-56 – Load versus position trace for Test 28.
Figure C-57 – Time domain load and position traces for Test 29.
Figure C-58 – Load versus position trace for Test 29.
Figure C-59 – Time domain load and position traces for Test 30.
Figure C-60 – Load versus position trace for Test 30.
Figure C-61 – Time domain load and position traces for Test 31.
Figure C-62 – Load versus position trace for Test 31.
Figure C-63 – Time domain load and position traces for Test 32.
Figure C-64 – Load versus position trace for Test 32.
Figure C-65 – Time domain load and position traces for Test 33.
Figure C-66 – Load versus position trace for Test 33.
Figure C-67 – Time domain load and position traces for Test 34.
Figure C-68 – Load versus position trace for Test 34.
Figure C-69 – Time domain load and position traces for Test 35.
Figure C-70 – Load versus position trace for Test 35.
Figure C-71 – Time domain load and position traces for Test 36.
Figure C-72 – Load versus position trace for Test 36.
Figure C-73 – Time domain load and position traces for Test 37.
Figure C-74 – Load versus position trace for Test 37.
Figure C-75 – Time domain load and position traces for Test 38.
Figure C-76 – Load versus position trace for Test 38.
Figure C-77 – Time domain load and position traces for Test 39.
Figure C-78 – Load versus position trace for Test 39.
Figure C-79 – Time domain load and position traces for Test 40.
Figure C-80 – Load versus position trace for Test 40.
Figure C-81 – Time domain load and position traces for Test 41.
Figure C-82 – Load versus position trace for Test 41.
Figure C-83 – Time domain load and position traces for Test 42.
Figure C-84 – Load versus position trace for Test 42.
Figure C-85 – Time domain load and position traces for Test 43.
Figure C-86 – Load versus position trace for Test 43.
Figure C-87 – Time domain load and position traces for Test 44.
Impact Test 44 - X2M - 24 Inch Drop

Figure C-88 – Load versus position trace for Test 44.
Figure C-89 – Time domain load and position traces for Test 45.
Figure C-90 – Load versus position trace for Test 45.
Figure C-91 – Time domain load and position traces for Test 46.
Figure C-92 – Load versus position trace for Test 46.
Figure C-93 – Time domain load and position traces for Test 47.
Figure C-94 – Load versus position trace for Test 47.
Figure C-95 – Time domain load and position traces for Test 48.
Figure C-96 – Load versus position trace for Test 48.
Figure C-97 – Time domain load and position traces for Test 49.
Figure C-98 – Load versus position trace for Test 49.

Impact Test 49 - X-2M - 36 Inch Drop
Figure C-99 – Time domain load and position traces for Test 50.
Figure C-100 – Load versus position trace for Test 50.
Figure C-101 – Time domain load and position traces for Test 51.
Impact Test 51 - X-2M - 36 Inch Drop

Figure C-102 – Load versus position trace for Test 51.
Figure C-103 – Time domain load and position traces for Test 52.
Figure C-104 – Load versus position trace for Test 52.
Figure C-105 – Time domain load and position traces for Test 53.
Figure C-106 – Load versus position trace for Test 53.
Figure C-107 – Time domain load and position traces for Test 54.
Figure C-108 – Load versus position trace for Test 54.
Figure C-109 – Time domain load and position traces for Test 55.
Figure C-100 – Load versus position trace for Test 55
Figure C-101 – Time domain load and position traces for Test 56.
Figure C-102 – Load versus position trace for Test 56. (Do not type text in this document beyond here)