Effects of Head Formation and Heat Treatment on the Mechanical Properties of Connecting Rod Bolts

A Senior Project

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By

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Abstract

Oliver Racing Parts (ORP; Charlevoix, Michigan) is looking to optimize their manufacturing process for high-strength connecting rod bolts. A high yield strength is desired for the bolts because deformation would result in catastrophic engine failure. The bolts were made of H11, a chromium hot-work tool steel; and MLX17, a precipitation hardenable stainless steel. Tensile testing was performed to determine the tensile and yield strengths of the bolts. Fracture surfaces were imaged via scanning electron microscopy to characterize the failure modes. To observe the effects of bolt heading on microstructure and bolt strength, two batches of MLX17 were prepared; one batch being headed then aged (Group A); the other batch being headed, solution annealed, and then aged (Group B). These bolts were compared to H11 bolts to determine their viability for use, with the results being in the order of highest to lowest yield strength: H11 (272 ksi), MLX17 Treatment B (250 ksi), and MLX17 Treatment A (235 ksi). In the order of highest to lowest tensile strength: H11 (300 ksi), MLX17 Group B (255 ksi), MLX17 Group A (238 ksi). It is suggested that the bolt heading process is causing some overaging in the MLX17 samples, shown by the increase in strength when strain and aging from the heading process are undone through heat treatment. H11 bolts were the strongest tested. Recommendations are to not replace H11 bolts with MLX17 due to a decrease in strength.

Keywords: Materials Engineering, Tensile Test, Automotive Engineering, MLX-17, H11, Connecting Rod Bolt, PH Stainless Steel, Tool Steel Bolt

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1. Introduction

1.1 Oliver Racing Parts (ORP)

Oliver Racing Parts (Charlevoix, MI) is a manufacturer of connecting rods for high performance automotive engines. Their connecting rods boast a high strength to weight ratio, which is beneficial in a racing engine application where a reduction in rotating mass will increase engine performance. ORPs connecting rods are sold as a package with bolts produced by Automotive Racing Products (ARP; Ventura, CA). ORP has developed their own bolt manufacturing capabilities to eliminate the need to purchase bolts from ARP. ORP needs to characterize and refine their manufacturing and heat treatment processes to maximize the strength of their bolts, and investigate the viability of replacement materials which will provide superior performance for their bolts. Alloys investigated were H11 (the current material) and MLX 17.

1.2 Problem Statement

Bolts made from MLX17 are demonstrably lower in strength than expected, and it is suspected this is being caused by the heading process during bolt manufacture, though the effects the process has are uncharacterized. The ideal heat treatment for MLX17 consists of a solution heat treatment followed by aging, either at 510°C or 540°C [1]. Following this heat treatment path, with bolt formation occurring after the solution heat treatment, MLX17 samples tested during the 2016-17 academic year were found to have much lower strength than maximum. The bolts should display a yield strength of 265 ksi and a tensile strength of 285 ksi, however previous tests show a yield strength of 215-220 ksi and a tensile strength of 220-230 ksi [2]. To address this problem, the project consisted of tensile testing reference H11 bolts, and MLX17 bolts of differing heat treatments, as well as performing fracture analysis on a selection of untested samples. The specific goals of the project are to determine a heat treatment plan to make MLX17 bolts as strong as existing H11 bolts, and to determine the effect of heading on bolt microstructures and properties. Testing methods and analysis techniques to accomplish the project goals were tensile testing H11 bolts and two different sets of MLX17 bolts, each with various heat treatments, to determine their yield and tensile strength. Representative fracture surfaces of each alloy were examined under scanning electron microscopy (SEM) to determine fracture type.

1.3 The Connecting Rod Bolt

1.3.1 Application

Connecting rods connect the piston of an internal combustion engine to the crankshaft, and allow the linear motion of the piston to be translated to rotary motion of the crankshaft. The connecting rod is connected to the piston on the small end, and the crankshaft by the bearing cap on the big end of the rod, which is held on with two bolts (Figure 1). The connecting rod is subject to cyclic loading at up to 18,000 cycles per minute, and extreme tensile forces. Because of this, the connecting rod bolts must have a high tensile strength and toughness. Toughness is important because it will prevent crack formation and propagation during the cyclic loading the bolt will experience during operation.

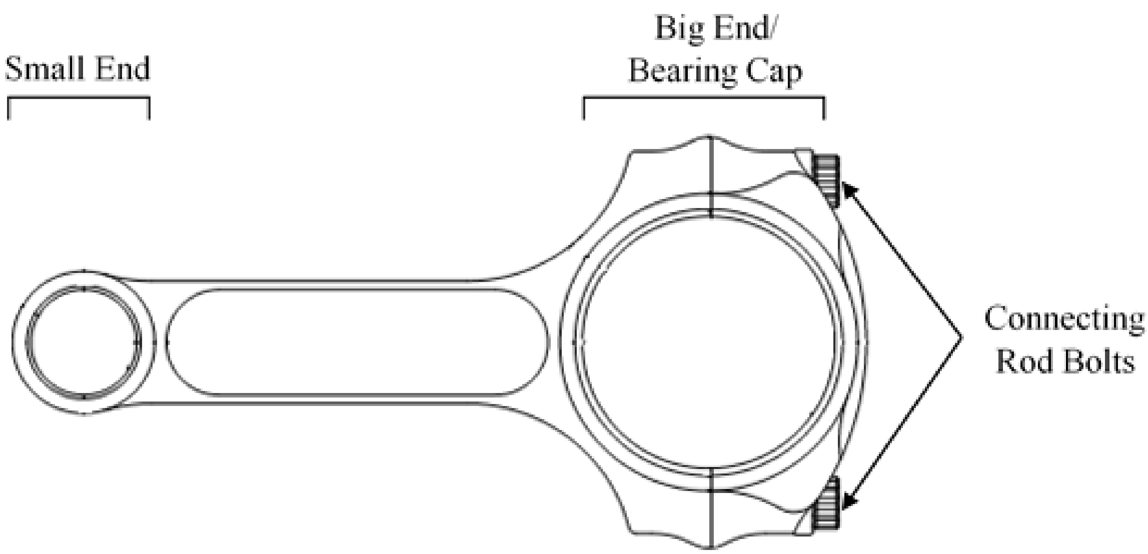
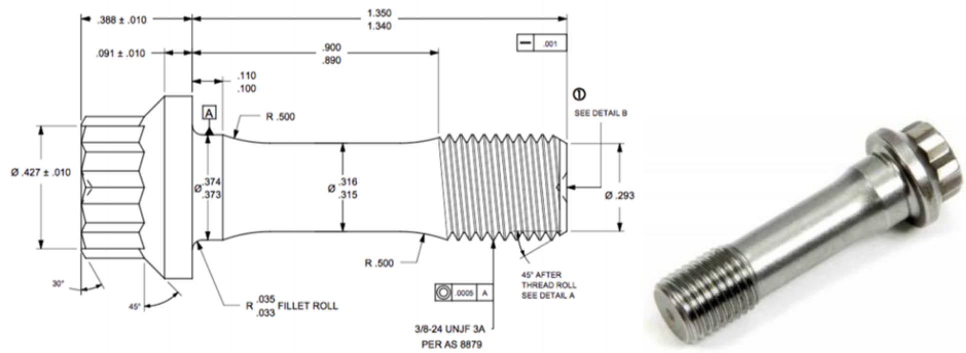


Figure 1. The connecting rod, which is made up of the “Small End” which connects to the piston and the “Big End” which connects to the crankshaft. The bearing cap is connected to the rod with two bolts [2].

1.3.2 Bolt Processing

The bolts are approximately 1.75" in length and ⅜" in diameter, with ⅜-24 UNJF 3A threads (Figure 2). The undercut in the center of the bolt is present to prevent bolt failure in the threads. Failure in the threads would damage the connecting rod upon failure and increase the cost and work needed to repair a failure.



(a) (b)

Figure 2. (a) Schematic of the connecting rod bolts produced by Oliver Racing Parts, depicting the bolt geometry and tolerances. All dimensions are listed in inches [2]. (b) A connecting rod bolt.

The bolts are produced from bar stock in a three-step process which consists of forming the head, heat treating, then warm rolling the threads. Forming the 12-point head of the bolt is done with a process called hot heading. In the hot heading process, the bar stock end which will be headed is heated using an induction coil until red hot, at which point it austenitizes, and then forged in a spring head press. The spring head press is designed to allow improved filling of the die with metal at a lower temperature [3]. The bolt is then sent out to be annealed and heat treated to achieve the desired strength. The heat treatment is specific to each material. A lathe is then used to turn the bolt to the desired dimensions and tolerances.

The threaded portion of the bolt is produced by a process called warm rolling. In this process, the threaded section is induction heated to a relatively low temperature and then passed through a series of dies. The warm rolling process produces stronger threads than a thread cutting process due to the cold working of the grains during processing [4]. Figure 3 shows a comparison between the microstructure of thread rolling compared to thread cutting.

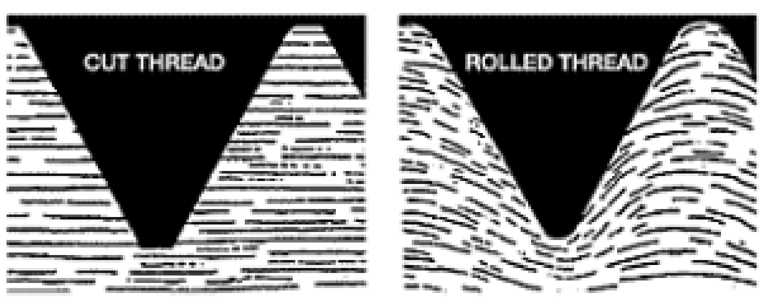


Figure 3. A representation of the difference between thread cutting and thread rolling. Thread rolling deforms the grains, increasing the strength of the threads [5].

1.4 Bolt Testing

The bolts are axially loaded in accordance with ISO 7961 [6]. The loading fixture is shown in Figure 4. The fixture is designed to ensure all the load applied by the tensile tester is transmitted to the bolt and accurate results are recorded. The bolt is secured to the fixture with a nut that simulates the threaded end of the connecting rod which the bolt would normally be threaded in. To ensure accurate results and fully test the strength of the bolts, sufficient thread engagement with the nut is necessary.

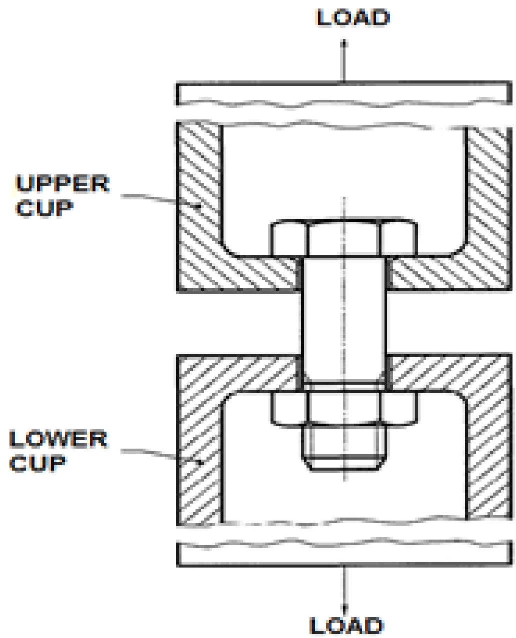


Figure 4. Schematic of the bolt testing fixture, as designed by recommendations from ISO 7961 [6].

A constant loading rate of 750 N/min is recommended per mm^2 of nominal shank cross sectional area [6]. The yield strength and ultimate tensile strength is calculated by dividing the load at which plastic deformation occurs and the maximum load by the minimum diameter of the bolt. In the case of these bolts, this is the area of the undercut. The ductility of the bolt is measured by the percent reduction in area (%RA) of the bolt, and is calculated as the percent difference between the bolt shank's cross-sectional area before and after failure. This method of measuring the reduction in area for full sized bolts is adopted from ASTM F606 for machined test samples [7].

1.5 Bolt Alloys

1.5.1 Tool Steel: H11

H11 is a chromium hot-worked steel, possessing high hardenability and high toughness, making it desirable for use in tools. The alloy contains 0.33-0.43% C with large amounts of Cr and Mo to aid in the formation of carbides (Table I). Carbides serve as the primary strengthening mechanism for H11. Austenitizing is used instead of normalizing to ensure all previous carbides are dissolved into solid solution. The solubilities of the alloying elements in Fe are dependent on the temperature, so a higher austenitizing temperature results in more alloying elements available to precipitate out during heat treatment. Any precipitates not dissolved in austenitizing can be used to prevent excessive grain growth and increase strength.

Table I Minimum and Maximum Elemental Composition of H11 [8]

	C	Mn	P	S	Si	Cr	V	Mo
Min	0.35	0.20	/	/	0.80	4.75	0.30	1.10
Max	0.45	0.60	0.03	0.03	1.25	5.50	0.60	1.60

While it is possible for H11 to achieve full hardness through air cooling, typical quenching occurs either in a nitrogen gas atmosphere or oil. This is done to prevent embrittlement during air cooling. After quenching, most of the martensite has formed in the alloy. Retained austenite is a risk with high dissolved alloying element concentrations, so the austenitizing temperature is carefully chosen to balance maximizing alloying element concentration in the material and minimizing retained austenite. Typical austenitizing temperatures range from 995 to 1025°C, with hold times around 15 to 40 minutes [9]. Tempering follows austenitizing, and transforms martensite into a ferrite matrix with carbide precipitates known as tempered martensite. Multiple tempers can be used to reduce the amount of retained austenite. Mechanical properties are influenced by a combination of tempering temperature and time (Figure 5). Ideal heat treatment involves austenitizing above 1000°C, with a tempering temperature of 540°C to allow for flexibility in tempering times depending on processing requirements.

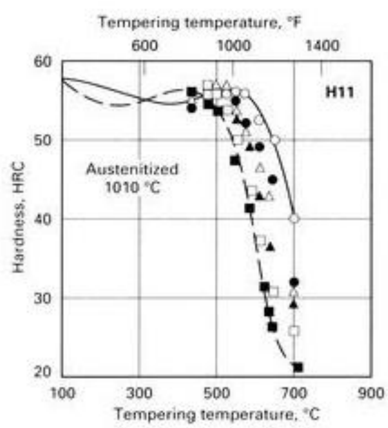


Figure 5. Tempering temperature vs HRC, showing the influence of austenitizing temperature, tempering time, and tempering temperature [9].

1.5.2 Precipitation Hardenable Stainless Steel: MLX 17

MLX 17 is a precipitation hardened, semi-austenitic stainless steel produced by Aubert and Duval (Paris, France). It has high toughness, high strength, and high corrosion resistance. This makes it of value for use in aerospace components and structural applications, including fasteners. This alloy has a low C content of less than 0.02%, along with Ni, Ti, Al, Cr, and Mo (Table II). The low C content functions to lower the martensite transformation start (M_s) temperature without influencing precipitation hardening. Ni gives the alloy its precipitation hardening ability, by forming precipitates Ni_3Ti and NiAl after aging. Cr and Mo both give the alloy its high corrosion resistance [10].

Table II Minimum and Maximum Elemental Compositions of MLX17 [1]

	C	Mn	Si	Cr	Mo	Ni	Ti	Al
Min	/	/	/	11.00	1.75	10.25	0.20	1.35
Max	0.02	0.25	0.25	12.50	2.25	11.25	0.50	1.75

Heat treatment of MLX 17 starts with solution treatment at 850°C, held for 2 hours, followed by quenching in oil or water. After, it is cooled to -73°C or lower and held for 8 hours to allow for complete transformation to martensite [1]. Aging follows which produces the end microstructure (Figure 6). Mechanical properties are influenced by aging temperature and time (Figure 7). Recommended aging temperatures from Aubert and Duval specify 510°C for aerospace components, and 540°C for components requiring high corrosion resistance, both held for 8 hours.

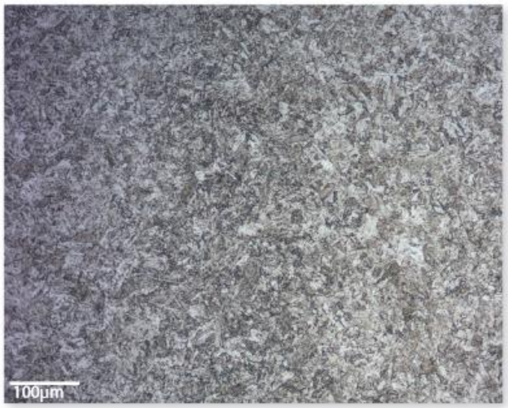


Figure 6. Microstructure visible under optical microscopy, showing martensitic matrix [1].

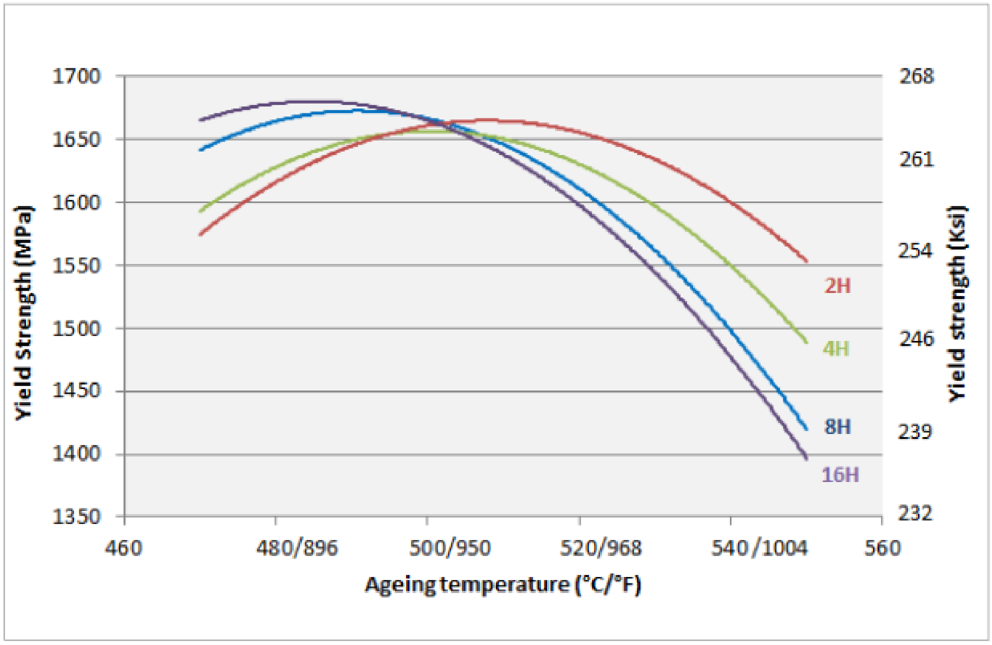


Figure 7. Aging temperature and time, and resulting yield strength for MLX17 stainless steel. A lower aging temperature held for longer will produce the highest strength possible [1].

2. Experimental Design

2.1 Heat Treatment

Heat treatments for H11 and MLX17 were chosen based on multiple factors. To maintain repeatability with prior experiments performed, heat treatments for MLX17 and H11 were duplicated, along with a new heat treatment for MLX17 (Table I). Due to changes in processing of the bolt, these duplicate heat treatments are required to ensure compatibility with prior results, and verify that these changes in processing have not significantly altered the properties previously observed. A second heat treatment was specified for MLX17 in an attempt to reverse any possible overaging influence from the heading process. The MLX17 is received by the manufacturer in the solution annealed condition; this second heat treatment repeats the solution anneal treatment after the heading process and prior to aging. These two groups are henceforth referred to as As Received and Re-Solution Annealed, respectively.

Table III. Bolt Materials and Heat Treatments

Material	Heat Treatment	Sample Size
H11	Standard Heat Treatment 1. Austenitize at 1750F 2. Triple Temper at 1000F	20
MLX17	Re-Solution Annealed 1. Heat to 1550F for 2 hours 2. Brine quench 3. Hold at -150F for 8 hours 4. Warm to room temperature in air 5. Age at 950F for 8 hours	20
	As Received 1. Age at 950F for 8 hours	20

2.2 Tensile Testing

Tensile testing was performed on a 150 kN Instron mechanical testing system. All testing was performed to the ISO 7961 standard, using a custom two-piece fixture to ensure purely axial loading during testing (Figure 8). The bolt was inserted between the two pieces of the fixture and a 17-4 PH stainless steel nut was hand-tightened to the bolt to secure it, with ISO 7961 calling for two threads outside of the bolt. The nut was replaced after every five tests, both for safety and reliability of measurements. To maintain a parallelism between the between the bolt and the loading axis, rounded collars made of O-1 tool steel heat treated to HRC 53 were inserted between the fixture and the bolt head and nut. 20 samples of each alloy and heat treatment were tested, with tests lasting approximately two to four minutes each. Bolts were tested to fracture, at a crosshead displacement rate of 0.15 inches per minute.

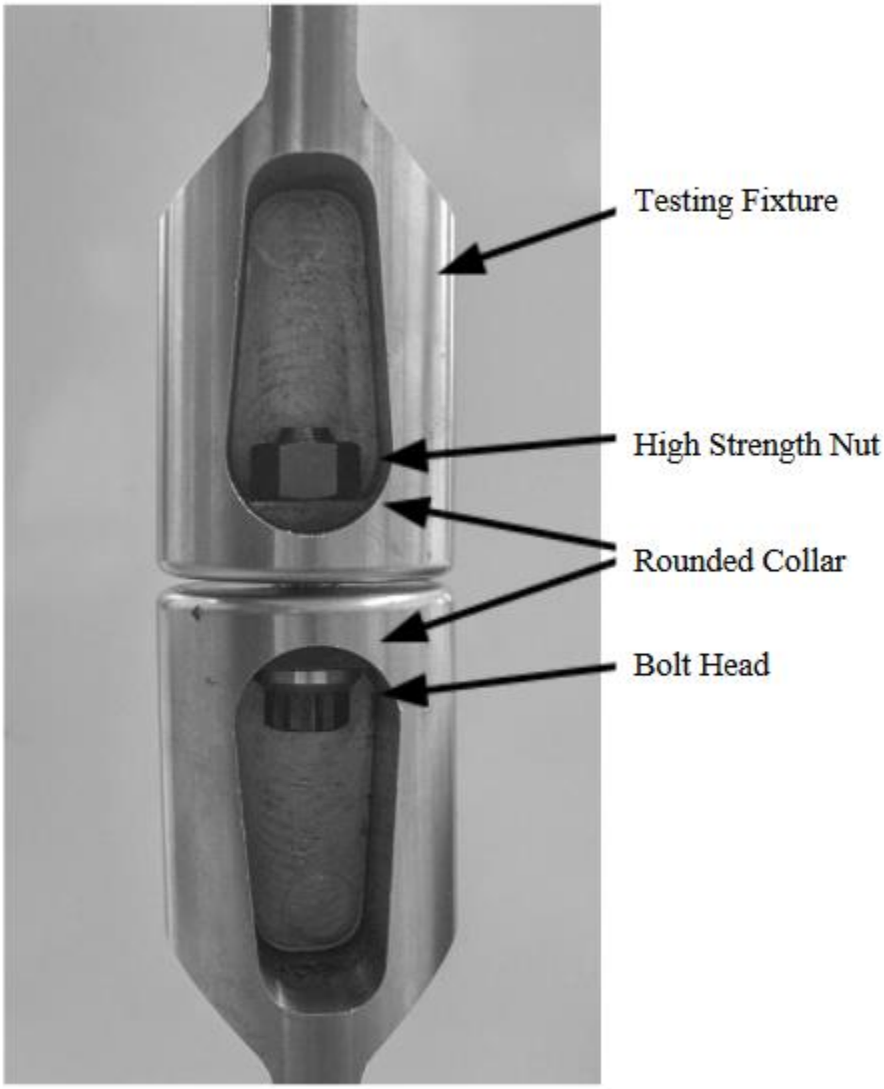


Figure 8. Custom test fixture designed to test automotive connecting rod bolts, showing bolt installation with rounded collars to ensure purely axialy loading [11].

2.3 Safety

Due to the extreme strength of the bolts, precautions needed to be taken during testing to ensure safety. The fracture of the bolts is loud and violent, so ear protection was worn during testing and a safety shield was placed in front of the Instron machine during testing. In addition to this, only certified operators could be in the room while testing was being performed. These precautions were taken in addition to standard lab safety procedures, including long pants, closed toed shoes, and safety glasses.

2.4 Tensile Strength and Yield Strength

Tensile strength is defined as the maximum stress a part can withstand before fracture. To calculate the tensile strength of the bolts, the maximum load was divided by the original cross-sectional area of the relief section. Yield strength is defined as the maximum stress a part can withstand before beginning to plastically deform. Since the bolt is a non-conventional geometry and the fixture does not allow room for an extensometer to be attached, the traditional 0.2% offset method cannot be used to calculate yield strength. The load associated with the yield strength was estimated to occur at the greatest change in slope of the load vs. extension plot, or the maximum of the second derivative of load vs. extension. A first derivative was calculated by dividing the change in load across the change in displacement. The second derivative was calculated in a similar manner, instead by dividing the change in the first derivative over the change in displacement. The data was also clipped to a range of data where the yield strength was expected. The lower limit of the interval was defined as 30% of all data, to eliminate the noise associated with the bolt settling in to the fixture at the beginning of the tests. The upper limit of the interval was defined as 90% of the maximum load, because yielding occurs before the maximum load is achieved. The yield load could then be determined as the load associated with the displacement where the second derivative reaches a maximum (Figure 9). Dividing this yield load by the original cross-sectional area of the relief section.

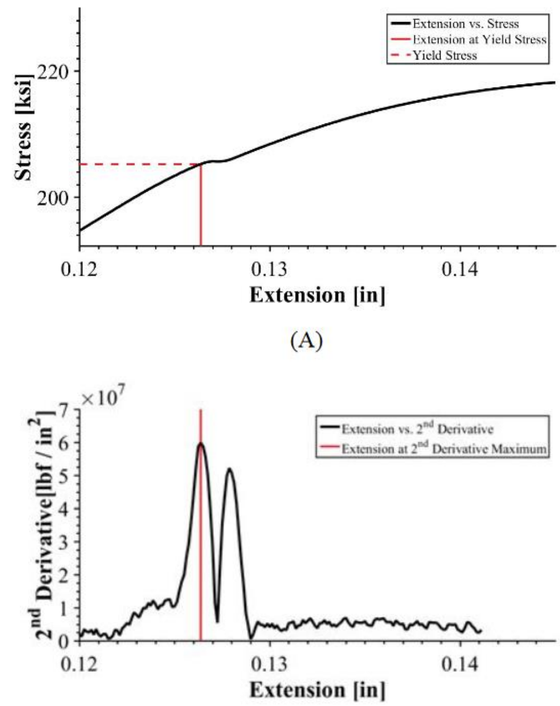


Figure 9. The extension at which the maximum of the 2nd derivative occurs corresponds to the extension at which the material yields. [2]

2.4 Microscopy of Fracture Surfaces

Macro- and microscopic examination was performed on the fracture surfaces of both H11 and MLX17 bolts following testing. Visual inspection noted differences in the fracture surfaces between the two materials. Scanning electron microscopy (SEM) was performed to gain further insight towards this, using a FEI Quanta 200 operating at a high voltage of 20.0 kV and a 4.0 nm spot size .

3. Results

3.1 Tensile Properties

Tensile testing gave the relationship of load and extension for each bolt, and by dividing load over cross-sectional area of the relief the relationship of stress and extension can be determined. Raw data from the Instron software was received as graphs of 10-sample groups (Figure 10) and as an excel file with time, load, and extension data in increments of 0.05 seconds. The raw data graphs show noise in the first 30% of the data, which is associated with the bolt, nut, and collar settling in to the fixture.

Stress-extension data for each material were clipped from 30% of the data to the tensile strength and compiled, to show characteristic elastic curves and tensile strengths. This was done using the excel data provided by the Instron software. H11 is shown in Figure 11, MLX17 Re-Solution Annealed is shown in Figure 12, and MLX17 As Received is shown in Figure 13. Averages, ranges, and standard deviations of yield strength (Table II) and tensile strength (Table III) were reported for each alloy and condition. The range and standard deviation are meant to illustrate the scatter in data, and the sample size is reported to show statistical significance. The dashes in Table II are present because of the way yield strength was determined for MLX17 samples. Due to the behavior of the alloy the 2nd derivative method used to calculate yield strength for H11 did not work for MLX17 samples, and is discussed further in section 4.5 of this report. Since the yield strength for MLX17 samples was determined qualitatively, no values for standard deviation or the minimum and maximum strength were available to report.

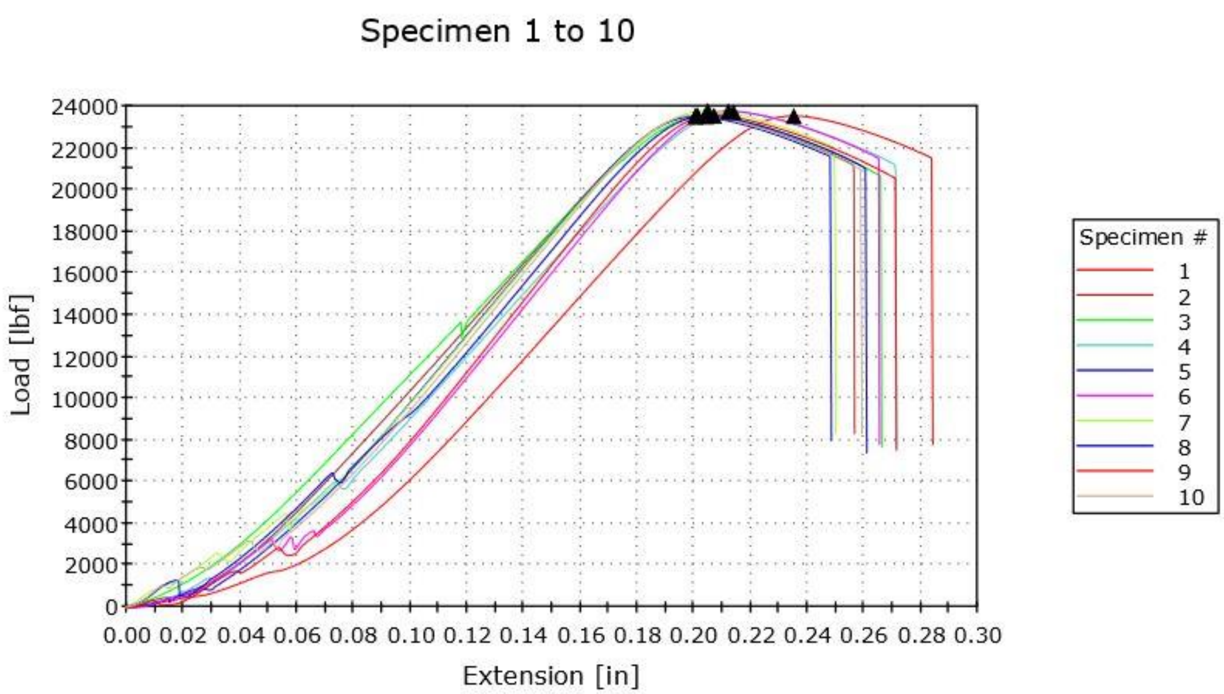


Figure 10. Typical raw data output from the Instron software, this graph showing samples 1-10 of H11. Complete results are available in the appendix.

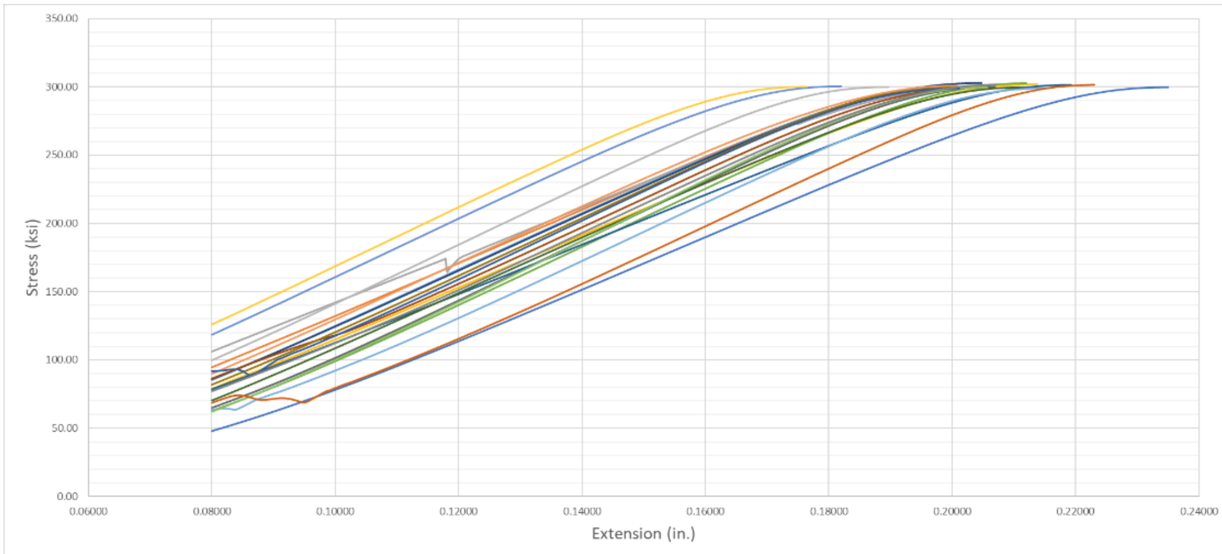


Figure 11. Compilation of H11 data. Some noise from settling is still visible in select samples, however a general trend of yield strength and tensile strength is visible.

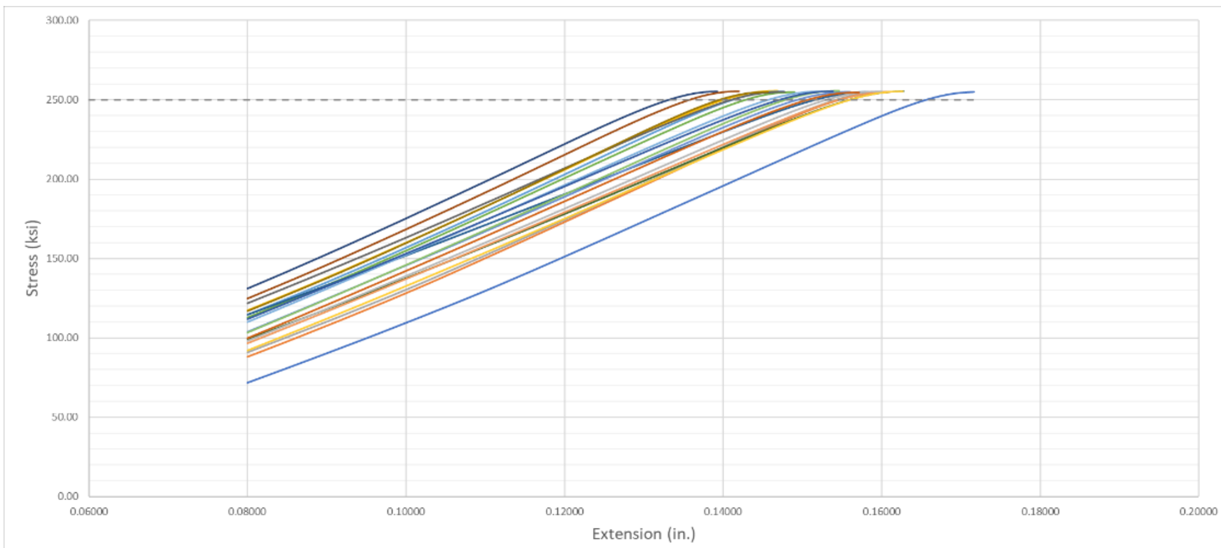


Figure 12. Compilation of MLX17 Re Solution Annealed data. The dashed line represents the estimated yield strength of 250 ksi.

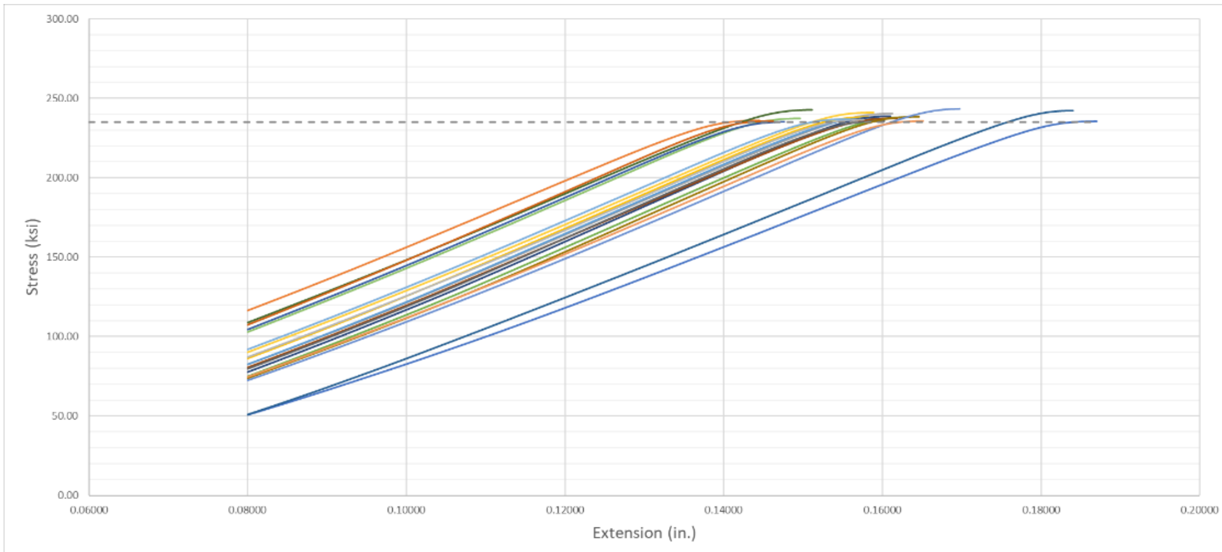


Figure 13. Compilation of MLX17 As Received data. The dashed line represents the estimated yield strength of 235 ksi.

Figures 13 through 15 show that consistency within each sample group was high, and all samples within a group had nearly the same elastic modulus, or slope of the elastic region. It is also significant to note that some settling noise was still present in the H11 data (Figure 11). While this is less than ideal, any second derivative peaks associated with this noise was disregarded when performing yield strength calculations. The two samples in Figure 13 which are shifted to the right are associated with samples where some extra extension was recorded initially, but had no significant load applied. This could have come from either the fixture shifting slightly in the Instron jaws during the first test of a group, or with the bolt being loose within the fixture at the beginning of testing. This should not be taken too seriously, since these samples still showed the same yield and tensile strength properties despite the additional recorded elongation.

Table IV. Yield Strengths of Connecting Rod Bolts

Alloy	**Heat Treatment**	**Sample Size**	**Mean Yield Strength (ksi)**	**Minimum Strength (ksi)**	**Maximum Strength (ksi)**	**Standard Deviation (ksi)**
H11	Standard Heat Treatment	20	272	261.4	283.6	5.3
MLX17	Re-Solution Annealed	20	250	-	-	-
	As-Received	20	235	-	-	-

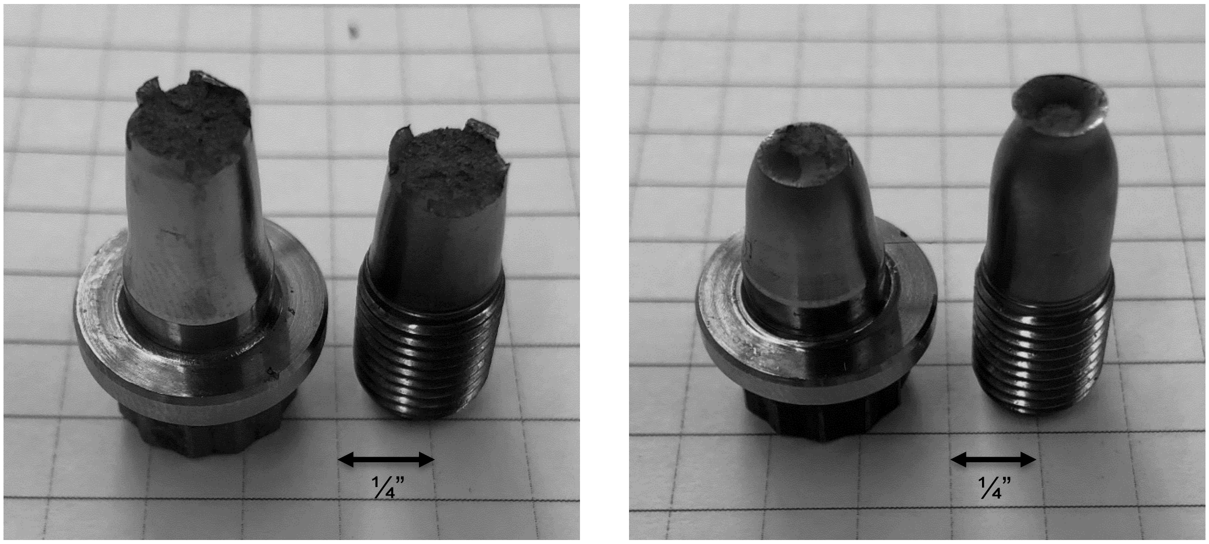
Table V. Tensile Strength of Connecting Rod Bolts

Alloy	Heat Treatment	Sample Size	Mean Tensile Strength (ksi)	Minimum Strength (ksi)	Maximum Strength (ksi)	Standard Deviation (ksi)
H11	Standard Heat Treatment	20	300	298.9	302.8	1.1
MLX17	Re-Solution Annealed	20	255	254.7	255.7	0.4
	As-Received	20	238	235.3	243.4	1.7

3.2 Macro- and Microscopic Views of Fracture Surfaces

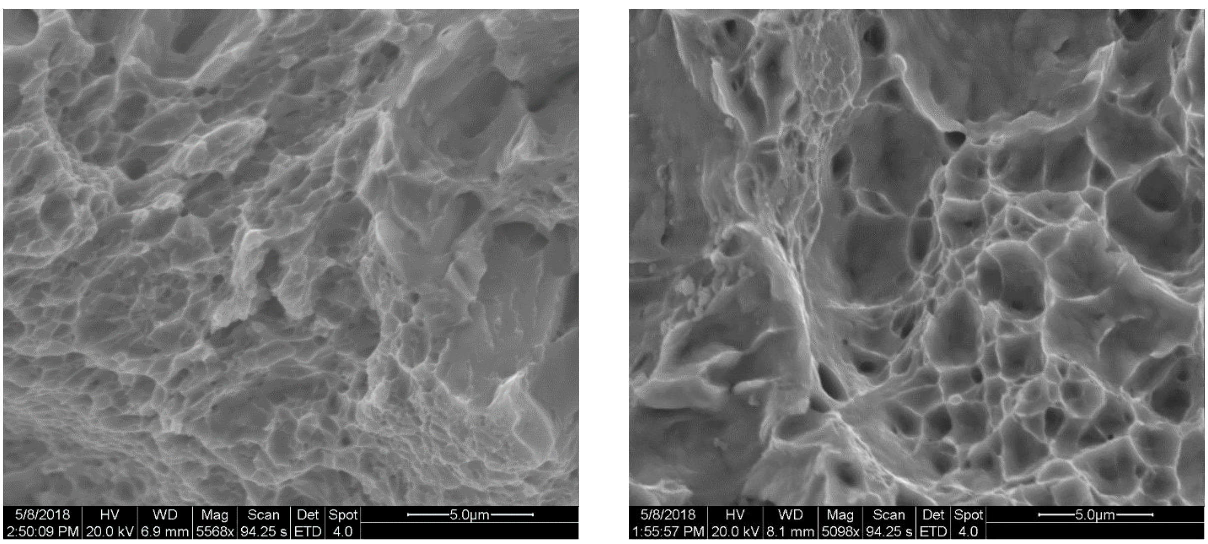
Fracture surfaces after failure were qualitatively assessed using visual and SEM inspection. Macroscopically, both bolts failed in the undercut as designed (Figure 14). H11 bolts exhibited almost no necking, forming a rough fracture surface with the only hint of possible ductile fracture occurring being small shear lips at the outermost edge of the sample. MLX17 bolts exhibited easily visible necking, forming a cup and cone fracture surface that is typical of a ductile fracture.

SEM inspection confirmed both H11 and both conditions of MLX17 bolts failed in ductile fracture. In both samples, microvoid coalescence is visible (Figure 15). For H11 bolts, a higher magnification was required to see the microvoid coalescence than in MLX17 bolts. There were no differences between either condition of MLX17 in their fracture surfaces.



(a) (b)

Figure 14. Macroscopic view of: (a) H11, showing a rough fracture surface with lips at the outermost edges, and (b) MLX17, showing a prominent cup and cone fracture surface.



(a) (b)

Figure 15. SEM imaging of fracture surfaces of (a) H11 and (b) MLX17. Due to being a less ductile alloy, the H11 had to be viewed at slightly higher magnification to see the same microvoid coalescence characteristic of a ductile fracture.

4. Discussion

4.1 Effect of post-heading solution anneal on strength of MLX17 bolts

Previous tests had shown MLX17 to have significantly lower strength than anticipated based on specifications given by the supplier. It was hypothesized that heat input during the bolt heading process caused overaging to occur, causing the significant decrease in strength. Aging is the process of growing precipitates in the material, which is the primary strengthening mechanism in precipitation hardened stainless steels like MLX17. These precipitates act to impede dislocation movement through the alloy, by different mechanisms depending on their coherency. Small precipitates (on the nanometer scale) are coherent with the surrounding lattice, that is their crystal lattice is oriented and connected with that of the surrounding matrix. However, since these precipitates are of a different composition than the surrounding, the lattice spacing is slightly different, putting a strain on the surrounding matrix. This strain field acts to slow dislocation movement, since the dislocations must re-orient themselves to make it through the field. As the precipitates grow, they become less coherent until they reach a point of being incoherent, that is their crystal lattice is no longer aligned with the matrix. When the precipitates are this size, they impede dislocation movement by forcing dislocations to bow around them. Precipitates will continue to grow with aging, with the material's strength growing proportionally. Once peak strength is achieved, the precipitates continue to grow which causes a decrease in strength. This decrease in strength is called overaging, and is caused by the precipitates becoming so few and large, that they no longer effectively impede dislocation motion as they once did.

Aging is achieved by holding a solution annealed alloy at an elevated temperature for a given amount of time. The aging process is extremely temperature dependent, a difference of 25 degrees or 30 minutes can raise or lower strength by 10 ksi or more [1]. The bolt heading process exposes the alloy to temperatures hundreds of degrees above an ideal aging temperature, which could cause the material to overage during the heading process. When a typical aging procedure is then carried out, the material could be overaged and have a lower than expected strength.

To confirm the posed hypothesis of heading causing overaging, two heat treatments for MLX17 were specified. The "As Received" samples would be the same heat treatment as in previous tests, with aging occurring for 8 hours at 950 °F. The "Re-Solution Annealed" samples would be subjected to a second solution annealing process matching the one specified by the manufacturer after heading but before aging. This solution annealing process consists of holding the sample at 1550 °F for two hours, then quenching in brine, then freezing and holding at -150 °F for 8 hours, and then warming to room temperature in air. Following this step, the bolts would then be aged at 950 °F for 8 hours. The purpose of this solution annealing is to return the bolts to the as-delivered condition before heat treatment occurs, thus theoretically reversing any aging that would have occurred during the heading process. The "Re-Solution

Annealed" bolts showed an average increase of 15 ksi yield strength and 17 ksi tensile strength. This is a significant and noticeable increase, which confirms the posed hypothesis that aging is occurring during the bolt heading process.

4.2 Increase in strength of H11 bolts

H11 bolts with the same heat treatment as previous work were tested as a baseline for the MLX17 bolts. Upon analysis, it was determined that the H11 bolts displayed an increase in yield strength and tensile strength of 7 ksi and 30 ksi, respectively. The difference between the bolts is the processing equipment used to process the current bolts versus the previous bolts. Previously, ORP has purchased a new induction coil and spring head press for bolt manufacturing. The new induction coil is designed to have tighter tolerances than the old one to prevent overheating the bolt outside of the area to be headed. The new spring head press is designed to allow better fill out of the mold during forging at a lower temperature, which should allow the alloy to be heated less during heading. While it is understood that the high temperature during heading will cause overaging in the MLX17 samples, it is not fully understood why the high heat would affect the H11 samples. This is because the H11 heat treatment consists of a high temperature (1850 °F) austenitizing step followed by a triple temper at 1000 °F. This austenitizing step should undo any previous processing stresses or similar experienced by the bolts. This increase in strength could be an area of investigation in future experiments.

4.3 Considering other properties

Initially, it was thought that there may be some corrosion concerns with the use of H11. Upon further research and discussion, it was decided that any corrosion concerns should be disregarded. While in operation, the connecting rod big end and connecting rod bolts are immersed in an oil bath. This oil bath would prevent significant corrosion from occurring during the service life of the bolts.

Another concern is the cyclic fatigue strength of the bolts. Connecting rods experience thousands of rotations per minute, therefore cyclically loading the bolts thousands of times per minute for hours on end. Fatigue testing is currently underway by ORP to determine the fatigue strength of H11 and MLX17.

4.4 Effect of quenching after bolt heading

The bolts tested in the experiment were air cooled after the heading process, however a second set of bolts was received which were water quenched after the heading process. Bolt sets underwent the same heat treatments, but there were less water-quenched samples received than air cooled (27 vs. 102). To ensure there was no significant difference associated with the cooling process after heading, 10 water-quenched bolts were tested. These bolts displayed the same average strengths as the air-cooled samples, so the rest were not tested. This is expected, since the quick cooling rate should not have a significant influence compared to the significance of the aging process.

4.5 Yield strength calculation for MLX17

As mentioned previously, a second derivative method was used to calculate the yield strength of the bolts, since the non-standard geometry and fixture did not allow for use of an extensometer. While this method was sufficient for calculating the yield strength of H11 samples, problems arose when attempting to calculate the yield strength of the MLX17 samples. Calculations returned yield strength values in the range of 140-175 ksi, which a quick reference to Figures 14 and 15 revealed to be erroneous. There was clearly still a large elastic region before any yielding was visible. To address this, the yield strengths for the MLX17 samples were qualitatively estimated based on what looked to be a consistent and reasonable yield point. While this is not ideal, it is important to keep in mind that yield strength is always an informed estimate, and the tight grouping of the data suggests that there are no outlying values which would artificially raise or lower the yield strength. Also of important note is the fact that the estimated yield strengths are significantly lower than that of the benchmark H11, so a qualitative estimate based on the graphs should be sufficient.

5. Conclusions

(1) H11 bolts were the strongest tested, with a yield strength of 272 ksi and a tensile strength of 300 ksi. This is significantly more than the strongest MLX17 samples, which had a yield strength of 250 ksi and a tensile strength of 255 ksi.

(2) The heading process is causing overaging in the MLX17 bolts, as shown by the lower than expected strength in both previous tests and the “As Received” samples. To address this, a re-solution annealing step must be added to the heat treatment of MLX17 bolts to optimize their strength. An increase of 15 ksi yield strength is significant, and justifies the extra processing step in a strength-driven application.

(3) Since strength is the primary concern for the connecting rod bolt application, H11 is the best alloy tested. While there may be some concerns with the corrosion resistance of H11, the constant immersion in oil prevents any significant corrosion. H11 also has the advantage of achieving significantly higher strength than MLX17 with less processing time and fewer processing steps.

References

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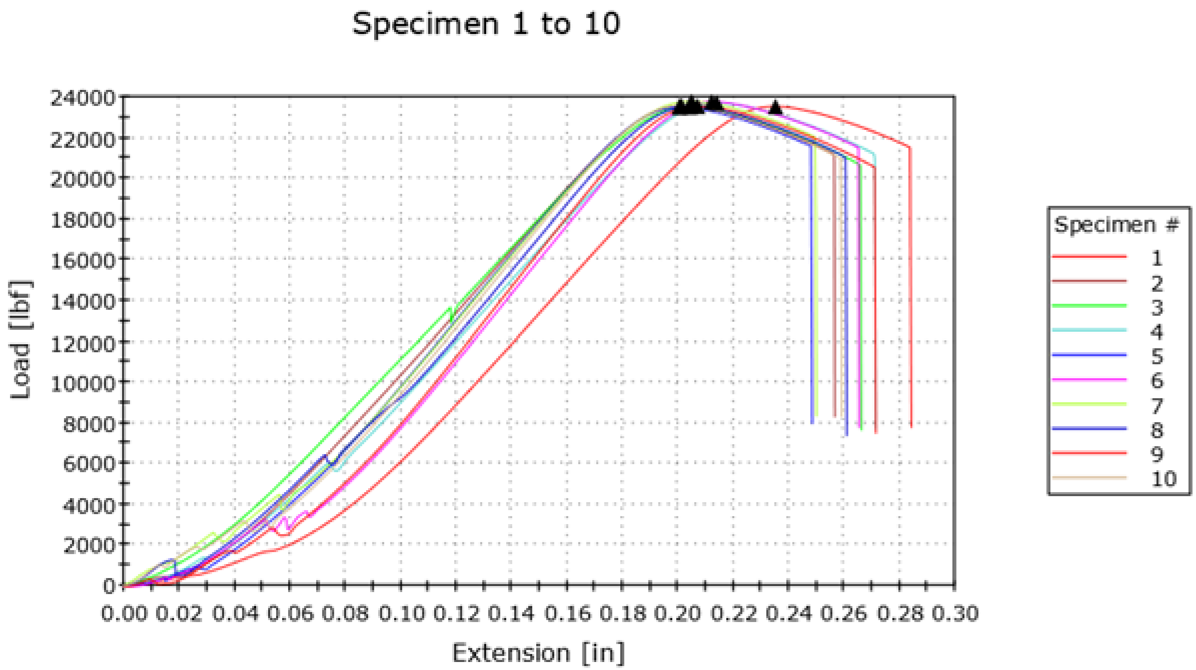
Appendix



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14000
12000
10000
8000
6000
4000
2000
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Specimen #
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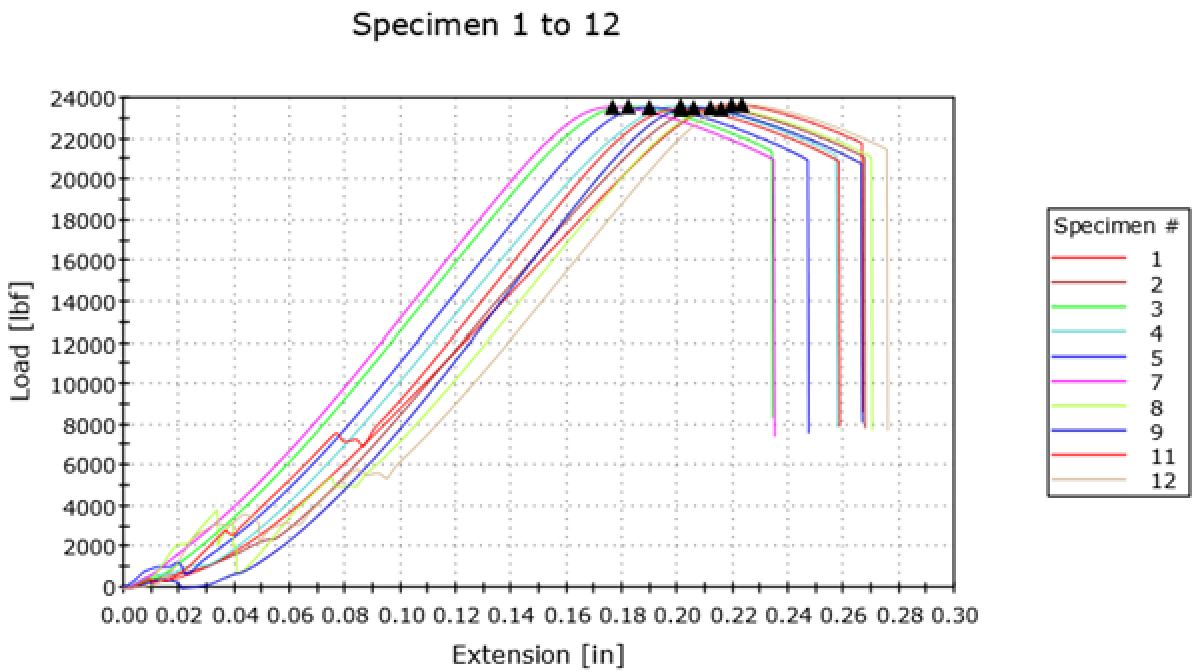
2
3
4
5
6
7
8
9
10



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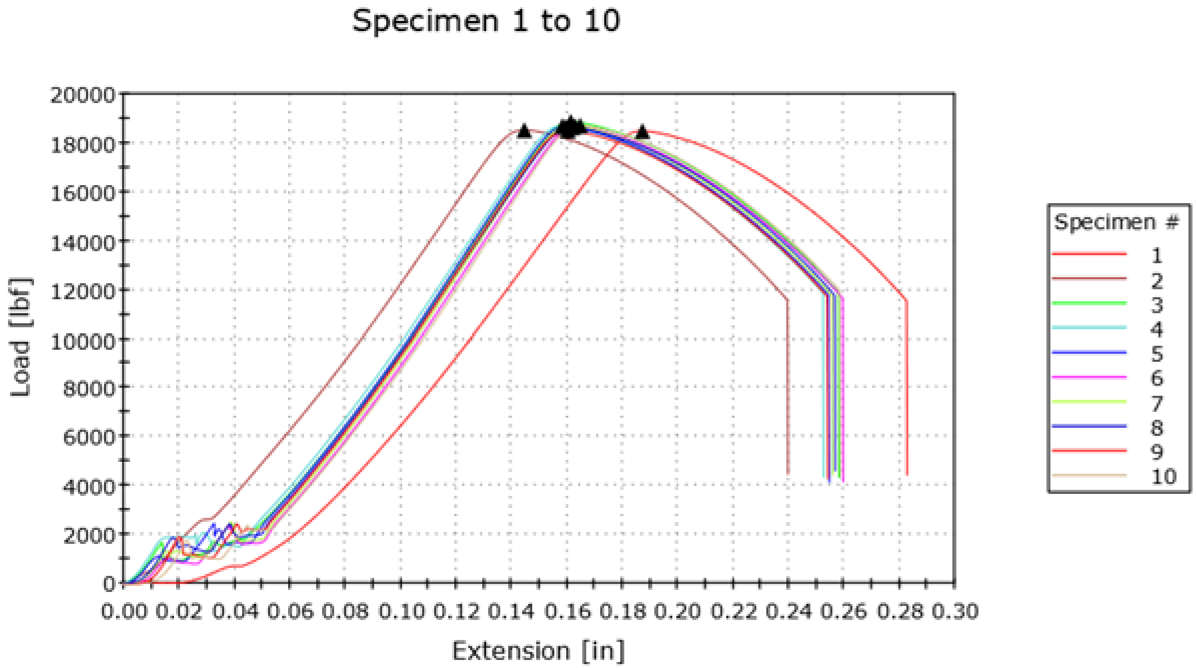
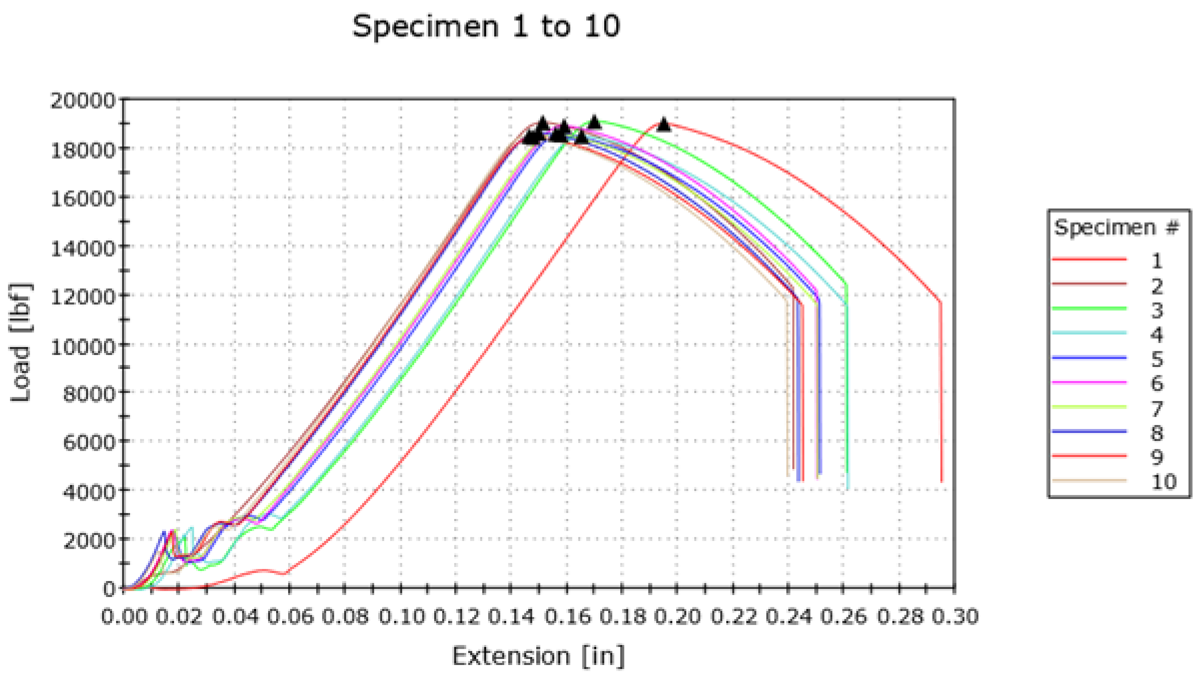
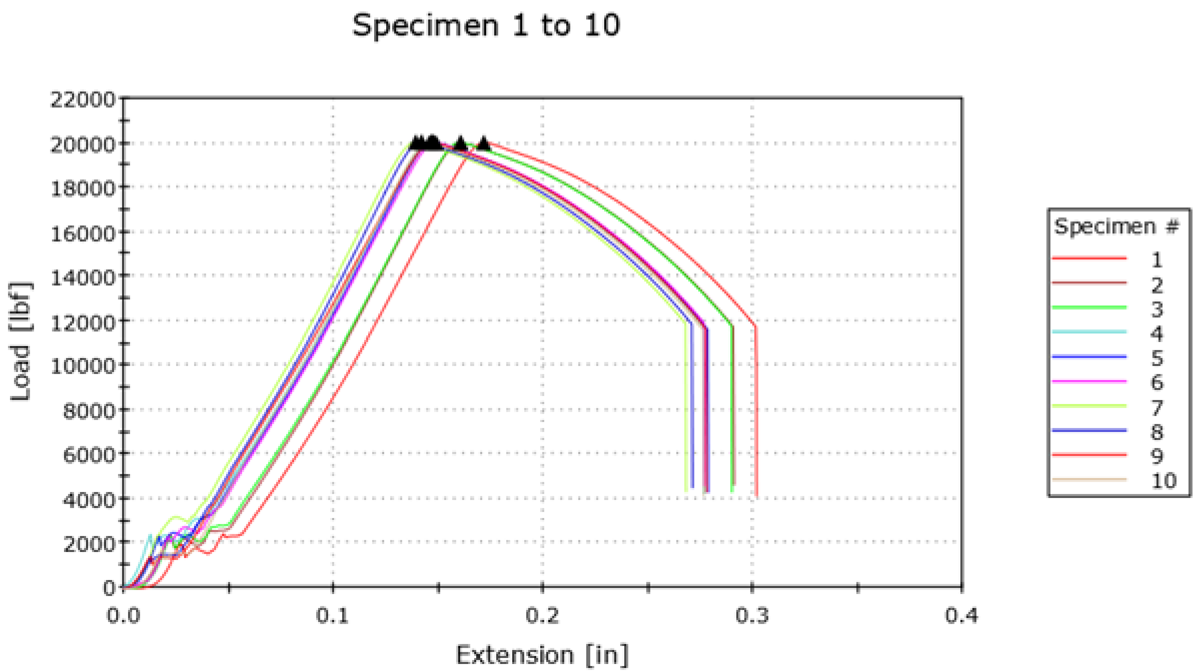
3
4
5
7
8
9
11
12

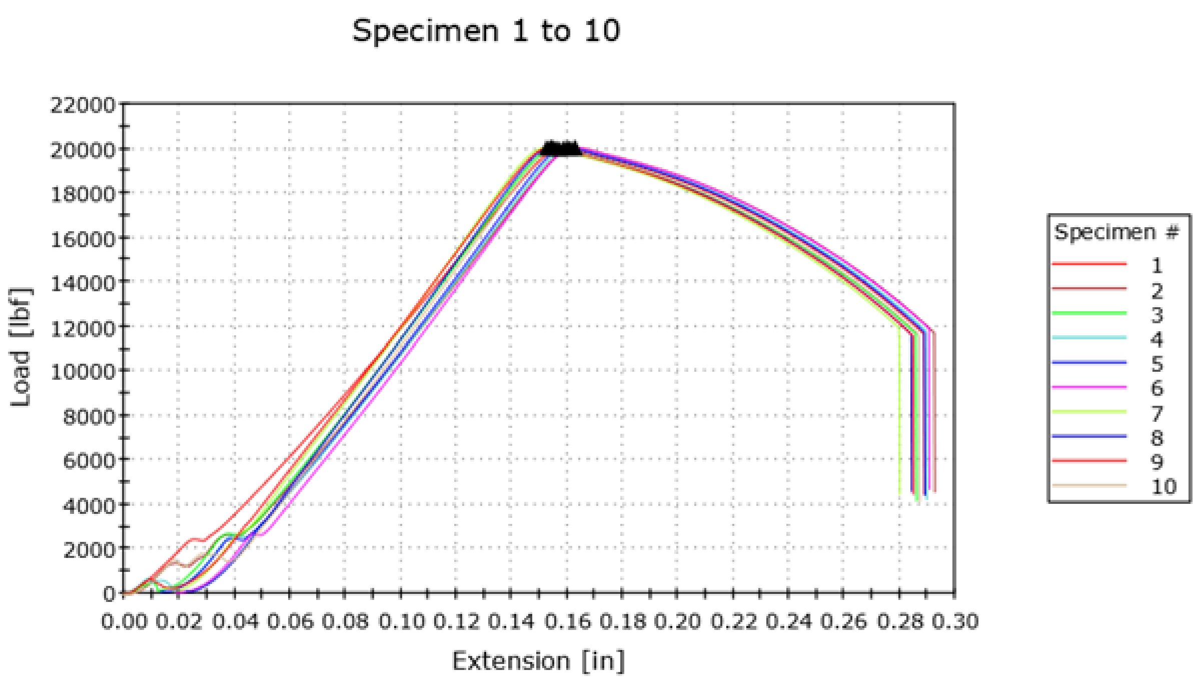
A.1. H11 Raw Data





A.2. MLX17 As-Received Raw Data





A.3. MLX17 Re-Solution Annealed Raw Data