The Effects of Austempering and Cryogenic Processing on the Mechanical Properties of Forged E4340 Steel for Automotive Engine Connecting Rods

In Partial Fulfillment

of the Requirements for the Degree

Bachelor's of Science in Materials Engineering

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June 2014

Abstract

The components in top-fuel dragster and stock car engines undergo significantly more force than their production passenger vehicle counterparts do. Therefore, they must be manufactured and processed to withstand those forces so that they do not catastrophically fail while in service. In this project, the effects of austempering and adding a cryogenic processing step to the control quench and double temper heat treatment on the tensile and hardness properties of E4340 high-strength steel were examined. Tensile test samples were machined from raw connecting rod forgings and underwent either a quench-double temper heat treatment, an austempering heat treatment, or the quench-double temper heat treatment with an added cryogenic processing step after the quench. The mechanical properties caused by each heat treatment were then measured through hardness and tensile testing. The average yield strength produced through austempering was less than that produced through the current heat treatment or through cryogenically processing. The cryogenically processed and control samples had statistically similar yield strength values, which is likely due to the difference in retained austenite between the two sample groups being relatively small.

Keywords: E4340, austempering, martempering, cryogenic processing, materials engineering

Acknowledgements

I would like to take this opportunity to thank the various people who made this project possible. First, I want to thank my parents, Mark and Christine Ludlow, for providing unceasing emotional support throughout my time at Cal Poly and during this project. I would like to thank my advisor, Dr. Blair London, for being a sounding board for my ideas and setting me straight when I needed it. I would also like to thank Ted Keating, the Vice President for Business Development and Sales at Oliver Racing Parts, for giving me this project and for always being there to provide any additional information I needed to complete this project. In addition, I would like to thank Sami Syammach, a Metallurgical and Materials Engineering graduate student at Colorado School of Mines, for performing the molten salt heat treatments required for my project when no one else could. Finally, I would like to thank my friends and classmates for helping me remain grounded and balanced throughout my college experience.

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Chapter 1: Introduction

1.1 Stock Car and Dragster Engines

In the world of automobile racing, nothing goes faster than a top-fuel dragster. In order for a dragster to reach a top speed of 325 miles per hour in less than 1,000 feet, the engine must be carefully designed to maximize the amount of horsepower it can generate while keeping the overall weight of the dragster to a minimum (Figure 1)[1]. In order to achieve this balancing act, the walls of the engine are made much thinner than a production (passenger) car engine to reduce weight. To maximize the power generated by the engine, all dragsters use a mixture of 90% nitromethane and 10% methanol, which vaporizes more readily than normal gasoline and gives the dragster between 8,000 and 10,000 horsepower (hp).[1] However, this maximizing of the ratio between power and weight comes at a cost- the engine vibrates much more than a passenger car engine, which correspondingly increases the wear on the engine components. To prevent a catastrophic failure within the engine that could destroy the dragster and potentially injure the driver, top-fuel dragsters do not operate at full power for more than 10 seconds, and all of the pistons in an engine are usually replaced after each race.[1,2]

Figure 2: A top fuel dragster shortly after the start of a race. The flames coming out of the exhaust pipes are caused by still-burning nitromethane being pumped into the exhaust system.[1,3]

With stock car racing, each car is based on a production vehicle (Figure 2). While each engine's maximum power output is only 850 hp (compared to 150-400 hp for a production vehicle), the same design principles that govern top-fuel dragster engine

Figure 1: A typical stock car in the middle of a race. Because of the emphasis on high power and low weight, stock cars rarely share parts with production vehicles.[3,4]

design govern the design of stock car engines. Like top-fuel dragster engines, stock car engines are designed to operate at 6,000 revolutions per minute (rpm) in order to give the maximum amount of power possible, which causes the same problems with a short engine service life.[1,4] The engine block of each stock car must be completely replaced after 1,000 miles of driving due to wear on the engine components.[4]

1.2 Connecting Rods and Their Role in an Engine

In an internal combustion engine, which is the class of engine that powers stock cars, top fuel dragsters, and most consumer automobiles, power is generated by the burning of fuel in a series of cylinders (Figure 3). That power is captured by a piston and transmitted to the crankshaft by a connecting rod, which links each piston in the engine to the crankshaft. The transmission and by extension the wheels of the vehicle are then connected to the pistons by the crankshaft[5]. For the engine to work properly, each component must withstand the forces generated by the burning fuel that is transmitted throughout the engine. Because of their proximity to the pistons and their failure leading to the destruction of the engine, connecting rods are considered the most critical components of any engine[6].

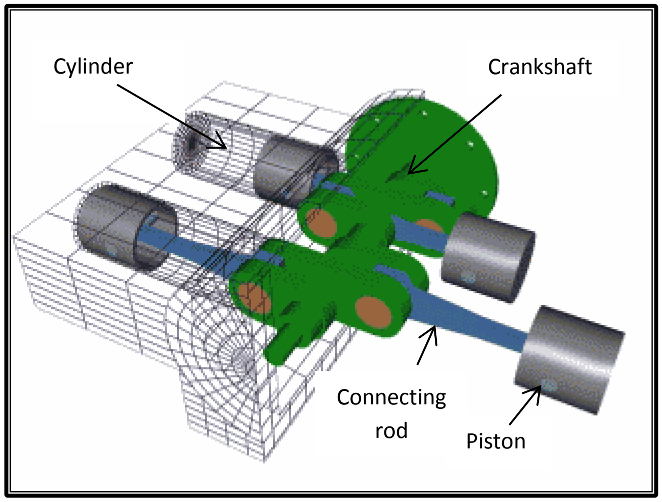

Figure 3: A computer model of an internal combustion engine. The sequence that determines when each cylinder fires is designed to maximize the amount of power generated by the engine without destroying it.[5]

Connecting rod failures are caused by inadequate lubrication, too much hp, the engine operating at 6,000 rpm or higher for too long, or a combination of all three[6]. These factors can lead to the rod failing due to fatigue. Because they are designed to operate at high rpm and high power output, top-fuel dragsters and stock cars are particularly vulnerable to connecting rod failure, which is why so much care goes into their manufacturing and processing.

1.3 Forging

There are two manufacturing processes that are used to manufacture the majority of connecting rods today- machining and forging. In machining, the connecting rod is essentially cut out of another piece of metal with various cutters and drill bits, while forging involves mechanically deforming a piece of metal, usually at elevated temperatures, into the rough shape of a connecting rod (Figure 4).

Figure 4: A connecting rod being forged. Steels are typically forged at temperatures above 800°C (1472°F)[8].

The majority of companies that sell connecting rods will forge them for several reasons. First, forged materials exhibit somewhat anisotropic properties. By mechanically deforming the material, its grain structure is distorted, causing it to become aligned[7]. As a result, the material is stronger when the stresses applied to it are also aligned with the grain structure. This is advantageous for connecting rods because the majority of the stresses it will experience while in service are along one axis, which also means that less material is needed for each connecting rod, saving manufacturing time and money as well as weight, which in a high-performance vehicle like a stock car is advantageous.

In addition, forging wastes less material than machining. Deforming the material to a shape close to the finished product means that more connecting rods can be made for a given volume of starting material. This also means that less finish machining is needed for each connecting rod, which saves the manufacturer money on both raw materials and tooling and allows them to deliver parts faster to their customers[9].

1.4 E4340 Steel Properties and Processing

One engineering alloy commonly used for connecting rods is E4340 steel, which is an aircraft-grade variant of AISI 4340 steel. A low-alloy, medium carbon steel, E4340 is used for structural applications where high strength is needed, such as in aircraft landing gear (Table I)[10]. The alloying elements in E4340 allow it to harden through the full thickness of the part, a property

Table I: Chemical Composition of E4340 Steel[10]							
Alloying Element	C	Mn	P & S	Si	Cr	Ni	Mo
Weight %	0.38-0.43	0.60-0.80	0.025	0.15-0.35	0.70-0.90	1.65-2.00	0.20-0.30

not all steels have. In addition, with the proper heat treatment, the mechanical properties of quenched and tempered (Q&T) E4340 are superior to those of titanium with the only difference being density (Table II). Because of its lower density and substantially higher cost, titanium is used in high performance applications where the combination of relatively high strength and low weight are required. For the majority of top fuel dragsters and stock cars, E4340 connecting rods are the most cost-effective option without sacrificing safety.

Table II: Mechanical Properties for Q&T E4340 and Aged Ti-6Al-4V[11-13]					
Alloy	Elastic Modulus (x 10^6 psi)	Yield Strength (ksi)	Tensile Strength (ksi)	Density (lb/in^3)	Price ($/lb)
E4340 (Q&T at 205°C (401°F))	30.3	242	262	0.284	0.46
E4340 (Q&T at 425°C (797°F))	30.3	197	212	0.284	0.46
Ti-6Al-4V (Aged)	16.5	136	146	0.16	11.90

Like most steels, the traditional heat treatment of an E4340 connecting rod starts with austenitization, or heating it above 800°C (1472°F) to form austenite[10]. After soaking it at that temperature to ensure that the entire part is heated evenly, it is quenched in oil or molten salt to transform the austenite into martensite, which is how steels are typically strengthened. The reasons for using oil or molten salt instead of water as a quenchant are twofold- the lower cooling rate associated with quenching in oil or molten salt ensures that no cracks or warps form as a result of the quench, which is a concern with quenching in water, and E4340 through-hardens so readily in oil or molten salt that a more aggressive quenchant is not needed. After quenching, the part is then immediately tempered, usually for an hour at temperatures

between 150°C and 400°C (302-752°F), to restore some ductility and toughness. For applications that require ultrahigh strength, temperatures closer to 150°C are used because the cementite particles that will form from the tempering process will be smaller, which make them more effective at inhibiting dislocation movement and thus producing a stronger steel.

1.5 Austempering

One heat treatment that could improve the properties of E4340 is an austempering heat treatment. Austempering starts the same way as the traditional heat treatment for E4340- with austenitizing the part. However, the next step involves an interrupt quench in 320°C (608°F) molten salt for 120 seconds[14]. Molten salt is used because it evenly distributes heat over the surface of the part. After the interrupt quench, the part is placed in a standard heat treatment furnace heated to the austempering temperature for 1,000 seconds (Figure 5). After that, the part is removed and allowed to cool in air.

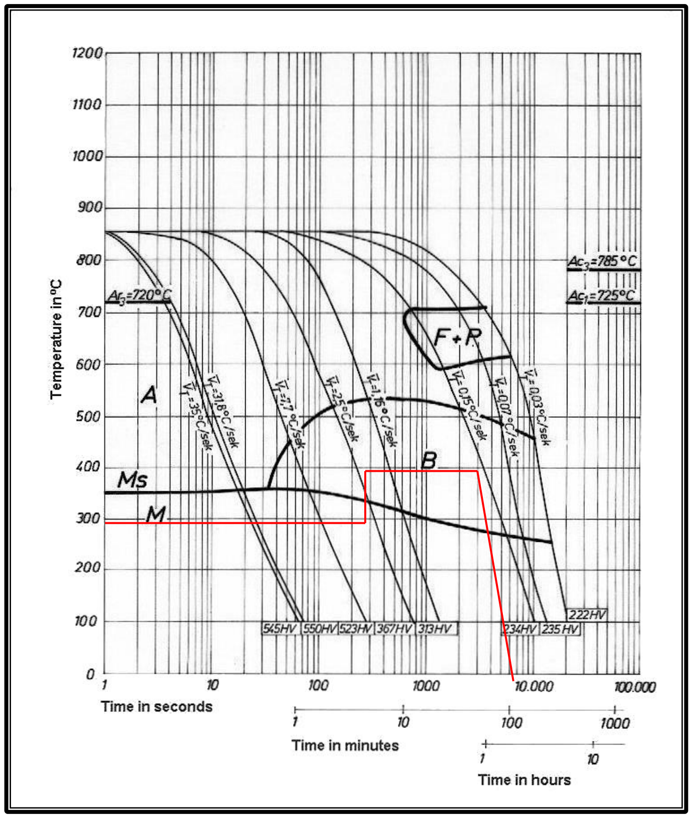

Figure 5: Continuous Cooling Temperature (CCT) diagram for E4340 steel. The red line represents the typical cooling path for an austempering heat treatment. A=Austenite, B=Bainite, Ms= Martensite Start, M=Martensite[16]

The reason for performing an austempering heat treatment is to form bainite, which is a combination of dislocation-rich ferrite and cementite[15]. Bainite exhibits properties that are between martensite and pearlite- it is slightly weaker than martensite, but is more ductile. These properties may be useful in that most connecting rods are shot peened as a final processing step to improve their fatigue properties. Because shot peening relies on the formation of strain fields near the surface of the part to improve the alloy's fatigue properties, having a more ductile material may improve shot peening's effects[17].

1.6 Cryogenic Processing

During cryogenic processing, parts are cooled to cryogenic temperatures, which are temperatures below -153°C (-307.4°F)[18]. This process is done as a secondary heat treatment done between quenching and tempering and is not a stand-alone process. In order to cause the necessary microstructural and atomic changes, parts undergoing cryogenic processing are usually in contact with either liquid nitrogen or liquid helium for between 6 and 24 hours[18]. Because the process takes such a long time, any changes that occur happen through the full thickness of the part.

Cryogenic processing has several effects on steels. First, the cryogenic temperatures will cause any retained austenite to transform into martensite, which leads to slightly improved mechanical properties. Second, it can form nanoscale eta-phase carbides, which improve the steel's wear resistance. More generally, cryogenic processing reduces the number of point defects and dislocations in metals, which leads to a improved fatigue properties (Figure 6)[18].

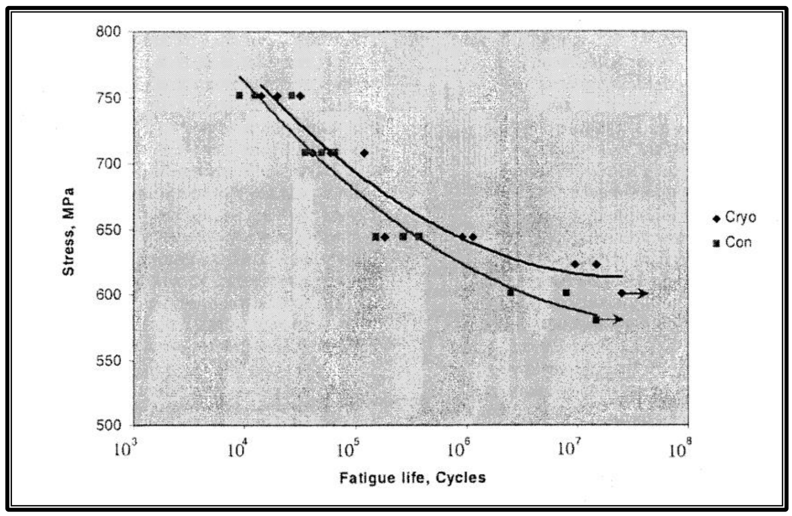

Figure 6: An S-N curve for 4340 steel with and without cryogenic processing. The steel was tempered at 455°C (851°F).

Chapter 2: Experimental Procedure

Figure 8: A connecting rod forging after cutting. Metallography was performed on the small end of this forging to verify the annealed microsctructure.

First, E4340 steel connect rod forgings were obtained. The ends of the forging were removed to leave only the straight section (Figure 7), from which sub-size tensile testing specimens were machined per ASTM E8. Each specimen then underwent either the control heat treatment, which is the current heat treatment for these components, the austempering heat treatment, the control heat treatment with an extra cryogenic processing step after the initial quench, or were left in their as-forged annealed condition (Figure 8). The samples were then cleaned with a rotary wire brush to remove any scale that had formed on the surface after heat treatment. Once the samples were cleaned, they underwent hardness and tensile testing to determine their mechanical properties. To verify that the correct microstructures were formed during heat treatment, metallography was performed on one sample from each testing group. A 2% Nital solution was used after polishing to etch each sample, and images were taken at 1000x with the exception of the annealed sample, where 500x magnification was used instead.

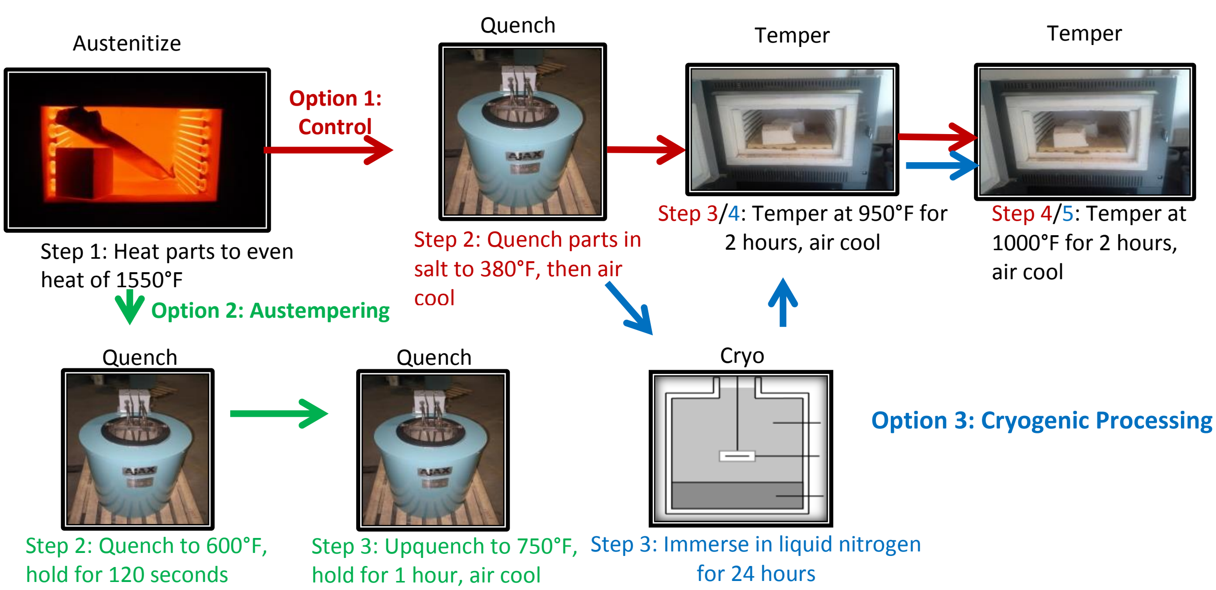

Figure 7: The heat treatment steps for each heat treatment. Ten samples were processed using each procedure.

Chapter 3: Results and Discussion

3.1 Microstructural and Heat Treatment Analysis

Based on the heat treatment parameters and the microstructures formed, the austempering heat treatment is actually a martempering heat treatment due to the formation of martensite and bainite instead of just bainite. Had there been more time, additional heat treatments that include an actual austempering heat treatment would have been performed. For the purposes of this report, however, the martempering heat treatment will be referred to as an austempering heat treatment.

The changes in microstructure as a result of the different heat treatments were documented (Figure 9). In general, the microstructures that formed as a result of the different heat treatments matched what was expected. However, due to the extremely small size of the tempered martensite plates, the difference in the relative amounts of retained austenite between the control and cryogenically processed samples was unable to be determined optically. In addition, there was no way to distinguish between the tempered martensite and bainite in the austempered sample optically.

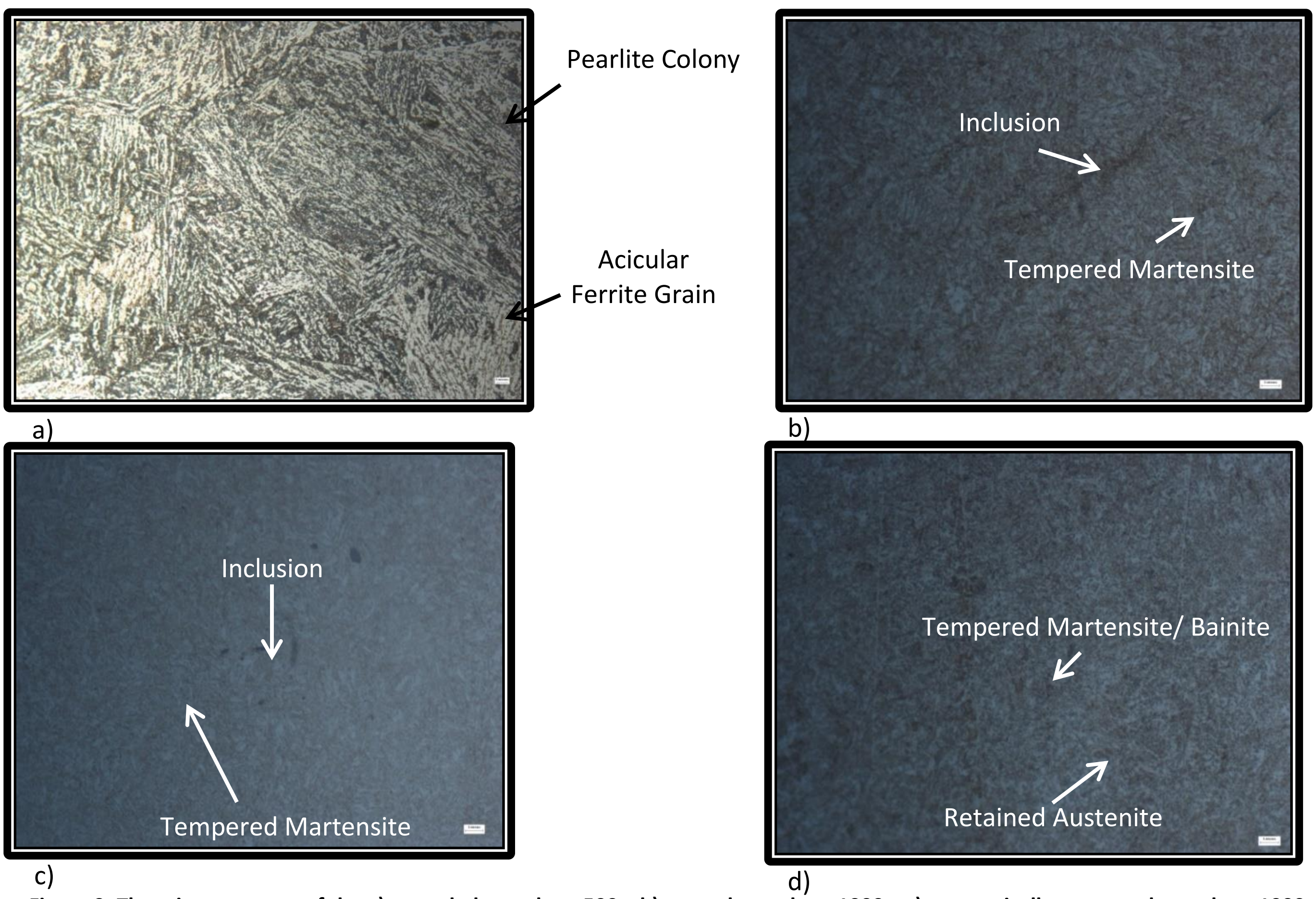

Figure 9: The microstructure of the a) annealed sample at 500x, b) control sample at 1000x, c) cryogenically processed sample at 1000x, and d) austempered sample at 1000x. All were polished to a 1 µm finish prior to etching with 2% Nital.

3.2 Hardness Testing

Based on the results of the hardness testing, the control heat treatment produced greater hardness values than the austempering heat treatment, but the cryogenically processed samples had hardness values that were within the ranges of both the control and austempered samples (Table III).

Table III: Hardness Testing Results		
Heat treatment	**Average Hardness (HRC)**	**Standard Deviation**
Control	40.05	0.355
Austempering	37.86	0.420
Cryogenic Processing	38.94	1.582

While the exact cause of the unexpected large range in hardness values for the cryogenically processed samples is unknown, several trends were noticed during testing. First, the hardness values for each sample were all within 0.5 Rockwell Hardness C (HRC) of each other. Second, of the six samples that underwent hardness testing, four had an average hardness of around 40 HRC, while the other two averaged around 37 HRC. Since the cryogenically processed samples were bundled prior to being lowered into the container of liquid nitrogen, it is possible that the difference in hardness values is due to the sample's position within the bundle.

3.3 Tensile Testing

Based on representative stress-strain curves, all of the heat treatments tested provided significant improvement to the tensile properties of the material, yielding similar tensile strength and elongation values (Figure 10). However, the austempered samples had

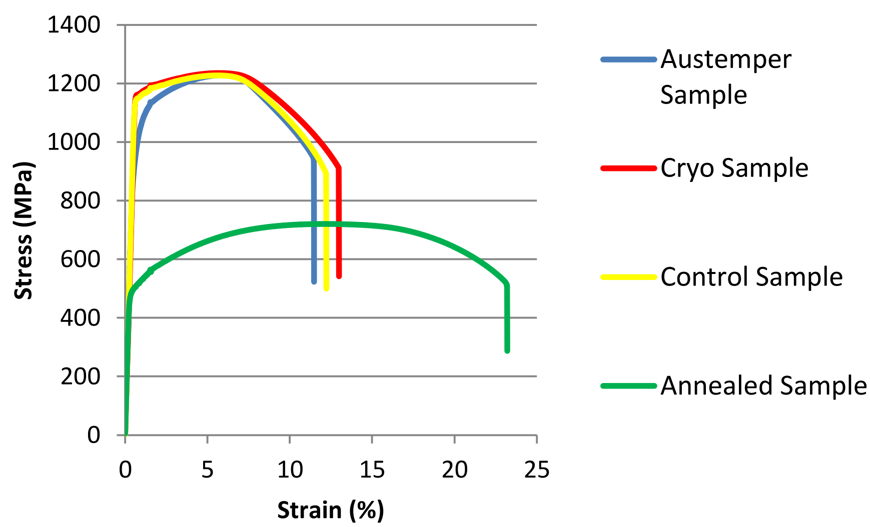

Figure 10: Representative stress-strain curves for all three heat treatments and the annealed samples. Four samples from each group underwent tensile testing.

noticeably lower yield strength values than either the control or cryogenically processed samples (Table IV). Based on those results, a boxplot was generated to better determine whether or not there was a statistically significant difference between the yield strengths of the control and cryogenically processed samples (Figure 11). Based on the boxplot and a two sample T-Test, the difference in yield strength between the control and cryogenically processed samples was not statistically significant. The small difference between the control and cryogenically processed samples is caused by the small amount of retained austenite transforming into martensite as a result of the cryogenic processing. The austempered samples' lower yield strength values is probably due to the bainite within the microstructure not impeding dislocation movement as well as tempered martensite.

Table IV: Average Mechanical Properties of E4340 Steel Before and After Heat Treating

Heat treatment	Yield Strength (MPa)	Tensile Strength (MPa)	% Elongation
Annealed (None)	741.30	949.85	15.02
Control	1149.85	1229.28	12.16
Cryo	1160.70	1222.58	12.73
Austemper	979.10	1213.89	11.46

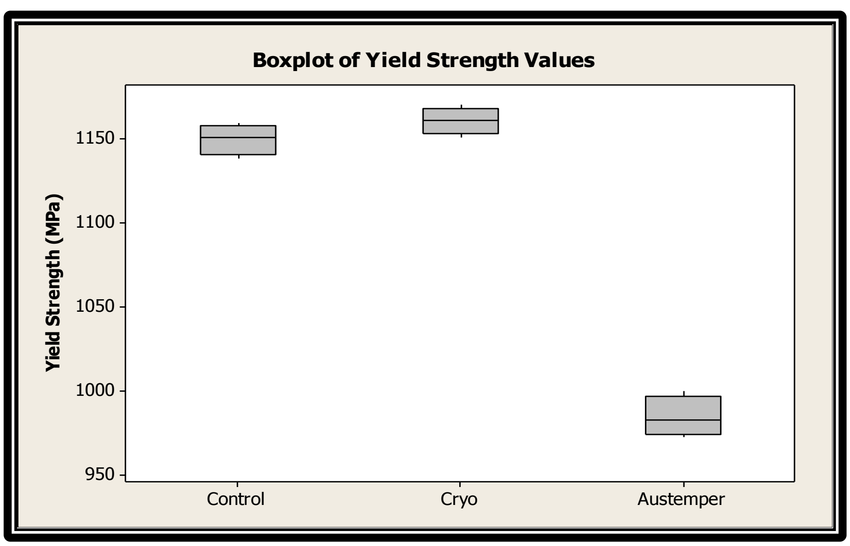

Figure 11: The boxplot of yield strength values for the three heat treatment groups. Because of its much lower yield strength values, there was no need for any statistical analysis with respect to the austempered samples.

Chapter 4: Conclusions and Recommendations

If a connecting rod were to start yielding while in service, it would have catastrophic consequences for the engine and potentially the driver of the vehicle. Based on the data gathered, austempered E4340 steel will start yielding at a lower stress level than cryogenically processed or quenched and double-tempered E4340 steel. Therefore, this particular austempering heat treatment does not represent a viable alternative for the quench and double temper heat treatment currently in use.

Based on the results of this experiment, adding cryogenic processing to a quench and double temper heat treatment plan does not yield statistically significant improvements in tensile properties. However, due to time constraints, cryogenic processing's effects on the fatigue properties of E4340 could not be determined and would serve as a good area for future research in this field.

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