Alternative Materials for Steam Locomotive Staybolt

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The main objective of this project is to examine the potential of using modern stainless steels or alloys to produce staybolts with better durability and corrosion resistance than those produced using current material standards. Staybolts act as spacer bars that suspend the coal burning firebox in the center of the boiler of a steam locomotive. This prevents direct contact between the intensely hot firebox and the rest of the components of the locomotive while applying the heat of the firebox to the water in the boiler.

The Peré-Marquette 1225, a steam freight locomotive located at the Steam Railroad Institute in Owosso, Michigan is an example where this application could be used. The 1225 was used as a model for the locomotive pulling the train in the movie “The Polar Express”. Recently it has been used for local events including the North Pole Express, a family event where children and their families can take a train ride from Owosso to “Santa's Village” in Chesaning. This locomotive is currently out of service and scheduled for a full overhaul. The boiler of the 1225 uses 3174 staybolts, all of which will be replaced when the firebox of the boiler is repaired.\textsuperscript{8} The majority of the staybolts currently in the 1225 were produced back in the 1940's.\textsuperscript{8} ASTM A86 was the designation for the material requirements of staybolts in 1941 when most of the staybolts currently in the 1225 where produced.\textsuperscript{10}

Currently, the standard ASTM A36 determines the base requirements for carbon steel used for staybolts and the standard ASTM SA675 determines additional recommendations such as fabrication, testing, and certification requirements.\textsuperscript{2} The staybolts will meet all of the requirements set by these standards with the exception that the material used will be stainless steel not carbon steel. Stainless steel will allow for better durability of the staybolts and a reduction of the damage caused by corrosion found on normal carbon steel staybolts.

**Project requirements**

The three primary requirements initially established for the material at the project’s start were: One, it must meet all required mechanical properties given in ASTM A36 or ASTM SA675. Two, it must have a better resistance to corrosion than current carbon steel staybolts. This will be shown by lower loss of surface material to oxidation in a comparable environment over a given time. Three, it must have a better heat tolerance than current carbon steel staybolts. This will be shown by a lower coefficient of thermal expansion which will result in reduced expansion and contraction thus resulting in less temperature fatigue.

Staybolts are designed so that one or two will fail if the boiler pressure reaches dangerous levels;\textsuperscript{2} therefore the staybolts yield strength should preferably be as close as possible to 30,000 psi without going under.\textsuperscript{13} When a staybolt breaks this releases high pressure steam through the drilled center hole to the welded cap on the outside of the boiler.\textsuperscript{2} This fires the cap off into the outer shell of the locomotive creating a loud bang warning the engineer that there is a problem.\textsuperscript{10}

Many of the staybolts must flex as the locomotive moves. One of the considerations that was brought to light was that the hardness of the staybolts should be close to, if not lower than, that of the firebox sheet metal. The average firebox sheet metal has an approximate hardness of 71 Rockwell B.\textsuperscript{12} If the firebox has a higher hardness then it will resist the flexing better but if it
is lower than the sheet metal will flex more easily leading to metal fatigue at the connection point.

Any stainless steel will cause at least a small amount of galvanic corrosion to carbon steel it is in contact with.\textsuperscript{5} There are several possible methods for dealing with this. These include covering the staybolts with an insulating coating that prevents electrical contact with the water in the boiler, the addition of a sacrificial anode to some part of the boiler to protect the carbon steel from galvanic corrosion, or the addition of a powered anode to the locomotive’s boiler.\textsuperscript{3}

The thermal conductivity of the staybolts can eventually result in thermal fatigue and an increase in corrosion. The carbon steel currently used for staybolts has a coefficient of thermal expansion of approximately 7.11 µin/in-°F in the temperature range they are expected to endure.\textsuperscript{12} Reducing the coefficient of thermal expansion should reduce wear on the staybolts increasing their reliability.

Material choice

After considering several options AISI 416 Stainless steel was chosen for the project.\textsuperscript{11} It shows a yield strength of 39900 psi, has a hardness of 82 Rockwell B and as a ferritic 400 series stainless steel has less galvanic corrosion potential than other stainless steels.\textsuperscript{1,7} Stainless steel 416 has a coefficient of thermal expansion 6.11 µin/in-°F in the temperature range they are expected to endure.\textsuperscript{1} It also shows machining characteristics almost identical to that of normal carbon steel.\textsuperscript{15}

One of the greatest advantages with stainless steel is that it is almost completely reusable. With the material experiencing so little corrosion when the staybolt needs to be replaced virtually all of the material can be reused to manufacture future staybolts. This will result in a more significant saving in the long run if the material can be reused for future overhauls.\textsuperscript{7}

The research shows the potential for excellent performance from these new staybolts. The materials selected show better characteristics than that of the current staybolts being used. The mechanical properties of this material demonstrate that it has the preferred values for yield strength, tensile strength, and ductility for the application of a staybolt in a steam locomotive. Better heat tolerances will also be factor in creating a more durable staybolt. Resistance to corrosion is also a strong aspect and is advantageous for sustainability and product life in and out of service. Using the input from several veteran railroad mechanics, based on these material characteristics, it was determined that there is the expectation of losing an average of 10 staybolts a year using the SA675 carbon steel staybolts over the lifetime of the locomotive.\textsuperscript{8,10,16} If testing can determine that an average of 5 staybolts a year of the 416 stainless steel staybolts over the lifetime of the locomotive then this approach would save on both money and labor. The 1225 has run for 70 years and this is the first time that all of her staybolts will have to be replaced so we can determine that she has probably gone through as many as 3874 staybolts in the last 70 years (3174 initial staybolts and 700 replacements at a rate of 10 a year for 70 years). If the 1225 had been using 416 stainless steel staybolts she may have only gone through as many as 3524 staybolts (3174 initial staybolts and 350 replacements at a rate of 5 a year for 70 years).
Corrosion and prevention

Oxidation corrosion is the most frequent corrosion observed in carbon steels. Stainless steels resist oxidation due to their high chromium content, which allows the steel to form protective chromium oxide scales. Thus, stainless steel 416 possesses superior oxidation corrosion resistance compared to carbon steels. Carbon steel will corrode approximately 0.7 mils per month due to oxidation corrosion, where stainless steel 416 will show negligible corrosion attack. This equates to a loss of about .1 millimeter per year for a carbon steel staybolt. For a stainless steel 416 staybolt one will see negligible loss due to oxidation corrosion. The only exception might be if the chromium oxide scales are repeatedly damaged.

Galvanic corrosion results when a metal or alloy is in electrical contact with another alloy or conductive nonmetal in the same electrolyte. The three essential components to galvanic corrosion are that the materials possess different surface potential, are in the same electrolyte, and have the same electrical path connecting them. In galvanic corrosion the less noble metal or less corrosion resistant metal, which is the carbon steel in this project’s case, will corrode at an increased rate when compared to normal. At the same the more noble metal or better corrosion resistant metal will decrease its rate of corrosion.

The rate of galvanic corrosion is based on a variety of factors. These factors include the potential difference between the metals or alloys, the nature of the environment they are in, the polarization behavior between them, and the geometric relationship of the component metals or alloys. The potential differences of the stainless steel to the carbon steel can cause an electron flow between each other when they are electrically coupled in a conductive medium. The direction of electronic flow is determined by which metal or alloy is more electrochemically active. This means that the more active metal being carbon steel acts as an anode, constantly losing electrons, which causes an accelerated corrosion. The more noble or less active metal being the stainless steel 416 acts as a cathode and will receive electrons which decelerates its corrosion. This action essentially is very similar to that of a DC cell.

The stainless steel 416 and the carbon steel will have easy polarization prediction due to the passive behavior of stainless steels in general. Thus, galvanic effects on steel can be induced by stainless steel, particularly in environments that include water, and adverse area ratios. One main concern is that these staybolts will be taking up an equivalent surface area greater than the area of the boiler shell in the conductive medium. This is an unfavorable area ratio when dealing with galvanic corrosion. The research into impressed current systems shows that it should be capable of eliminating the risk of galvanic corrosion.

Galvanic corrosion can be stopped by the use of cathodic protection. The cathodic protection that would be used is called an impressed current system, also known as a powered anode. It works by impressing a direct electrical current between an inert anode and a structure that could be subject to galvanic attack. The system for this project creates a current flowing through the electrolyte interface, which the galvanic reaction favors over the anodic metal. Therefore the entire structure acts as a cathode. The structure receives the needed electrons that are produced by the current and is protected from galvanic corrosion.
For the impressed current system the source of electricity is given externally. A steam locomotive should have no problems producing the needed current for a powered anode to prevent galvanic corrosion. In most cases a rectifier converts a high voltage AC current to a low voltage DC current. The preferred position of the powered anode places the positive end of the current in the water, and the negative end of the current is the structure, in this case the boiler shell of the locomotive. The positive end of the anode should be composed of an inert anodic material. The recommended materials for these inert anodes include graphite, silicon, titanium, and niobium plated with platinum. In this case the more available and cost effective material is desired, this being graphite.

There are two things to keep in mind when using a powered anode or impressed current system. One, is for a given applied voltage, the current is limited by electrolyte resistivity and by the anodic and cathodic polarization. This means that the right amount of voltage, based on the electrode difference between the metals, must be applied. Also, with impressed current systems it is possible to impose whatever potential is necessary to obtain the current density required using the rectifier. Also, to assist the anodic protection, the use of a coating called Apexior can be applied to all internal components of the boiler reducing the surface area exposed to the electrolytic medium.

Testing for galvanic corrosion consists of two objectives. These include assessment to see if the materials have the compatibility in terms of polarity and rate of galvanic corrosion by bimetallic couples, and prediction of the extent and spatial distribution of corrosion damage. Galvanic corrosion testing has specific requirements of geometry, in most cases it is generally not feasible to use a universal geometry for different situations encountered. This means that galvanic corrosion is distinctive within its cell design. The geometry of the design should also result in a uniform potential distribution on the surface of the anode and cathode. In order to meet this requirement the distance between the anode and cathode, in this case the carbon steel and the stainless steel 416, needs to be larger than the dimensions of the samples.6

Testing for galvanic corrosion in atmospheric conditions, the stainless steel 416 and carbon steel need to be in close contact and have small dimension in the direction perpendicular to the contact line. This is done so the electrolyte formed under an atmospheric environment is very thin, and the galvanic action generally does not extend over a few millimeters from the contact line. In order to achieve accurate test data the materials should be placed into electrical contact within an electrolytic medium in an environment as similar to that which they are expected to experience during final use as possible. Therefore, the staybolts would be tested in a mock up of a locomotive boiler. The two metals, in this case the stainless steel 416 and the carbon steel, should be placed in the exact places they would be placed within a normal boiler. Water would be added and then the boiler would be heated until it reached the desired temperature. In order to get an accurate reading the testing would have to run for an estimated four to six months before the galvanic current had stabilized and an accurate result could be shown. This test would also have to be conducted by the requirements set by ASTM code G 71.6

Cost

The associated costs with this project are a major factor to the decision of using stainless steel 416. The objective is for the material cost to be something that does not seem unreasonably
more than that of the material already in use. If the stainless steel costs more than the current steel already in use, the resulting extension of the life of the staybolt must result in money savings over the life of the locomotive boiler.

It has been determined that, accounting for the cost of machining the staybolt materials and the additional number of staybolts likely to fail throughout the life of a firebox, stainless steel should provide an overall savings, as shown below. This is just an example and the savings will vary somewhat based on the particular staybolts replaced.

A powered anode for a large boiler can be expected to last 50 years. Once the powered anode was installed, it would most likely have to only be replaced once in the lifetime of the boiler. The powered anode could be installed in one of the plugs that already exist on the boiler so there would be no additional costs to modify the boiler to install it.

<table>
<thead>
<tr>
<th>Cost Comparison</th>
<th>416 Stainless Steel</th>
<th>SA675 Carbon Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Cost for a 12 in. Staybolt$^{14}$</td>
<td>$8.69</td>
<td>$4.32</td>
</tr>
<tr>
<td>Approximate Cost Machining &amp; Labor$^{9, 14}$</td>
<td>$50.00</td>
<td>$50.00</td>
</tr>
<tr>
<td>Total Cost for a 12 in. staybolt</td>
<td>$58.69</td>
<td>$54.32</td>
</tr>
<tr>
<td>Expected number of Staybolts over 70 yrs.</td>
<td>3524</td>
<td>3874</td>
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<tr>
<td>Approximate Cost for Anodes and Replacement</td>
<td>$1200.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Total Cost after 70 yrs.</td>
<td>$208,023.56</td>
<td>$210,435.68</td>
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</tbody>
</table>

Conclusion

During research it was determined that stainless steels, in this case, type 416, could be used for staybolt manufacturing. Stainless steels have great resistance to corrosion, and have comparable mechanical and material properties to that of the current low-carbon steels. One problem is the potential for galvanic corrosion. This corrosion can be prevented using solutions such as a sacrificial anode or a powered anode. The most efficient solution is to use a powered anode which will counteract galvanic corrosion and does not produce corroded sediment which would result from the use of a sacrificial anode. The other problem is cost. Stainless steel has a hard time competing with regular carbon steel because it is significantly more expensive. When examined in more detail however, the material cost is only a tiny fraction of the total cost of a staybolt. Since the machining cost is equivalent to that of carbon steel, the extended lifespan of a stainless steel staybolt should more than pay for itself over the entire lifetime of the firebox and boiler of a locomotive.

In order for this project to serve in any practical application it would have to be examined by the FRA (Federal Railroad Administration) or ASME. It is possible that this could allow for a reevaluation of the current standards and include a broader selection of materials in the current modern standards. Approval requires that all of the material data be submitted to the NBBI Secretary of the Code of Construction and the Secretary of the Code of Materials and also to the ASME. Unfortunately having a material reviewed by these organizations is a lengthy task. Current estimates given by technicians in the NBBI (National Board of Boiler Inspectors) state a minimum of one year before the material could be approved.$^{10}$
8. Gaffney, T. J. (2010). Personal communication