Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2019, 6(3):309-312**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Assessing the Impact of Water-Induced Corrosion on Fuel System Components: A Comparative Mechanical Analysis

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Abstract: Water-induced corrosion poses significant risks to fuel system components across various industries, including automotive, aviation, and marine sectors. This study examines the impact of water contamination on the structural integrity and mechanical performance of critical fuel system parts, focusing on the comparative analysis of corroded and uncorroded fuel shims. Corrosion mechanisms, such as electrochemical and microbial-induced corrosion, accelerate the degradation of metal components, leading to failures in fuel tanks, injectors, and pumps. Using a universal testing machine (UTM), the mechanical behavior of corroded and uncorroded shims was evaluated, revealing that corroded shims exhibit reduced maximum load capacity and increased variability in performance. These results highlight the detrimental effects of water-induced corrosion on fuel system reliability. The study underscores the importance of preventive strategies, such as water separators, regular maintenance, and fuel additives, to mitigate corrosion and extend the lifespan of fuel system components.

Keywords: Fuel System Components, Water-induced corrosion, Electrochemical corrosion, Mechanical performance, and Preventive maintenance strategies

Introduction

Water is one of the most common and costly fuel contaminants in the automotive, aviation, marine, and energy generation industries. However, it is not always easy to identify water as the root cause of fuel system failures. Water induces corrosion in metals. While the chemical principles of the galvanic cell are complex, the bottom line is that water will speed up a metal's corrosion. This article explains the corrosion mechanisms, failure types, and mitigation strategies that will allow us to identify water as the source of concern.

Mechanisms of Corrosion Due to Water in Fuel

Water can make its way into a fuel system through condensation, leaks, or injections of blended fuel. After entering the system, it can promote corrosion in several ways, including:

1. **Electrochemical Corrosion**: Water is a strong corrosive substance by itself. When it includes dissolved salts or acids, it becomes a highly effective electrolyte that helps accelerate electrochemical reactions between the different metals in the fuel system (such as aluminum and steel in the fuel system components). This is commonly known as galvanic corrosion. Consequently, the aluminum and steel components in the fuel system are likely to be affected when exposed to water in some form in the fuel.
2. **Microbial-induced corrosion (MIC):** In addition to consuming fuel, the water in the fuel can also become a breeding ground for microorganisms. Bacteria and fungi can establish colonies at the water-fuel interface and secrete acidic metabolic products, which accelerate the rate of corrosion [1]. MIC can speed up fuel system damage and cause pitting and leaks.
3. **Hydrolysis and Chemical Reactions:** Some fuel additives and impurities will react with water to form corrosive chemical compounds. For instance, the hydrolysis of fats in biodiesel to create fatty acids or glycerol can promote corrosion [2].

Types of Failures Caused by Water-Induced Corrosion.

Corrosion due to water in fuel can lead to various component failures.

1. **Fuel Tanks**: Corrosion of metal fuel tanks, the most common material being steel, can cause pitting, rusting, and perforation. This often leads to fuel leakages, which in turn increase safety hazards for the user and may lead to environmental hazards.
2. **Fuel Injectors:** Corrosion particles produced inside these rust-contaminated fuel tanks can accumulate inside a fuel injector and create poor engine performance. High-precision fuel injector parts are particularly vulnerable to corrosion-caused failure. [3]
3. **Fuel Pump:** Rust that occurs in the internal parts of a fuel pump due to water being present can lower the efficiency of the fuel pump and eventually cause complete failure. A corroded fuel pump can also inject debris into the fuel system, which can cause more wear to other parts of the fuel system.
4. **Degradation of Pipelines and Fuel Lines:** Corrosion can degrade pipelines and fuel lines, increasing the likelihood of leakage and ruptures. This is primarily a concern in high-pressure fuel systems, where the integrity of fuel lines is crucial to safety.

Shims used in fuel injectors are critical to controlling the stroke, the distance the injector needle moves as it opens and closes. The stroke of the injector needle sets the timing, duration, and quantity of fuel injected into the combustion chamber. Shims are used to control the following parameters:

1. **Needle Lift**: The distance the injector needle will travel from the closed to the fully open position. Shim thickness sets the preload on the injector's retaining spring, and the technician can alter the stroke of the needle by changing the shim thickness to provide the proper amount of preload [4].
2. **Injection Timing:** The injector stroke influences fuel injection timing. When shims are changed, the opening pressure can be changed. The injector will open to the correct pressure at the proper time to inject fuel into the cylinder for the best possible combustion timing[5].
3. **Quantity of Fuel:** For any given pressure, the needle lift sets the amount of fuel delivered to the combustion chamber; more distance means more fuel, and less distance means less fuel. Shims help to precisely set this distance so that the correct amount of fuel for any given combustion cycle is delivered [6].
4. **Performance Over Time:** If injector components were to change over time due to wear and tear, then without shims, this could change the characteristics of the injector. Shims help compensate for such instability, keeping the injector stroke consistent to achieve uniform fuel delivery to the cylinder, thereby keeping engine performance within an acceptable range [4].

This manuscript will focus on high-precision shims and how corrosion can cause premature failures.

Methodology

This test evaluated the differences in force versus deflection values between non-corroded shims and corroded shims. A systematic test method using a universal testing machine (UTM) was used to evaluate corroded and uncorroded shims' mechanical performance and structural integrity. The samples were prepared by cleaning them after they were removed from disassembled fuel injectors.

The dimensions of each shim were measured using calipers or micrometers, and these values were recorded. The surface conditions were documented, noting any visible corrosion or defects. This step ensures accurate data for subsequent analysis. The appropriate fixtures to securely hold the shims in the UTM were machined. The fixtures must match the shape and size of the shims to prevent premature failure due to misalignment or improper gripping.

The UTM was set up to ensure it was calibrated, and a suitable load range for the expected forces was selected. The test parameters, including a constant displacement rate (e.g., 1 mm/min), were defined to ensure uniform loading conditions. The maximum load or displacement at which the test will terminate was established, and it was ensured that this threshold was sufficient to cause failure in the shims. The shims were securely mounted in the UTM, aligning them properly to avoid eccentric loading, which could skew the results. The data acquisition system was connected to record force and displacement throughout the test.

The test was initiated by starting the UTM and applying load to the shim at the defined displacement rate. The force and displacement readings were continuously monitored, and the shim's behavior was observed for any signs of yielding or failure. All the data was recorded using the data acquisition system. Documenting the failure mode (e.g., fracture, yielding) and capturing relevant observations or photographs is crucial.

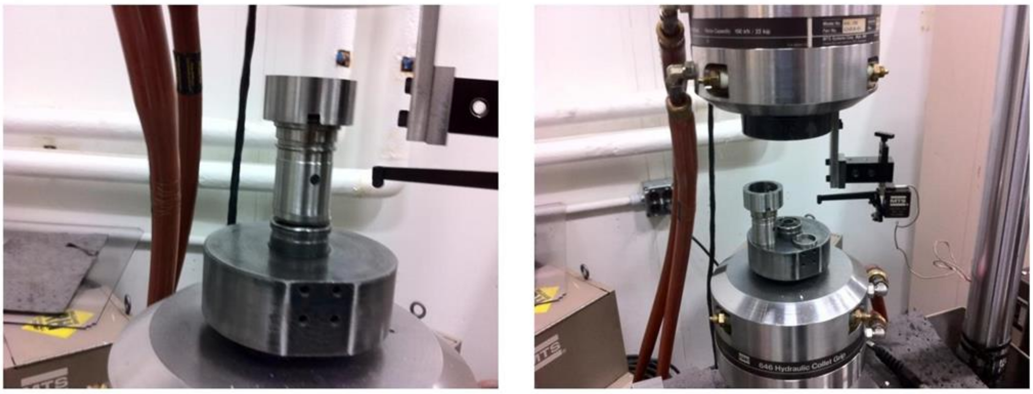

Figure 1: *Test setup for the universal test machine.*

Results and Discussion

Figure 2 compares the force-displacement behavior of corroded and uncorroded shims. The force increases with displacement for the corroded shims, showing a general upward trend with a maximum force of around 14,000 N. The force-displacement curves exhibit some variation, indicating different responses among the samples. These curves show a peak followed by a slight drop, suggesting that the material reaches a maximum stress point before experiencing failure or yielding. This variability and drop-off after the peak highlight the compromised structural integrity due to corrosion.

In contrast, the uncorroded shims demonstrate a similar initial increase in force with displacement, but they can withstand a higher maximum force of around 18,000 N. The force-displacement curves for the uncorroded shims are more consistent and tightly grouped, indicating more uniform behavior among the samples. The peak force is higher than the corroded shims, and the drop-off after the peak is less pronounced. This suggests that the uncorroded shims maintain better mechanical performance and reliability, showcasing the negative impact of corrosion on the shims' structural integrity and mechanical properties.

Figure 3 compares corroded and uncorroded shims, highlighting their physical condition and structural integrity. The corroded shims displayed evident surface corrosion and degradation before the test. After the test, the shims fractured into multiple pieces, demonstrating substantial structural deterioration caused by the corrosion. On the right, the uncorroded shim is in good condition with no visible signs of damage or corrosion, maintaining its structural integrity. The uncorroded shims fractured when tested to failure, but their fracture patterns were cleaner and less indicative of extensive damage than the corroded shims. This contrast between the two sets of images highlights the significant impact of corrosion on the structural integrity and durability of the shims.

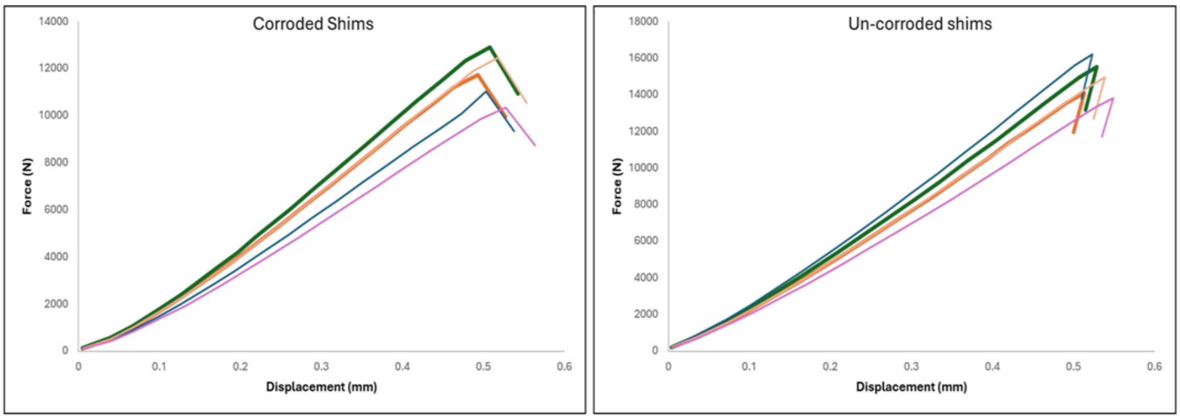

Figure 2: *Force vs. Displacement for corroded and un-corroded shims.*

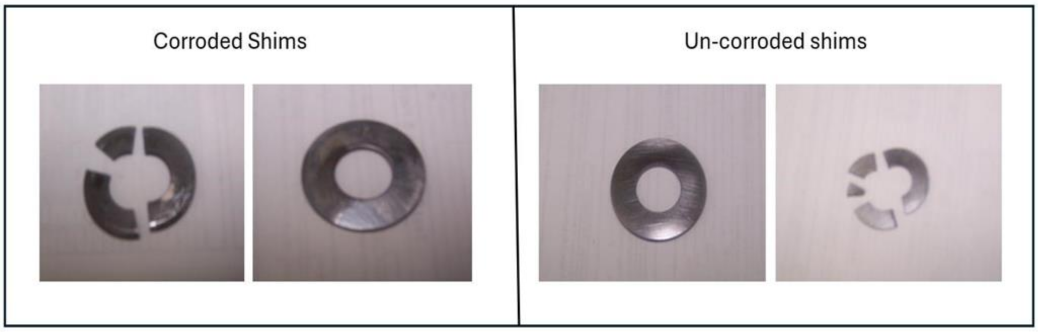

Figure 3: *Pre- and Post-Test Conditions of Corroded and Uncorroded Shims*

Conclusion

Fuel water contamination is a serious issue that, if left unchecked, can lead to severe component corrosion and mechanical failure, as demonstrated by the testing on corroded and uncorroded shims. Knowing how corrosion mechanisms work is paramount to identifying the relevant mitigations. Reducing water contamination can go a long way toward improving the longevity and reliability of your fuel system, which can help you meet your business's demands.

Preventing and mitigating water-induced corrosion in fuel systems involves several strategies:

Regular inspection and maintenance: Inspection and maintenance of fuel systems can detect and mitigate water contamination early (i.e., by draining water separators, looking for signs of corrosion and pitting, and checking for sediments in filters).

Incorporating Water Separators and Filters: If a water separator and high-efficiency fuel filters are installed, water entering the fuel system can be significantly reduced.

Fuel additives: Some can mitigate corrosion by neutralizing acids or dispersing water. Other additives, such as biocides, can reduce microbial growth and thus reduce the risks of microbialinduced corrosion. [7].

Quality control of fuel: The fuel quality should be ensured at purchase. Certified fuel suppliers who can provide the relevant certificates and ensure that fuel is tested periodically with certified measuring equipment for water content help mitigate this risk factor.

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