Evaluation of Advanced Coatings for Improved Performance on Military Hydraulic Equipment

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The U.S. military employs a sizeable fleet of hydraulic-based vehicles and systems in routine operations, including tactical forklifts, air defense artillery systems, cranes, armored vehicles, and aircraft. Since hydraulics are essential to the functionality of these assets, the corrosion of these systems is a considerable issue. Indeed, in some systems, the hydraulics are so critical that corrosion can render the asset inoperable. Commercial off-the-shelf technologies are available that can mitigate corrosion and subsequently reduce costs and maintenance. This paper discusses the work conducted under the U.S. Army Technology Demonstration for Prevention of Material Degradation Program to evaluate advanced coatings for two critical military hydraulic components: hose-end fittings and actuator shafts.

Keywords: corrosion, hydraulic, U.S. Army, fluid power

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Introduction

Hydraulic systems, often simply referred to as hydraulics, are devices that contain and control a liquid and use it to do work. As hydraulic systems are simple, easy to control, and cost-effective, they are employed in a wide variety of commercial and military applications. Construction equipment, elevators, and brake systems are a few of the applications that utilize hydraulics.

The main disadvantage of hydraulics is the constant need to maintain the precision components within the system. Hydraulic components are often exposed to aggressive climates, bad weather, and dirty atmospheres in daily operation, and this can lead to significant corrosion and material degradation of components. Figure 1 depicts significant corrosive attack on the hydraulic components of a front-end loader[1].

Figure 1. Commercial Front-End Loader (left), with Blackened Hydraulic Lines and Extensive Rust and Paint Chipping on Cylinders (right)

Protection against dirt, corrosion, and material degradation is essential for hydraulic components. Without such protection, dirty/corroded components can cause pressure and efficiency losses that can destroy the functionality of the entire hydraulic system. Often, this can render the entire hydraulic-bearing piece of equipment nonfunctional.

The effects of hydraulic corrosion/degradation on military vehicles and weapons systems are particularly significant. The U.S. Army utilizes a large fleet of vehicles, weapon systems, and support equipment containing hydraulics. Among the most prominent components of this fleet are armored vehicles, air defense artillery equipment, tactical vehicles, transportation and logistics assets, aircraft, and engineering equipment. Downtime of these hydraulic assets, which is generally in large part attributable to corrosion/degradation-related failures, reduces mission readiness and operability, and subsequently generates significant maintenance and replacement costs.

Objective

Under the U.S. Army Technology Demonstration for Prevention of Material Degradation (TDPMD) Program, an effort was conducted to identify and validate commercial off-the-shelf (COTS) technologies that can be used to mitigate corrosion and material degradation of Army hydraulic components. This specific activity is part of a larger ongoing effort to gather information on the most critical hydraulic components and systems, and to then identify and validate corrosion-prevention technologies with the end uses in mind. The overall effort is being accomplished in several phases:

1. The identification of the most critical hydraulic-bearing Army assets, and the assessment of the impact of hydraulic corrosion/degradation upon the identified critical assets.
2. The identification of the most critical hydraulic components within these assets, and the impact of corrosion on these components.
3. The identification of advanced coatings to mitigate corrosion on the identified critical hydraulic components.
4. The testing and validation of corrosion-resistant coatings for these components.

Phases 1 and 2 were conducted under past efforts and have been presented elsewhere[2]. The results of these efforts will be briefly summarized herein, illustrated by photographs of hydraulic components on actual Army vehicles. Test results generated under the current activity on available coating technologies for corrosion mitigation will also be discussed.

Technical Approach

As mentioned earlier, this effort is directed toward testing and validating coatings for corrosion resistance on Army hydraulic components. However, in order to obtain a maximum return on investment to the government, it was first necessary to determine the most serious corrosion concern on Army hydraulic equipment. Efforts were therefore first directed at identifying the most critical corrosion-prone components of Army hydraulic systems. To accomplish this goal, information was gathered through document research, site visits to Army depots, interviews with Army maintenance personnel and equipment manufacturers, and data mining of military maintenance databases. Based on this information, two critical hydraulic components that are particularly susceptible to corrosion were identified: hydraulic actuators and hydraulic hose-end fittings.

Hydraulic Actuators

Hydraulic actuators (also referred to as shafts or arms) are the heart of hydraulic systems. They are the components that are actually "pushed" by the pressure generated from incoming hydraulic fluid; this motion is in turn used to do work. Actuators are typically made of low-alloy carbon steel (some actuators found in commercial systems are made of stainless steel, but few Army systems were found with this upgrade). These steels are generally insufficient to resist the corrosive/erosive attack of the environments in which they are most commonly deployed. Protective coatings are therefore utilized to prevent extreme corrosion damage and prolong the life of the hydraulic system. Hard chrome coatings are most commonly used, primarily on hydraulic cylinder piston rods, shock rods, valve stems, and piston rings[3]. Hard chrome is designed to impart improved wear resistance, anti-galling characteristics, and low coefficient of friction. While it does also provide some degree of corrosion resistance, hard chrome is not meant to mitigate aggressive corrosion attack. The "microcracked" structure of plated chromium, generally accepted to be due to chromium hydride inclusions[4], creates a degree of porosity that, over time, can allow moisture and acids to enter the cracks and corrode the base metal. Failures can also arise from hard-particle impingement, wear from abrasive particles caught in the sealing collar, and cracks from straining due to surface expansion. In any case, these defects roughen the rod surfaces and eventually damage seals, initiating and propagating leaks.

Several additional points should be understood concerning actuator corrosion and subsequent hydraulic fluid leakage. Firstly, the military hard chrome specification[5] recognizes that electroplated hard chrome is not a corrosion resistant coating per se, and as such does not contain a corrosion resistance requirement. Secondly, it should be noted that a hydraulic system leak does not need to be significant in order to severely impact the readiness of a piece of equipment; the Army Technical Manuals (TMs) for two military hydraulic-bearing assets, the M9 Armored Combat Earthmover (ACE) and the Palletized Load System (PLS), both define a critical leak as a singular falling drop of hydraulic fluid[6, 7]. At this point, the vehicle is considered Not Mission Capable (NMC) and must be sent for maintenance and/or overhaul. Finally, it should be noted that many commercial vehicles mitigate actuator corrosion by enclosing the exposed arms in a housing or expandable rubber boot; however, few arms on military assets were observed with this protection.

Examples of visual corrosion on actuators are presented photographically in this section. These photographs were taken during military depot visits that were conducted under earlier work, and are representative of assets that have been sent for depot-level repair. Therefore, the corrosion shown in these photographs is indicative of aggressive attack requiring repair.
Figure 2 presents the condition of the ram and cylinder on a military D7 Bulldozer at one of the depots visited, before and after repair.

Figure 2. Ram and Cylinder from D7 Bulldozer: Before Repair (left), Showing Pitting and Worn Seals, and After Repair (right), with Smooth Ram Surface and New Seals

A close-up photograph of aggressive pitting attack on a hydraulic actuator arm from another military bulldozer is presented in Figure 3. It should be noted that this asset was still in service at the time that this photo was taken. Further use of the actuator in this condition would most likely rupture the seals and cause fluid leakage.

Figure 3. Close-up of Pitting on Hydraulic Actuator Arm

Figure 4 displays significant pitting on the hydraulic actuator arm of an M4K tactical forklift. Once again, this asset was still in service at the time that the photo was taken.

Figure 4. Cylinder on M4K Tactical Forklift, with Corrosion on Extended Portion of Main Vertical Actuator Arm

The aggressive corrosive attack on the actuators of this asset can be partly attributed to the design. To comply with safety protocols, the M4K tactical forklift is normally stored in the "forks down" position, with the cylinder actuator arms extended approximately ten inches. This leaves the actuator arms exposed to the environment. Over time, the thin layer of hydraulic fluid that protects the arms disappears, and corrosion is initiated.

Hose-End Fittings

The corrosion of hydraulic hose-end fittings was identified as a significant issue during the course of earlier work. A corroded hose-end fitting in need of maintenance is presented in Figure 5.

Figure 5. Hydraulic Hose-End Fitting Corrosion

Hose-end fittings are procured for military vehicles and weapons systems in accordance with the Society of Automotive Engineers (SAE) specification J516[8]. This specification does not specify a particular coating; it merely requires hose-end fitting coatings (external surfaces and threads) to pass a 72-hour salt spray test in accordance with ASTM B117[9] with no appearance of red rust. The standard coating that is currently used is zinc-nickel electroplate with yellow iridite topcoat. It should be noted that recent studies[10] have concluded that the B117 test is a poor life prediction tool for the corrosion performance of coatings in fielded systems.

Advanced Coatings for Corrosion

Mitigation

Having identified the critical corrosion-prone components of Army hydraulic systems, efforts were then directed toward the identification of technologies that can mitigate corrosion in the identified applications.

Actuator Coatings

As mentioned earlier, hydraulic actuators are generally protected by a hard chrome coating, which provides limited corrosion resistance. While hard chrome is the most prevalent actuator coating in use, alternative coating schemes and surface treatments have been evaluated under previous efforts. A cursory review of the literature provided relevant data on a number of approaches and technologies, for both corrosion-resistance and wear-resistance applications. Among the technologies considered are nickel-based coatings (electroplated nickel alloys, electroless nickel alloys, and composite coatings of both), surface modification technologies (plasma treatments, laser energy systems, and diffusion technologies), trivalent chrome plating, thermal spray coatings, coatings deposited by physical vapor deposition, and others[11-13].

Since the alternatives for hard chrome replacement are many, efforts were made to consider those alternatives that have either already been implemented for similar applications or are being considered by other military organizations. The most dominant replacement technologies at the time of this writing are those coatings deposited by thermal spray, particularly tungsten carbide and chromium carbide alloys. The work of the Hard Chrome Alternatives Team, a consortium of government and commercial organizations evaluating hard chrome replacement technologies for aerospace applications, has found that there are significant benefits to the use of thermal spray coatings in place of hard chrome for many applications[14, 15]. Electroless nickel (EN) coatings have also been considered for this application, both as a stand-alone coating and as a barrier coat between the substrate and the hard chrome coating. The enhanced corrosion performance of EN coatings over hard chrome coatings of the same thickness in established corrosion tests has been documented[3]. Corrosion performance improvements have also been realized through the utilization of duplex EN coatings[16].

Hydraulic Hose-End Fitting Coatings

Several improved coatings were identified for hydraulic hose-end fittings. The considerable work of commercial industry was reviewed, and an alternative hose-end fitting coating was identified[17]. This coating has been used in Europe for some time, and is reported to provide greatly improved corrosion resistance[18]. An experimental coating system was also identified; this system is reported to provide outstanding corrosion resistance as well as excellent torque-tension properties[19]. While this system has been approved for use on a similar application (brake line conduits) on U.S. automobiles, it has not yet been evaluated for hydraulic hose-end fittings. Two variants of this system were selected for evaluation.

Experimental Design

After identifying the coatings that are currently employed on military hydraulic actuators and hose-end fittings, as well as several likely alternatives for each, efforts were directed toward procuring specimens and conducting corrosion testing.

Actuator Coatings

1045 alloy cold rolled steel bar shafts of 38 mm (1.5") diameter were procured to simulate the alloys and configurations of actual hydraulic actuators. These were cut to 101.5 mm (4") lengths and then sent to various vendors for plating.

As mentioned above, hard chrome electroplate is the most prevalent coating in use. Shafts were plated and finished with hard chrome in accordance with the military specification[5]. These electroplated hard chrome specimens, along with bare shafts, were utilized as controls.

Alternative coatings were selected on the basis of three potential applications: chrome repair, chrome enhancement, and chrome replacement. A chrome repair process would be useful for repairing corrosion damage without removing the chrome coating. Thermal spray coatings and technologies such as electrospark deposition could be employed in this regard. As much work has already been done on the most available of these technologies, a newly developed thermal spray process was selected[20]. For chrome enhancement technologies, a COTS surface treatment was selected[21].

Chrome replacement technologies, in which the chrome coating is replaced altogether, were also considered. A new electroless nickel product that is being considered for Air Force applications was selected[22]. Shafts were finished with the above coating systems and submitted for ASTM B117 testing.

Hydraulic Hose-End Fitting Coatings

Four coatings were evaluated for hose-end fittings. The first was the standard zinc-nickel electroplate with yellow iridite topcoat, which was the control. The second coating was the proprietary process that has been used on commercial hydraulic systems in Europe. The third and fourth coating systems were the experimental systems. The fittings were subjected to standard salt spray corrosion testing per ASTM B117[9] and also to cyclic corrosion testing in accordance with SAE J2334[23].

Results and Discussion

Actuator Coatings

The actuator coatings were placed into the chambers for ASTM B117 salt spray testing. The results are being generated at the time of this writing.

Hydraulic Hose-End Fitting Coatings

The procured coated fittings were placed in the salt spray chambers for a total of 1000 hours. While this exposure time far exceeds the requirements set forth in SAE J516, it was useful to separate the population in terms of corrosion resistance.

The specimens were removed, cleaned, and photographed at 0, 100, 250, 500, 750, and 1000 hours of exposure. The 100-hour photographs are presented in Figure 6.

Figure 6. Hydraulic Hose-End Fittings After 100 Hours of B117 Exposure: Zinc-Nickel Electroplate (upper left), European (upper right), Experimental 1 (lower left), Experimental 2 (lower right)

As witnessed above, none of the tested coatings exhibit red rust after 100 hours of salt spray exposure, and thus all of the coatings are acceptable for military procurement under SAE J516.

Figure 7. Hydraulic Hose-End Fittings After 1000 Hours of B117 Exposure: Zinc-Nickel (upper left), European (upper right), Experimental 1 (lower left), Experimental 2 (lower right)

After 1000 hours of exposure, there is a more clear separation of performance. Both of the experimental coatings have outperformed the standard zinc-nickel electroplate and the European coating system. Once again, while this extended test exposure exceeds that required by the procurement specification, the benefits of the experimental coatings would be appealing to the military community if an associated positive return on investment could be realized. Such determinations will be provided under future efforts of this activity.

The J2334 test results are being generated at the time of this writing.

Summary

Under this effort, information was gathered on hydraulic materials of construction and coatings, and the most critical corrosion issues on both asset and component levels were researched. Two primary components – hydraulic actuators and hose-end fittings – were found to present corrosion issues on Army assets. Based upon these findings, recommendations for mitigating corrosion on Army hydraulic systems include the evaluation of new hydraulic actuator coatings and new hydraulic hose-end coatings. The most promising of these technologies were procured, and corrosion testing has been initiated.

COTS technologies exist that can apparently mitigate corrosion on the identified assets and provide enhanced readiness and operator safety while reducing the maintenance burden. The implementation of these technologies can provide improved life cycle cost, sustainability, and readiness for the warfighter.

Acknowledgements

This work was funded under the U.S. Army's Technology Demonstration for Prevention of Material Degradation (TDPMD) Program. The authors wish to thank Dr. Joe Argento and Mr. John Theis of the U.S. Army Corrosion Office for their continued support. The authors also wish to thank the depot maintenance personnel interviewed under this effort. Finally, the authors wish to recognize Mr. Larry Gintert, Mr. James Failor, and Mr. Scott Ryan of Concurrent Technologies Corporation in Largo, Florida, for their contributions to this work.

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