Corrosion in Industrial Applications:

How next generation anti-corrosion plating achieves higher fluid power product performance

Parker

ENGINEERING YOUR SUCCESS.

Abstract

Fluid power connectors must deliver first-class performance in all environments. Fluctuating humidity, temperatures and salt levels - as well as harsh chemicals and media used in applications - can be ideal conduits for corrosion. Left unresolved, corrosion can cause poor appearance, force costly maintenance, and eventually lead to total equipment failure. Scientists and engineers at Parker worldwide have pooled their metallurgical know-how to deliver next-generation plating technologies. This provides a leap forward in long-term anti-corrosion performance while maintaining compatibility with existing products and without impacting assembly procedures and performance benchmarks.

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Philipp has been working in the field of material science, electrochemistry and chemical engineering for over 15 years. At Parker Hannifin, he established the Metals Innovation Center for the development and application of new surface technologies and corrosion protection innovations for fluid power systems. Philipp holds an MSc. in Chemistry, a PhD in Physical Chemistry and a habilitation degree in Technical Chemistry.

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Yindong is a materials scientist with 15 years' experience in surface engineering, corrosion science, electrochemical processes, and materials development. He is currently leading the Metals Innovation Center in Columbus, OH USA, where he leads the development of innovative surface protection technologies for fluid power components. Yindong has a BS in Ceramics Engineering and holds both an MS and a PhD in Materials Science and Engineering.

The Cost of Corrosion

Corrosion is the enemy of metal components and systems. Under the right conditions, accelerated rusting can take hold quickly and silently - leaving an enormous amount of damage in its wake.

According to NACE International, the worldwide corrosion authority, the global cost of corrosion is around $2.5 trillion, equivalent to 3.4% of global GDP. This staggering figure reflects the severity of the problem, with corrosion having a negative impact on assets' lifetime across multiple sectors.
The study shows that in industry – including off-road and manufacturing – the global cost of corrosion stands at almost $1.5 trillion, while in agriculture alone, it amounts to $152 billion. The actual cost in each case is likely to be even higher as these figures do not include individual safety or environmental consequences, says NACE International.

Corrosion can happen in every environment. The severity of corrosion on fluid power components is highly dependent upon the end user application and operating environment. For example, hydraulic fittings used on a hydraulic press located within a climate controlled production facility will suffer minimal corrosion effects. In contrast, for outdoor environments, specifically applications found in off-road, trucking, agriculture, mining, and marine segments, corrosion can take hold rapidly.

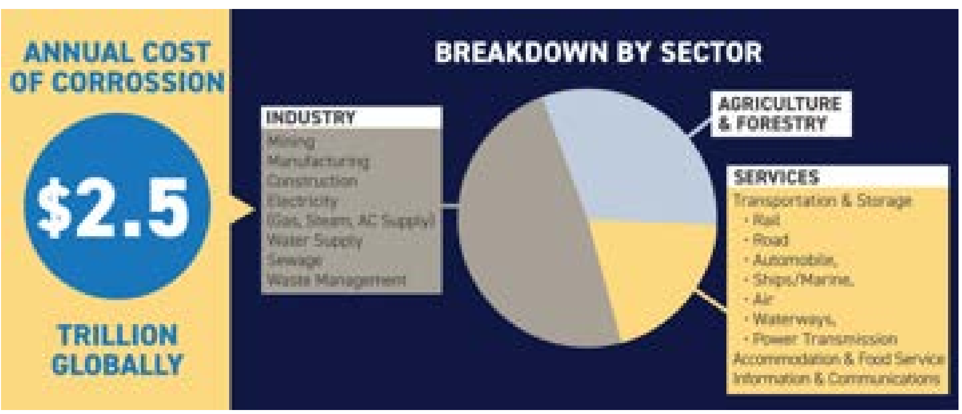

Figure 1: Cost of corrosion according to NACE report

Factors such as humidity, fluctuating temperatures, airborne salt, chemicals and media can all contribute to the initiation and accelerated spread of corrosion. Left unchecked, this damage can impact other more expensive components, resulting in a multitude of problems such as unscheduled maintenance and downtime, and expensive warranty claims. Ultimately, corrosion can lead to the total failure of systems or equipment, resulting in equipment overhaul or wholesale replacement, or jeopardizing personnel safety in severe cases.

Figure 2: Corrosion can quickly develop on off-road equipment even in normal environmental conditions

How Corrosion Forms and Spreads

As an electrochemical reaction, corrosion occurs when atoms on a metal surface such as steel become oxidized, damaging the entire surface.

Many metals are easily oxidized: they tend to lose electrons to oxygen (and other substances) in the air or water. As oxygen is reduced (gains electrons), it forms an oxide with the metal, and corrosion occurs. In some environments, this process begins to take place in a very short space of time.

The most common type of corrosion is general corrosion. In this case, according to the ***NACE International Basic Corrosion Course Handbook***, corrosion spread proceeds more or less uniformly over an exposed surface without appreciable localization, causing uniform thinning on sheet and plate materials and general thinning on one side or the other (or both) for pipe and tubing.
This type of general corrosion is characterized by roughening of the surface and frequently, but not always, with a change in color. The attack mechanism typically is an electrochemical process that occurs at the surface of the material. Differences in composition or orientation between small areas on the metal surface create anodes and cathodes that facilitate the corrosion process.

As illustrated in figure 3, in a corrosion cell, electrons and ions flow through a metallic path where anodic reactions are occurring to sites where they allow cathodic reactions to occur. Once this reaction starts, it is difficult to stop, and corrosion can spread quickly, for example, from tube fittings/ adapters to other critical and more expensive components.

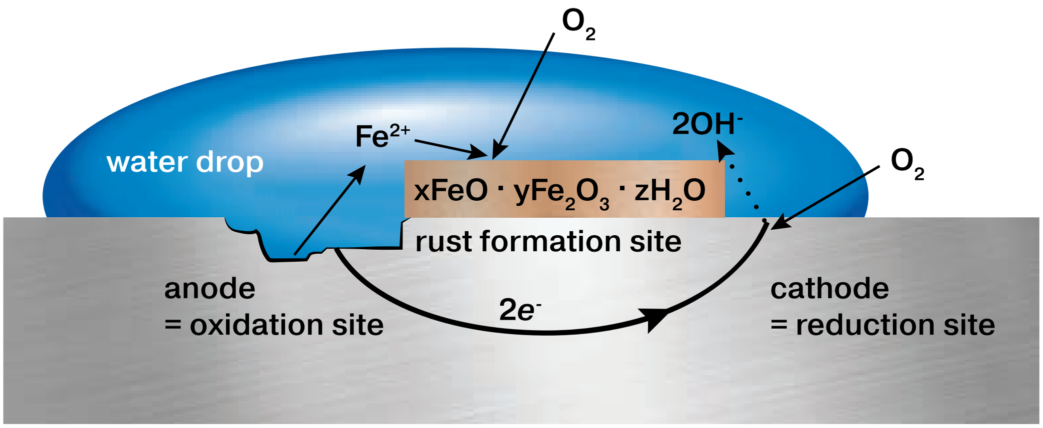

Figure 3: Illustration of the electrochemical reactions during the corrosion of steel

The Use of Zinc Plating

Common practices for preventing corrosion may include the selection of more expensive materials (such as stainless steel) or subjecting critical components to a plating process. For modern steel fluid power connectors, zinc electroplating is the industry norm. When bonded with steel, this coating provides a sacrificial layer, keeping base metal corrosion in check.

However, zinc plating only delays the inevitable. Harsh conditions with high humidity, aggressive agents, muddy environments, air pollution or the presence of salts can still lead to severe corrosion.

Figure 4: Corrosion migration to adjacent components

In such environments, the zinc will start to sacrifice itself to protect the steel substrate, producing a white oxidation by-product, commonly called white corrosion (or white rust). As this sacrificial process progresses, the protective zinc layer is consumed and the base metal is exposed, with red rust soon becoming visible.

Once the zinc at one area is consumed, zinc at neighbouring areas will also be affected.

So, even when components are zinc-plated, corrosion can accelerate by migrating from one component to another. This can result in a need for earlier and more regular repair work to adjacent fittings and mating components, such as a hydraulic cylinder, valve, or hydraulic hose assembly. Corrosion makes service and repairs more difficult as mating components tend to be “rusted” together and wrenching surfaces may have been compromised.

While providing sacrificial protection to the substrate, white corrosion exhibits a counterproductive characteristic. The by-product created by this sacrificial zinc oxidation is voluminous. So not only does it spread as it protects the substrate, but it also expands volumetrically. This volumetric expansion frequently causes mechanical stress, leaving these adjacent areas more vulnerable effectively providing a path of destruction for base metal corrosion to take hold.

In short, corrosion can have significant operational and economic consequences. Therefore, the advancement of anti-corrosion technology has been a priority for many industry manufacturers and for OEMs, resulting in intense research and development activity globally.

Figure 5: Zinc Oxidation on a Steel Tube Fitting

Figure 6: Corrosion can cause unplanned downtime and more frequent need for maintenance

Recent Advances in Plating Technology

Several improved plating solutions have been introduced over the last several decades-in part due to environmental compliance as well as increased corrosion performance. Neutral salt spray testing (SST), such as ASTM B117/ISO 9227, is the industry-wide accepted evaluation method for determining the corrosion protection for electroplating.

For example, previous Parker zinc plating solutions have provided SST resistance to 1000 hours prior to red corrosion. However, most industry advancements have been limited to incremental improvements in zinc plating.

More recently, metallurgical and surface analysis capabilities have progressed and increasingly more optimized alloys and nanotechnologies have been applied. Simultaneously, the experienced team of scientists and engineers at Parker have been dedicated to gaining an even deeper understanding of the causes of corrosion and how it progresses.

Much of this work has been carried out at state-of-the-art metallurgical laboratories, which support the development of alternative materials and technologies to augment zinc electroplating. These materials can then be rigorously tested in the laboratory in conditions that simulate customers' real-world applications.

This research has proven that not all plating technologies are equal. The latest electroplating developments are combined with additional protection technologies and processing methodologies to further protect substrate materials from oxygen and moisture. Significant research has been undertaken to better understand the interaction between the surface coating or plating and the substrate underneath.

Ultimately, the target has been to develop an electroplating plating technology that provides leading-edge performance - resulting in a plating withstanding even the harshest environments, is visually appealing and, in the end, provides a lower cost of ownership for the equipment manufacturer and end users.

As part of rigorous testing and qualification procedures, Parker subjects these next generation plating technologies well beyond traditional neutral salt spray testing. Specifically, corrosion testing is conducted under various controlled conditions at both Parker laboratories and independent/third-party corrosion test facilities.

Specific tests include simulating a range of corrosive atmospheres, salts, and other known corrosive chemicals including exposure to harsh agricultural fertilizers. See Box 1.

1 ***Salt spray and Cyclic Corrosion Testing (CCT) procedures***

Salt spray testing (SST) provides a standardized approach to validating the corrosion resistance of metals and surface coatings. In such tests, samples are subjected to a highly corrosive attack.
Salt spray tests have been used for decades. The most widely used standard is the ASTM B117 or ISO 9227 , where a sodium chloride solution is sprayed within a sealed environmental test chamber to create an aggressive saltwater fog. The samples are then checked at regular intervals to assess corrosion resistance.

Cyclical Corrosion Testing (CCT) has evolved more recently and is widely considered as providing stronger correlation to field exposure. Tests like ISO 16701, SAE J2334, and OEM specific tests combine exposure to salt spray with with alternating cycles of humidity, dry heat, and temperature variations under controlled conditions. Additionally, some tests add corrosive agents such as calcium chloride and even sulfuric acid. Distinct climates can be created, halted, and then recreated numerous times, in different sequential order. The aim is to simulate the sort of corrosive environment and failures that might occur naturally but in an accelerated manner.

ToughShield Plus™ - Next-Generation Plating

The quest for performance enhancement never stops. Parker's scientists and engineers remain committed to developing anti-corrosion technologies to help customers' hydraulic systems to perform better and last longer – and therefore save costs.

Parker's recent focus has been bringing the existing zinc-nickel plating technology - which already offers good performance in most applications - to the next level. This was achieved by gaining a better understanding of the relationship between metal structures, properties, and processing – all validated under controlled conditions.

From the outset, the aim has been to develop a new zinc-nickel plating solution that achieves the highest corrosion-resistance performance levels, without impacting other parameters such as assembly procedures, operating pressure, and performance, along with compatibility with existing zinc-plated products.

The starting point was the development of a patent-pending plating technology combining a protective topcoat with a chromate conversion layer. While the specific details are protected by intellectual property, Parker's global team of chemists, metallurgists, and engineers have deployed the latest surface analysis and spectroscopy techniques to gain a greater insight into the complex interaction between the different materials. This IP includes developing a process that enables the plating to be structured in a highly optimized way. The advanced structuring makes it possible to build additional functionality into the plating, resulting in superior performance. The result: ToughShield Plus, the first fluid power industry commercially available standard plating system to provide up to 3,000 hours of resistance to red corrosion in SST.

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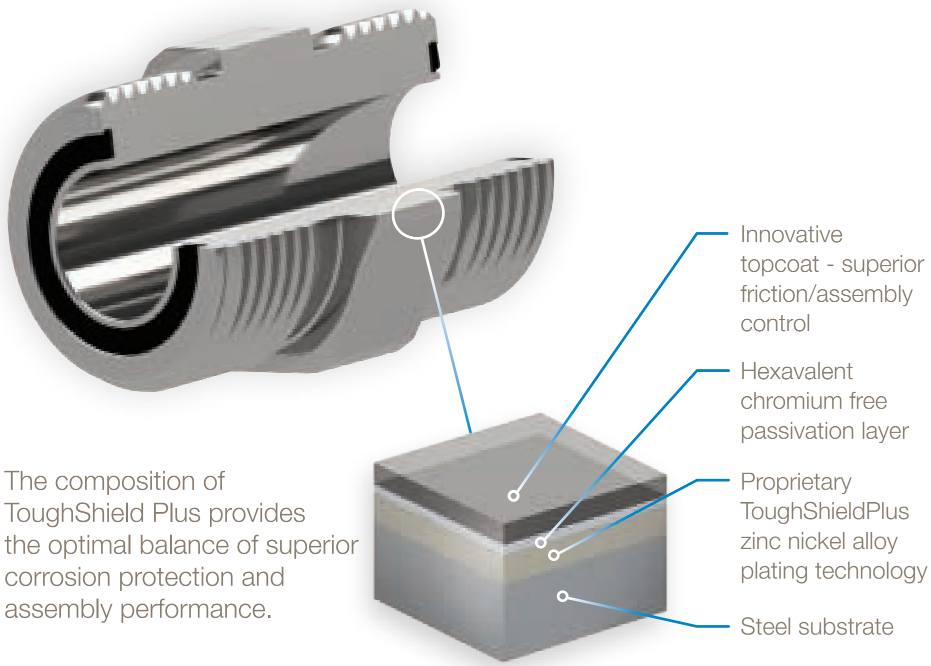
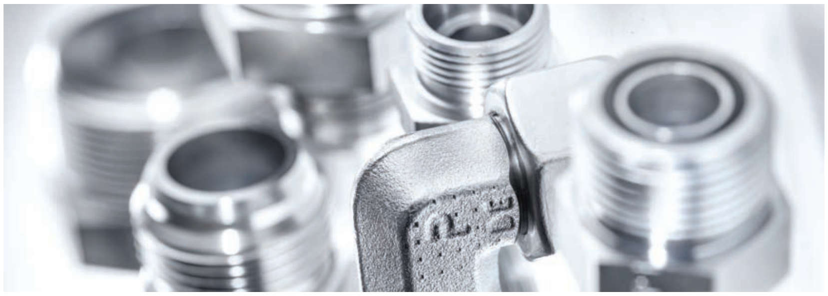


The composition of ToughShield Plus provides the optimal balance of superior corrosion protection and assembly performance.

Figure 7: Composition of ToughShield Plus Zinc-Nickel Plating

Figure 8: State-of-the-art Metal Labs at Parker

Beyond Corrosion Resistance



The aim of Parker was to improve corrosion-resistance of steel fluid connectors while keeping other attributes constant. Corrosion resistance is just one property of several in the broader and interlinked process of surface technology, where there is often a very definite cause and effect.

For example, a protective layer that delivers a very high corrosion resistance, yet increased, decreased or inconsistent friction/assembly properties - would be unable to meet the demands of the industry that requires defined assembly procedures and product performance.

Historically, a drawback of zinc-nickel plating for fluid power connectors has been its impact on assembly. Zinc-nickel and zinc have different physical properties. Zn-Ni plating is rougher due to a different crystal structure and therefore has a higher coefficient of friction.

This, in turn, means there is a requirement for higher assembly torque or turns to provide appropriate connection loading for a safe and leak free connection. Early industry attempts to mitigate this drawback through the use of low-friction topcoats provided highly inconsistent performance results.

Therefore, the control of consistent assembly properties and optimized coefficient of friction was of highest priority to Parker in developing ToughShield Plus.

The result is a zinc-nickel anti-corrosion surface that delivers significantly higher corrosion protection without altering assembly procedures or assembly performance. The result also provides full "backwards compatibility" with existing zinc-plated components, allowing end users to confidently proceed with the use of both zinc and ToughShield Plus Zn-Ni fluid power components as needed.

Enhanced Formability

Historically, electroplating has not performed well on components that require post-plating mechanical deformation. For example, the fluid power industry uses crimping and formed backup washers for adapters and hoses. These surfaces traditionally exhibit corrosion more rapidly due to the plating being compromised by metal deformation. In fact, industry governing bodies such as SAE and ISO discount the corrosion in these areas during SST qualification, yet they are known corrosion failure points. This challenge required a strong focus on research and development to provide higher levels of corrosion protection for parts subjected to post-plate deformation.

Parker scientists and engineers used state-of-the-art equipment such scanning electron microscopes and x-ray spectrometry as well as electrochemical analysis methods such as impedance spectroscopy to reveal and study highly detailed surface characteristics. This knowledge led to the development of new and unique plating structures. As a result, the ToughShield Plus process was optimized to provide higher formability than commercially available zinc-nickel plating, ensuring that it performs comparably even on post-plate deformed parts. Corrosion testing was conducted to confirm this monumental leap forward in corrosion protection.

Figure 9: ToughShield Plus (left) and Zinc-crimped (right) swivel adapters after 3,000 hours SST

Ensuring Performance Consistency

Throughout the ToughShield Plus plating development, there was a strong focus on process stability and control. The principles of statistical process control were implemented on critical production variables with strict monitoring procedures and control limits established to assure ToughShield Plus performs uniformly throughout the broad Parker product range and numerous global plating operations. As a result, the high process capability of the ToughShield Plus plating system has been demonstrated for a mass production environment. The robust process has little variation from day-to-day operation and from part-to-part on the same day. This quest for consistency also applies to the uniformity in plating color.

Environmental

The improved technical solution of ToughShield Plus required process reconfiguration to Parker's plating operations. The addition of nickel to the plating process required carefully engineered upgrades to wastewater treatment and monitoring systems within production facilities to ensure no environmental impact.

ToughShield Plus is compliant with REACH, RoHS, and ELV environmental directives.

Similar to commercially available zinc-nickel electroplating, there is minimal release of nickel from ToughShield Plus plated production parts - providing assurances of safe handling. Modern spectroscopy methods were employed to validate the results as tested to DIN EN 1811 confirming a release rate compliant with REACH Annex 17.

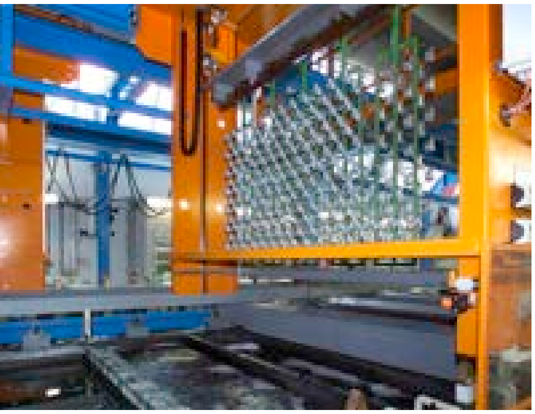


Figure 10: Parker invested in state-of-the-art electroplating technology

White Haze

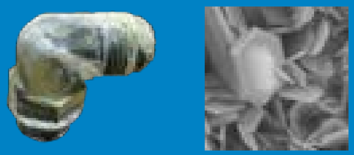
Zinc nickel electroplating corrodes both similarly and yet differently than pure zinc plating. Both are sacrificial with the first sign of corrosion exhibiting a white discoloration. However, zinc-nickel's initial form of corrosion product is a non-voluminous "white haze" which is often misinterpreted as white rust. Consult Box 2.

2 ***White rust versus white haze***

There are two distinct types of white corrosion – voluminous white rust and white haze.

Voluminous white rust often observed as a powdery deposit on pure zinc or zinc-iron surfaces. It occurs primarily in environments with high moisture content and corrosive chemicals, and is indicative of a rapid, localized attack beneath the deposit build-up. Voluminous white rust is visible when dry or wet and exhibits a raised texture. Due to its porous structure, it is typically quickly followed by the appearance of base metal corrosion.

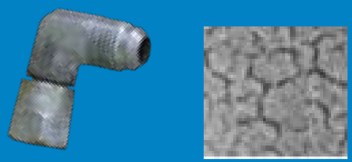
White Rust



Macro appearance *Micro structure*

Conversely, white haze is often the first observable surface change during corrosion testing for zinc-nickel alloy surfaces. It is a thin, dense, non-voluminous type of corrosion compared to white rust. It can form quickly in both SST and CCT and remains generally unchanged over extended periods. In spite of the visual appearance, white haze on zinc-nickel electroplated parts forms a protective barrier layer- actually slowing the progression of corrosion. White haze forms on clear and black surfaces and is not easily visible when wet.

White Haze



Macro appearance *Micro structure*

Engineering for a Better Tomorrow

Corrosion is not simply an unsightly inconvenience, rather a costly drain on operating and OEM warranty budgets. The full cost extends beyond the expense of replacement fittings or even more costly adjacent components – but also to equipment downtime. When valuable equipment is underutilized with skilled operators idle, this magnifies these losses. Downtime can lead to losses of revenue, reputation and customers.

Parker understands these concerns, particularly -but not only- in off-road mobile and transportation equipment, where harsh operating environments are a way of life.

The development of ToughShield Plus represents Parker's dedication to ensuring customer systems exceed their performance expectations. This dedication is supported by in-house materials science expertise, ongoing research and development, and investment in advanced testing capabilities.

This drives our commitment to collaborate with customers within these highly corrosion-centric segments to optimize the performance of fluid conveyance products - delivering innovation and enabling engineering breakthroughs that lead to a better tomorrow.

ToughShield™ Plus

3 *The importance of effective Corrosion Management Systems*

While NACE International estimates the cost of corrosion to be $2.5 trillion, it believes that implementing best-practice corrosion control policies could save between 15 and 35% of this cost annually on a global basis.

The key to achieving improved performance in this area is the implementation of an effective Corrosion Management System. This approach includes creating a documented set of processes and procedures that a company would require for planning, executing, managing, and continually assessing the threat of corrosion for existing and future assets.

Managing the threat of corrosion requires contemplation of both the likelihood and consequence of corrosion events, says NACE International. The process includes analyzing the result, or impact, of corrosion in terms of potential or actual financial loss associated with the safety, environment, or integrity of assets.

This value is typically quantifiable when considering factors such as lost revenue, cost of repairs, and clean-up costs. Other critical aspects of corrosion impact include the deterioration of an asset to the stage where it is no longer fit for intended purpose, resulting in lost future production.

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