

A Guide To Corrosion Protection

An analysis of corrosion-related issues for passenger car and light truck underbody structural components.

Auto/Steel Partnership



A GUIDE TO CORROSION PROTECTION

**For Passenger Car and Light Truck
Underbody Structural Components**

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Preface

This is the first edition of *A Guide to Corrosion Protection - Passenger Car and Light Truck Underbody Structural Components*, written and published by the Light Truck Frame Project Team of the Auto/Steel Partnership (A/SP).

The publication brings together basic corrosion conditions, materials, coatings, manufacturing processes, design considerations, test methods and "lessons learned". It has been prepared to meet the needs of OEM engineers. It is also intended to meet the needs of the Tier 1 and 2 suppliers of underbody components and steel industry marketing and technical personnel. As experience in its use is gained, revisions and additions will be issued.

This publication was prepared by the Light Truck Frame Project Team of the A/SP and reflects the combined efforts of the following:

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Auto/Steel Partnership
1999

Executive Summary

Auto/Steel Partnership

The Auto/Steel Partnership (A/SP) is an innovative international association that includes DaimlerChrysler, Ford, General Motors and twelve North American sheet steel producers. The Partnership was formed in 1987 to leverage the resources of the automotive and steel industries through research projects leading to excellence in the application of sheet steels in the design and manufacture of vehicles. The Partnership has established project teams to examine issues related to steel properties including strength, dent resistance, surface texture and coating weights, as well as manufacturing methods including stamping, welding and design improvements.

Objective

The automotive industry is under extreme pressure to minimize vehicle weight. One method for achieving weight reduction is the use of thinner, higher strength steel for underbody structural components. Doing so may, on occasion, compromise stiffness requirements. The judicious use of thinner, higher strength steel does enable designers to achieve a degree of weight reduction. Corrosion becomes a concern, as a thinner piece of steel will reach the critical thickness at which structural failure occurs sooner than a thicker piece of steel. Therefore, if steel thickness is reduced to save weight, it may be necessary to take additional measures to control corrosion. Four main factors contribute to overall corrosion resistance: material, design, manufacturing process and post-coating. The objective of this Guide is to help designers address these four factors.

Types of Corrosion

Four types of corrosion are relevant to underbody structural components: crevice, pitting, galvanic and cosmetic. Crevice corrosion is often associated with small volumes of stagnant solution or electrolyte trapped in crevices of joints or in surface deposits and poultices. Pitting corrosion is a localized attack, usually caused by chlorides as pits form, resulting in a roughened surface. Crevice and pitting corrosion can lead to steel perforation and premature functional failures. Galvanic corrosion occurs when dissimilar metals are in contact with one another. For example, an aluminum component in contact with a steel component may corrode, or sacrifice itself, to protect the steel component. Corrosion that initiates on a visible surface of a vehicle, usually at nicks or scratches in a post-coating, is called cosmetic corrosion. In most instances, cosmetic corrosion is an appearance issue; however, it can lead to damage including perforation.

Steel Materials

A full spectrum of steel materials is available for automotive structural components. Low-carbon, formable steels offer yield strengths up to 260 MPa (38 ksi), dent resistant steels offer yield strengths up to 280 MPa (40 ksi), high-strength steels offer yield strengths up to 830 MPa (120 ksi) and ultra high-strength steels offer tensile strengths up to 1500 MPa (215 ksi). Most steel can be supplied with a metallic coating, such as zinc, zinc-iron or aluminum to enhance corrosion protection. The Society of Automotive Engineers (SAE) publishes standards to facilitate selecting and specifying appropriate sheet steel materials for underbody structural components. SAE J2329, *Categorization and Properties of Low-Carbon Automotive Sheet Steels*, classifies low-carbon sheet by five grade-levels, with yield strength, elongation, r_m and n-value requirements. SAE J2340, *Categorization and Properties of Dent-Resistant, High-Strength and Ultra High-Strength Automotive Sheet Steel* classifies high-strength and ultra high-strength steels.

Coatings

Underbody structural components are typically coated to provide a first line of defense against corrosion. Commonly used coatings include conversion, hot melt wax, electrocoat, metallic, organic, autodeposition and powder. Phosphate conversion coatings are employed to enhance paint adhesion, thereby indirectly enhancing corrosion resistance. Hot melt wax coatings are used extensively on underbody structural components to provide corrosion protection, and are usually applied through a dipping process. Electrocoating or E-coating is a process in which electrically charged particles are deposited out of a water suspension to coat a conductive part. The process requires a coating tank in which the part is completely immersed. E-coat is widely used to protect underbody structural components from corrosion. Metallic coatings such as zinc, zinc-iron and aluminum are applied to steel components to inhibit corrosion, using the electroplating, mechanical plating, electroless or hot dipping process. Many underbody structural components are manufactured from sheet steel with a metallic coating. The steel mills supply hot or cold rolled sheet in coil form with metallic coatings applied by either electroplating or hot dipping. Organic, autodeposition and powder coatings are also available to protect underbody structural components. An organic coating such as paint is a cost effective corrosion protection method. It prevents, or retards, the transfer of electrochemical charge from the corrosive solution to the metal beneath the coating. Autodeposition is a waterborne process that relies on chemical reactions to achieve deposition. A mildly acidic latex bath attacks a steel part immersed in it. Iron ions are released and react with the latex in solution causing a deposition or coating on the surface of the steel part. A powder coating is achieved by applying a dry powder to a part. The part is then heated, fusing the powder into a smooth, continuous film.

Manufacturing Processes and Design Considerations

A vehicle underbody is an assembly of components. The processes used to manufacture the components and the methods used to join the components have a significant impact on the corrosion resistance of an underbody. Of particular importance when designing parts and joints is ensuring that coatings can access individual parts and joints. Often, openings must be provided in parts for coating access and drainage. The openings must be strategically located to preserve structural integrity. E-coating lacks the ability to throw a coating into a long, closed section. One approach to overcoming this problem is to pierce holes along the length of the section. The coating achieved inside the section depends on the location, size and frequency of the holes. Similarly, holes are required to permit the entry of hot melt wax or powder into a closed section. Provision must be made to allow hot melt wax to drain after dipping from a closed section. Open sections, depending on the position after dipping, may also require openings to permit the wax to drain.

Corrosion Testing

Corrosion tests must simulate service conditions as closely as possible and can be divided into two broad classes: accelerated laboratory tests and field tests. Laboratory tests may include the testing of small coupon specimens or the testing of a fully assembled component. Field tests may include the testing of specimens attached to vehicles subjected to a specified length of field service.

A/SP Corrosion Testing

In order to obtain a relative ranking of the corrosion resistance of steel materials for underbody components, A/SP is currently conducting laboratory tests. Materials currently used for underbody components, such as low-carbon and high-strength steels in the bare and metallic coated condition, as well as materials that may prove useful for underbody components (high-chrome and high-copper with nickel steels) are included in the program. The SAE J2334 test cycle is being used to evaluate weight loss and perforation corrosion. A/SP is also evaluating the relative performance of five types of post-coatings: hot melt wax, high temperature hot melt wax, electrocoat, polymer (paint) and autodeposition. Three test methods are being used: the SAE J2334 test cycle, the SAE J2334 test cycle in combination with an oven bake and shot blast, and the General Motors Corporation's trailer test. Results from the A/SP materials and coatings tests are expected early in the year 2000.

Lessons Learned - Review Questions

A handy checklist of questions, based on lessons learned, covers material, design, processing, testing and environmental exposure issues. The checklist may be used to ensure that corrosion is properly addressed. If the questions are addressed early in the development of an underbody component, the chances of successfully combating corrosion are greatly increased. As materials, design, processing and test engineering groups pursue these questions individually, as well as across disciplines, optimized component corrosion retarding will result.

1.0 Introduction and Definition of Basic Corrosion Conditions

Introduction

The Auto/Steel Partnership (A/SP) is an innovative international association that includes DaimlerChrysler Corporation, Ford Motor Company, General Motors Corporation and twelve North American sheet steel producers. The Partnership was formed in 1987 to leverage the resources of the automotive and steel industries to pursue research projects leading to excellence in the application of sheet steels in the design and manufacture of vehicles. The Partnership has established project teams that examine issues related to steel properties including strength, dent resistance, surface texture and coating weights, as well as manufacturing methods including stamping, welding and design improvements.

The Light Truck Frame Project Team was established to address mass reduction initiatives associated with light truck frames and includes representatives from DaimlerChrysler, Ford, General Motors, frame manufacturers, and the producers of frame component steels.

Reducing the steel thickness of the components in a frame would reduce the mass of a frame. However, doing so may not satisfy all of the frame stiffness requirements. Judicious use of thinner, higher strength steel enables designers to achieve a degree of mass reduction and satisfy many of the engineering and performance criteria. If significant corrosion occurs, one critical performance parameter that could suffer as material thickness decreases is structural strength. Given the same corrosion rate, a thinner steel component will reach the critical thickness at which structural failure occurs sooner than a thicker component. Therefore, if steel thickness is reduced to decrease mass, then additional measures may have to be taken to control corrosion in order to maintain the same structural performance of the frame over time.

Bare steel, in the presence of oxygen and moisture, corrodes. To mitigate corrosion, frame engineers select design characteristics that prevent poutices and water entrapment. In

addition, frames are often coated after fabrication to improve corrosion resistance. Corrosion protection is the result of the combination of the material, design, post-coating and the manufacturing processes selected.

Recognizing the importance of corrosion resistance, particularly with the use of thinner, higher strength steel underbody components, the Light Truck Frame Project Team developed this Guide. Focusing on the elements of protecting underbody structural components against corrosion, this Guide is aimed at automotive underbody component engineers who are responsible for design, process, product, material selection or corrosion performance. The relative importance of the various options within each of the corrosion protection factors (material, design, post-coating and manufacturing processes) is outlined. It is intended to assist designers in addressing the issue of corrosion protection.

1.1 Definition of Basic Corrosion Conditions

In automotive applications, there are five types of steel corrosion: uniform corrosion, crevice corrosion, pitting corrosion, galvanic corrosion and cosmetic corrosion.

The most familiar type of corrosion is termed uniform corrosion [Ref. 1.1]. It tends to proceed evenly over the entire exposed surface of any uncoated part and eventually causes a general thinning of the metal. While best known, it is the least damaging. In automotive applications, uniform corrosion is not related to perforation or structural damage, and therefore, it is not addressed further in this publication.

Crevice corrosion is often associated with small volumes of stagnant solution or electrolyte trapped in crevices of joints, or in surface deposits and poutices. Pitting corrosion is a localized attack, usually caused by chlorides. Pits form resulting in a roughened surface. Crevice corrosion and pitting corrosion result in an accelerated attack on the metal. In some instances, the attack is severe enough to lead to premature, and often catastrophic, functional failures. For example, structural requirements may be compromised or a body panel may be perforated.

Galvanic corrosion occurs when dissimilar metals are in contact with one another in the presence of an electrolyte. It can be detrimental or beneficial. For example, an aluminum component in contact with a steel component may corrode in order to protect the steel. This situation is injurious to the aluminum component. On the other hand, steel is often given a metallic zinc coating. The zinc sacrifices itself, thereby prolonging the life of the component made from the zinc coated steel. Corrosion that initiates on a visible surface of a vehicle, usually at nicks or scratches in a post-coating, is called cosmetic corrosion. Of primary concern is poor appearance due to red rust, stain and paint blisters.

1.2 Crevice Corrosion

Crevice corrosion is a damaging type of corrosion because it is sharply focused on localized areas, usually invisible in its early stages. The attack is swift, often resulting in unexpected or premature failure. Crevice corrosion is often associated with small volumes of stagnant solution or electrolyte trapped in holes, on gasket surfaces, at joints (Figures 1.1 and 1.2), under fasteners, and in surface deposits or poultrices (Figure 1.3).

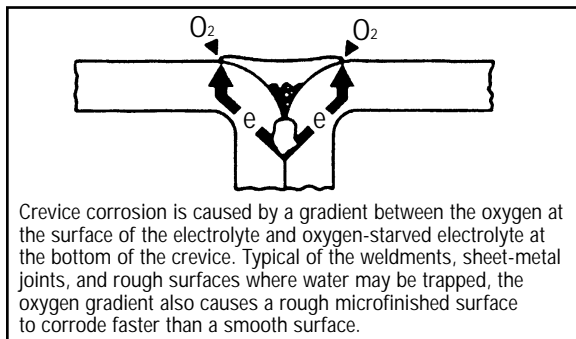


Figure 1.1 Crevice corrosion at weld joint.

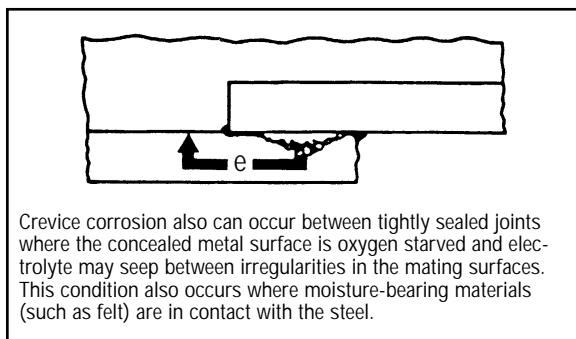


Figure 1.2 Crevice corrosion at lap joint.

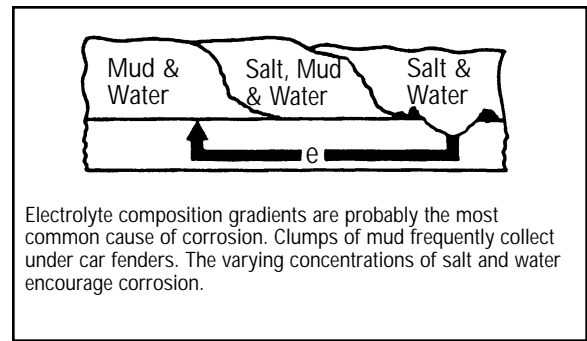


Figure 1.3 Crevice corrosion under poultrice.

There is disagreement among researchers regarding the mechanism governing crevice corrosion. One school of thought believes crevice corrosion is the result of differences in the metal ion or oxygen concentration within the crevice and on surrounding surfaces. Often, crevice corrosion is described as oxygen concentration cell corrosion, caused by oxygen availability at the surface of the electrolyte and oxygen starvation at the surface of the metal.

Other studies have shown that although metal ion and oxygen concentration differences exist, the corrosion mechanism is more complex and can be explained by acid formation within the crevice. Although oxygen is depleted in the crevice, metal dissolution continues because the excess of positively charged metal ions is balanced by the migration of anions (especially chloride ions) from the bulk solution into the crevice (Figure 1.4). The metal chloride concentration in the crevice increases. Hydrolysis of the metal chloride follows and the pH falls within the crevice, resulting in an autocatalytic anodic process.

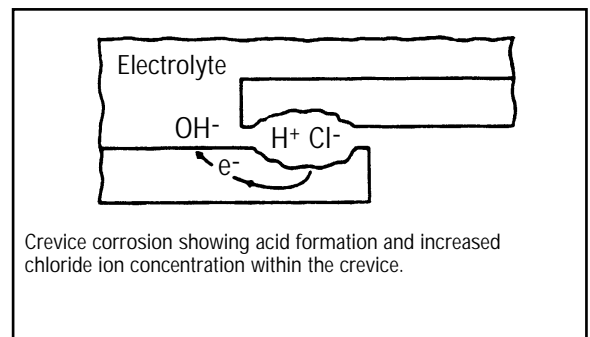


Figure 1.4 Crevice corrosion at lap joint.

Crevice corrosion remains a major problem because current vehicles have a multitude of box sections and joints. It is virtually impossible to eliminate the minute gaps between joined surfaces, which are the prime sites for crevice attack. The severity of crevice corrosion is evidenced by perforation of body panels and chassis components.

Much of the crevice corrosion problem is due to road debris trapped in pockets, corners, ledges, and on some vertical surfaces (Figure 1.5). These poultices hold salty electrolyte or moisture in intimate contact with the metal. The lack of run-off and thorough air-drying of the metal explains why vertical and upper surfaces (such as on fenders) frequently corrode.

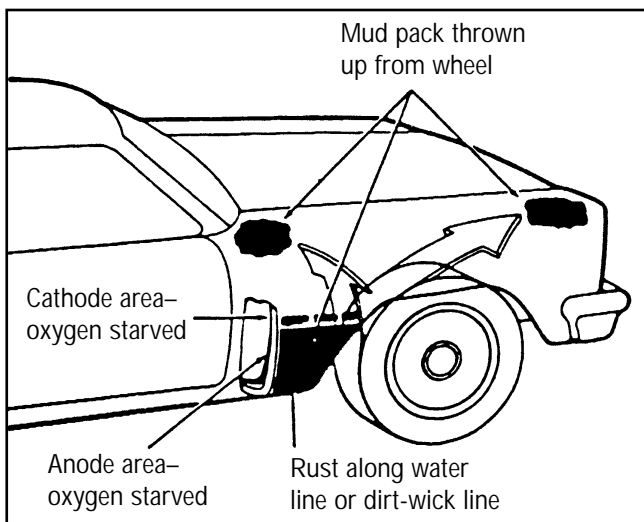


Figure 1.5 Mud packs.
Crevice corrosion caused by mud, leaves and other road debris packed against the under-side of fenders usually is undetected until perforation takes place. This form of corrosion also can occur along the upper edge of mud packs on vertical fender surfaces.

Plugging of drain holes is another cause of crevice corrosion. A damp poultice builds up in the lower interior of doors, rocker panels and tailgates, and perforation results.

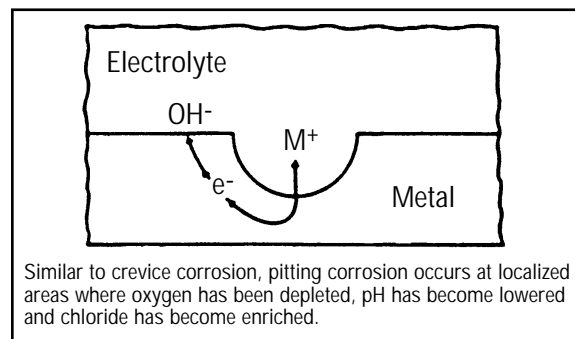
Some metals or alloys that rely on passive layers or oxide films for corrosion protection, for example, some aluminum and stainless steel alloys, are particularly susceptible to crevice attack in chloride media. The high concentration of chloride or hydrogen ions destroys the films, resulting in

increased metal dissolution rates. Aluminum and stainless steel can be specially alloyed to improve their crevice corrosion resistance.

An effective way to combat crevice corrosion is to minimize or eliminate crevices during the design stage. Once a vehicle is in service, proper maintenance to keep surfaces clean also helps control crevice corrosion.

1.3 Pitting Corrosion

Pitting corrosion is a localized attack, usually caused by chlorides. The mechanism governing pit growth is similar to that of crevice corrosion. In fact, pits are "mini" crevices which usually have diameters equal to their depth. They can occur so closely spaced that they give the appearance of a roughened surface. Pitting corrosion is a self-initiating form of crevice corrosion, in that the corrosion process creates the pit or crevice, which propagates at an accelerated rate and eventually perforates the metal. Initiation of pits usually results from non-homogeneity in the metal, breaks in protective films, surface deposits, defects or imperfections (Figure 1.6).



Similar to crevice corrosion, pitting corrosion occurs at localized areas where oxygen has been depleted, pH has become lowered and chloride has become enriched.

Figure 1.6 Pitting corrosion.

1.4 Galvanic Corrosion

Galvanic corrosion, also referred to as two-metal or bimetallic corrosion, occurs when dissimilar metals are in contact in the presence of an electrolyte. The more active, or anodic, metal corrodes rapidly while the more noble, or cathodic, metal is not damaged. On the galvanic scale, aluminum and zinc are more active than steel [Ref. 1.2] and, in the presence of a chloride-containing electrolyte, will corrode preferentially when in contact with steel (Figure 1.7).

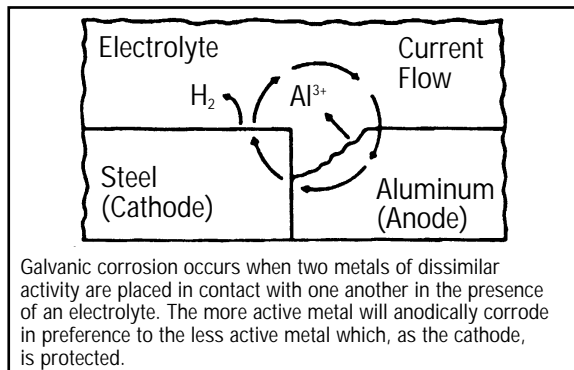


Figure 1.7 Galvanic or bimetallic corrosion.

If an aluminum automotive part is in direct contact with a steel part, the aluminum part will corrode. To prevent the galvanic corrosion of the aluminum, the aluminum and steel parts should be electrically separated by a non-conductive spacer or sealer.

The galvanic corrosion mechanism can be used beneficially. It is widely employed as the primary protection system for steel. A thin coating of zinc on steel will corrode preferentially, and this sacrificial action provides long-term protection for the steel substrate.

1.5 Cosmetic Corrosion

Corrosion that initiates on a visible surface of a vehicle, usually at nicks or scratches in the post-coating, is called cosmetic corrosion. Figure

1.8 shows some of the factors involved during the corrosion of painted cold rolled, zinc or zinc-alloy coated sheet steel at areas of localized paint damage.

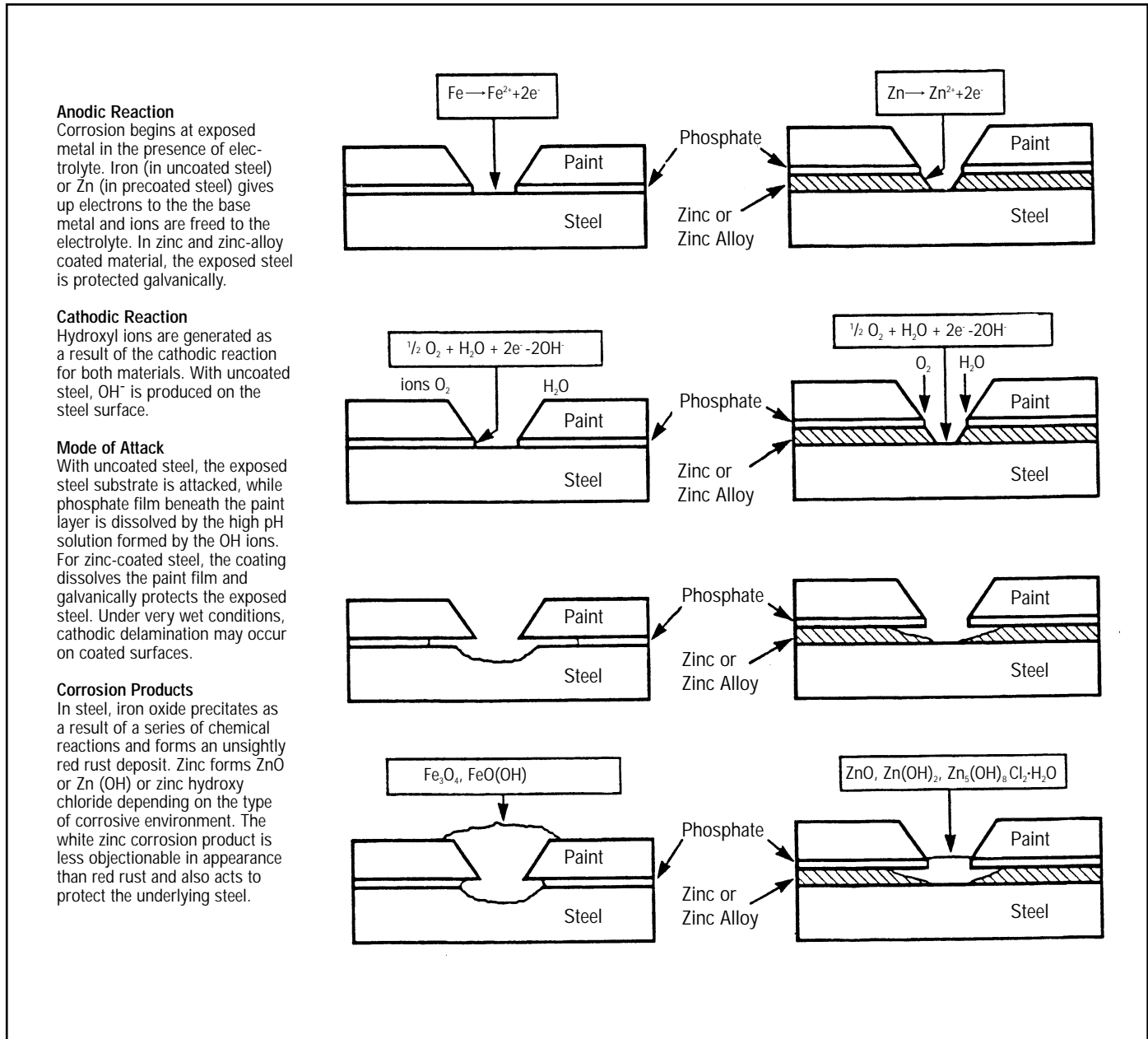


Figure 1.8 Corrosion processes at damaged paint site. Corrosion of steel at regions of paint damage is an electrochemical process. Metal is oxidized at anodic sites with the formation of electrons and ions. The electrons are transported through the metallic substrate to cathodic sites where they combine with water and oxygen to form hydroxyl ions. Zinc and zinc-alloy coated steels differ from uncoated steel in the locations of the anodic and cathodic sites, the mode of attack, and the corrosion products, as shown.

In the case of cold rolled sheet steel, exposure to wet conditions leads to anodic dissolution of the steel at the exposed area with the formation of unsightly red rust. Because water, oxygen and ions migrate through and under the paint film, a cathodic reaction takes place beneath the paint adjacent to the damaged region. Electrons flow through the steel to balance the separated anodic and cathodic reactions. The high pH solution that is developed at the steel/paint interface causes a loss of paint adhesion, which is termed cathodic disbonding. Depending upon the types of paint system, pre-treatment and substrate, cathodic disbonding can proceed by one or more of several possible mechanisms, including: (1) saponification of the paint resin, which is a degradation of the polymer by hydroxyl ions, (2) dissolution of the phosphate layer, or (3) reduction of an oxide layer on the metal surface. During subsequent exposure to drying conditions, oxygen becomes available for increased cathodic activity at the area of initial damage. This oxygen allows anodic dissolution to spread into the delaminated region, and leads to further attack by anodic undermining. The formation of a rust layer beneath the film may lead to further damage due to mechanical wedging.

Repeated exposure to wetting and drying cycles leads to a continuing attack on the steel substrate, formation of red corrosion products and a spreading loss of paint adhesion termed paint creepback. During initial stages of re-wetting, reduction of red corrosion products to magnetite [$\gamma\text{-FeO(OH)} \rightarrow \text{Fe}_3\text{O}_4$] may also contribute to the cathodic reaction [Ref. 1.3]. However, red rusting and paint creepback can usually be minimized by using a zinc or zinc-alloy coated steel substrate. For this reason, there has been widespread substitution in automotive bodies of zinc and zinc-alloy coated sheet steel for cold rolled sheet steel.

When a zinc or zinc-alloy coated sheet is used, the zinc coating corrodes preferentially as shown in Figure 1.8 on page 1-5. In doing so, the coating

acts as the anode in a galvanic couple and the exposed steel acts as the cathode. While the steel is thus protected, there is some loss of paint adhesion due to anodic undermining as the zinc coating is consumed. There may be further loss of adhesion in advance of the dissolution front due to cathodic disbonding.

Zinc ions, produced by dissolution of the coating, migrate to the exposed steel surface. There, they combine with hydroxyl ions from the cathodic reaction and form a white precipitate. The white precipitate is generally less objectionable in appearance than red rust. It also serves to inhibit the cathodic reaction in this region and slows the rate of zinc dissolution. Red rust will eventually develop on the exposed steel once the available zinc in the coating is consumed.

During intervals of dryness, both anodic and cathodic reactions are halted and the spread of paint damage is stopped. Thus, when dryness intervals are present, the degree of paint delamination for zinc and zinc-alloy coated steels exposed to actual service conditions is less than that for cold rolled steel. Further, with intervals of dryness, the oxides formed on coated steels are more protective in nature than the oxides formed on cold rolled steel.

It should be noted that when coated steel and cold rolled steel are tested under conditions of continual wetness, such as in a salt-spray test, results opposite to those experienced in the real world, where intervals of dryness are present, can occur. For example, constant wetness tests would indicate cold rolled sheet experiences less paint delamination than coated sheet. Constant wetness tests also obliterate the superior protection offered by the oxides on a coated sheet. For these reasons, constant wetness tests, such as the salt-spray test, should not be used to evaluate the corrosion resistance of body panels.

2.0 Steel Materials

Flat rolled steels are versatile materials. They provide strength and stiffness with favorable mass to cost ratios, and they allow high speed fabrication. In addition, they exhibit excellent corrosion resistance when coated, high energy absorption capacity, good fatigue properties, high work hardening rates, aging capability, and excellent paintability, which are required by automotive applications. These characteristics, plus the availability of high strength low alloy (HSLA) and alloy steels in a wide variety of sizes, strength levels, chemical compositions, surface finishes, with and without various organic and inorganic coatings, have made sheet steel the material of choice for the automotive industry.

Numerous steel grades, produced to precise specifications, offer the designer a wide range of mechanical properties. Low-carbon steels offer yield strengths up to 260 MPa (38 ksi), dent resistant steels offer yield strengths up to 280 MPa (40 ksi), high-strength steels offer yield strengths up to 830 MPa (120 ksi) and ultra high-strength steels offer tensile strengths up to 1500 MPa (215 ksi). Low-carbon steels have excellent ductility. They are widely used for underbody structural components that are formed by stamping or roll forming sheet steel and by hydroforming steel tubes. High-strength steels usually have less ductility than low-carbon steels. However, they can be supplied with sufficient formability for the production of stamped or roll formed underbody structural components. Ultra high-strength steels have less formability than high-strength steels. However, they are suitable for roll formed sections and less severe stampings. A listing of available low-carbon and high-strength steels, along with their typical properties, is given in Reference 2.1. A listing of ultra high-strength steels and their typical mechanical properties is given in Reference 2.2.

Manufacturers often select a steel grade based on minimum yield strength. For example, a frame manufacturer may select a hot rolled sheet with a minimum yield strength of 250 MPa (36 ksi). The frame manufacturer may also require that the grade selected meet a desired chemical composition.

2.1 Current Method for Specifying Low-Carbon Steel

A relatively new SAE document, J2329, "Categorization and Properties of Low-Carbon Automotive Sheet Steels" [Ref. 2.3], is increasing in acceptance. SAE J2329 classifies low-carbon sheet by five grade-levels, with yield strength, tensile strength, elongation, r_m and n-value requirements. The intent is to assure that certain minimum levels of strength and formability exist for each grade. The system employs four characters. The first two alphabetic characters designate hot rolled (HR) or cold rolled (CR) method of manufacture. The third numeric character defines the grade level (one through five) based on yield strength range, minimum tensile strength, minimum percent elongation, minimum r_m value, and minimum n-value. The fourth alphabetic character (E, U, R, F, N or M) classifies the steel type with regards to surface quality and/or aging character. An optional fifth character (C) may be used to restrict carbon content to a minimum of 0.015%. If the steel sheet is a metallic-coated product, then the coating would be specified in accordance with the soon to be issued SAE J1562 [Ref. 2.4]. An example of the above is HR2M 45A5AU, a hot rolled sheet, with Grade 2 mechanical properties and chemical composition, free of coil breaks and non-aging. It has an unexposed galvalume coating on each side of 45g/m² (0.15 oz/ft²).

2.2 Current Method for Specifying High-Strength and Ultra High-Strength Steel

High-strength steels were formerly specified in the automotive industry in accordance with SAE J1392 [Ref. 2.5]. However, SAE J1392 will be replaced by SAE J2340 [Ref. 2.6] early in the year 2000. In SAE J1392, up to six characters are used. The first three characters denote the minimum yield strength in kips per square inch (ksi). One kip equals 1000 pounds force (4.45N). The fourth alphabetical character denotes general chemical composition, the fifth denotes general carbon level and the sixth alphabetic character denotes deoxidation/sulfide inclusion control practice. For example, 050XLK is a steel grade having a minimum yield strength of 50 ksi (345 MPa) and a minimum tensile strength of 60 ksi (414 MPa), an HSLA composition, a carbon content of 0.13% maximum and it is produced to a killed (fine grain) practice. In addition to grade, it is necessary to specify whether the material is hot rolled sheet, cold rolled sheet, hot dip galvanized (hot rolled) sheet, hot dip galvanized (cold rolled) sheet, galvanneal (hot rolled) sheet, etc. For example, some full frames on light trucks have crossmembers made from 040XLK and 050XLK hot rolled sheets. Front rails on some passenger cars are made from 050XLF 45A45AU, which is a formable high-strength steel grade with an unexposed quality galvanneal coating of 45g/m² (0.15 oz/ft²) on each side.

At the present, there is no generally accepted standard for ultra high-strength steel grades. SAE J2340 [Ref. 2.6], which will be available early in the year 2000, will cover these grades. However, it is fairly common to specify ultra high-strength steel using numbers to express minimum yield or tensile strength and alphabetic characters to denote quality. For example, 120X is a microalloy steel having a minimum yield strength of 120 ksi (827 MPa). Grade 140T is dual phase steel with a minimum tensile strength of 140 ksi (965 MPa). The grade M130HT is a martensitic steel with a minimum tensile strength of 130 ksi (896 MPa). It should be noted that dual phase (T) and martensitic (M-HT) steels are specified using a minimum tensile strength (rather than a minimum yield strength, which is the prevalent practice for steel).

2.3 Former Methods for Specifying Low-Carbon Steel

A quality descriptor is the traditional method employed to specify low-carbon steel. A descriptor such as CQ (commercial quality), DQ (drawing quality) or DQSK (drawing quality special killed) is used to ensure that the steel possesses the essential characteristics for the application/manufacturing process. A descriptor basically defines steelmaking practice, degree of chemical segregation, uniformity of properties, surface quality, internal soundness, etc. In other words, the quality descriptor is the steel grade. However, it is also necessary for the specifier to state the material required, e.g., hot rolled sheet, cold rolled sheet, hot dip galvanized (hot rolled) sheet, hot dip galvanized (cold rolled sheet), galvanneal (hot rolled) sheet, etc. Many side rails and crossmembers in light truck frames are specified as CQ hot rolled sheet, DQ hot rolled sheet or DQSK hot rolled sheet. SAE J403 [Ref. 2.7] is another traditional method used to specify low-carbon steels.

SAE J403 uses a four-digit number to identify the chemical composition. The last two digits represent the nominal carbon content in hundredths of a percent. For example, SAE 1010 has a 0.10% nominal carbon content. Although no mechanical properties are specified, the chemical composition is. For example, SAE 1010 hot rolled sheet, which is used for some components in full vehicle frames, must satisfy the following composition requirements:

Carbon	- 0.08 to 0.13% by weight,
Manganese	- 0.30 to 0.60% by weight,
Phosphorous	- 0.040% maximum by weight and
Sulphur	- 0.050% maximum by weight.

3.0 Coatings

Underbody structural components are typically coated to provide a first line of defense against corrosion. For light truck frames, the two most common coatings are hot melt wax and electrocoat (E-coat). Paints are also used on current light truck frames. Conversion coatings enhance the adhesion of electrocoat or paint, and they are commonly used in conjunction with these two coating types. Many underbody structural components, such as front rails on passenger cars, are made from sheet steel pre-coated with a metallic coating, e.g., galvanized or galvanized sheet steel. Autophoretic and powder coatings are also used on underbody structural components.

3.1 Application Methods

The use of spray equipment to apply coatings is proven and well defined. Spray equipment acts upon a stream of coating (solvent or water borne particles) and by various means disperses the coating into a cloud of finely divided particles. The atomized particles are then deposited on the intended surface forming a protective or decorative coating.

Dip application is a method that involves dipping a part into a coating bath, draining the part, and force drying or baking the part. Dip coatings are often used for primer and one-coat applications.

Flow coating is an automatic coating operation in which the product to be coated is conveyed through a chamber equipped with low pressure nozzles that completely flood the product with a coating. The process does not involve any atomization. It is used for large articles that would require a dipping tank of impractical size and for articles with a shape that makes spray painting impractical.

3.2 Conversion Coatings

Phosphate conversion coatings are employed to enhance paint adhesion. By enhancing paint adhesion, they indirectly enhance corrosion resistance. There are several varieties of phosphate coatings, e.g., iron, zinc or manganese.

Prior to the application of a conversion coating, the metal surfaces must be free of shop soils, oil, grease, lubricants and rust. The metal surfaces must be receptive to the formation of a uniform, adherent chemical film or coating. Surfaces may be cleaned by mechanical methods or, more commonly, by immersion or spray cleaner systems.

A phosphate coating is applied by immersing a clean metal part in a hot processing solution for 4-6 minutes, depending on the bath chemistry. The weight (thickness) of the conversion coating is dependent upon the manner in which the part is cleaned, the immersion time, the composition of the processing bath and the chemical composition of the metal itself.

3.3 Hot Melt Wax Coatings

Hot melt wax coatings are thermoplastic corrosion prevention compounds. They have a solvent or waterborne formulation. Since the 1970's, hot melt waxes have been used extensively on underbody structural components to provide corrosion protection and enhance vehicle durability. Hot melt waxes are usually applied through a dipping process. The wax is preheated to a temperature between 125 and 195 degrees C (257 and 383 degrees F). Following an alkali cleaning and water rinsing operation, parts are immersed in the molten wax. The thickness of the wax deposited on the parts is controlled through a preheat of the parts prior to dipping and the actual time of immersion in the hot melt wax. Following the immersion process, the coated parts are allowed to return to ambient temperature through a process that controls the uniformity and finish of the hot melt wax. Hot melt wax thickness is commonly specified as 75-125 micrometers (3-5 mils). Typically, hot melt wax coatings can withstand temperatures up to 143 degrees C (290 degrees F) without dripping.

3.4 Electrocoat (E-coat)

Electrophoretic deposition is a process in which electrically charged particles are deposited out of a water suspension to coat a conductive part. The process is more commonly known as electrocoating or E-coating. The idea of electrically discharging polymers to coat an object was first considered in the 1930's. Most of the basic research was conducted in Europe in the 1960's. North American companies began electrocoating in the late 1960's, and the process has been widely used for coating metal parts ranging from simple stampings to complex auto bodies.

The process requires a coating tank in which to immerse the part, as well as temperature control, filtering and circulation equipment. Electrocoating systems are known as anodic or cathodic depending upon whether the part is the anode or cathode in the electrochemical process. Cathodic systems are more common since they require less surface preparation and provide better corrosion resistance.

Electrocoating requires that the coating binder, pigment and additives be given an electrical charge. These charged materials, under the influence of an electric field, migrate through water to the part surface.

Once at the part, the charged materials give up their charge due to neutralization by electrochemically generated OH^- ions (cathodic process). Upon giving up their charge, the coating materials drop out of the water suspension and coalesce as a coating on the part surfaces. Electrocoat thickness typically ranges from 10 to 30 micrometers (0.4 to 1.2 mils).

Automotive parts that are electrocoated usually receive a zinc or iron phosphate treatment prior to deposition. This treatment enhances the application of the E-coat.

3.5 Metallic Coatings

Various types of metallic coatings can be applied to ferrous and non-ferrous substrates to inhibit corrosion and/or provide a decorative finish. The choice of a particular coating material is dependent upon the severity of the corrosive environment, whether the part is subject to wear and abrasion,

and the degree of visibility of the part in service.

Four common methods for applying metallic coatings are:

- **Electroplating.** The coating is deposited onto the substrate metal by applying an electrical potential between the substrate metal (cathode) and a suitable anode in the presence of an electrolyte. The electrolyte usually consists of a water solution containing salt of the metal to be deposited and various other additions that contribute to the plating process.
- **Mechanical plating.** Finely divided metal powder is cold welded to the substrate by tumbling the part, metal powder and a suitable media such as glass beads, in an aqueous solution containing additional agents. Mechanical plating is commonly used to apply zinc or cadmium to small parts such as fasteners.
- **Electroless.** In this non-electric plating system, a coating metal, such as cobalt or nickel, is deposited on a substrate via a chemical reaction in the presence of a catalyst.
- **Hot dipping.** A coating metal is deposited on a substrate by immersing the substrate in a molten bath of the coating metal.

Many underbody structural components are manufactured from sheet steel with a metallic coating. The steel mills supply hot or cold rolled sheet in coil form with metallic coatings applied by either electroplating or hot dipping. The most commonly supplied coatings include zinc, zinc-iron, zinc-nickel, aluminum, aluminum-zinc, tin and lead-tin.

3.6 Organic Coatings

The application of an organic coating, such as paint, is a cost effective corrosion protection method. Organic coatings act as a barrier to a corrosive solution or electrolyte. They prevent, or retard, the transfer of electrochemical charge from the corrosive solution to the metal underneath the organic coating.

An organic coating is a complex mixture of materials designed to protect the substrate and to enhance appearance. A coating is composed of binders, carriers, pigments and additives. Binders provide the major properties to the coating while the carriers (solvents and/or water) adjust the viscosity of the coating for application. Pigments impart specific properties to a coating such as corrosion resistance and color. Furthermore, when formulating a coating, the type of pigment and its volume are critical to the optimization of properties such as adhesion, permeability, resistance to blistering and gloss. Additives include thickeners, flow agents, catalysts and inhibitors.

Coating systems are often identified by the type of polymers employed. Commonly used organic coatings are:

- Alkyd and epoxy ester coatings (air dried or baked to promote cross-link oxidation),
- Two-part coatings such as urethane coatings,
- Radiation curable coatings (acrylic and epoxy polymers),
- Latex coatings such as vinyl, acrylic or styrene polymer combinations,
- Water soluble coatings (versions of alkyd, epoxy ester or polyester coatings),
- High-solids coatings and
- Powder coatings (vinyl, polyester or epoxy polymers).

3.7 Autodeposition Coatings

Autodeposition is a waterborne process that depends on chemical reactions to achieve deposition. This process has been used commercially since 1973. The composition of an autodeposition bath includes a mildly acidic latex emulsion polymer, de-ionized water and proprietary ingredients. The chemical phenomenon consists of the mildly acidic bath attacking the steel parts being immersed and causing an immediate surface reaction that releases iron ions. These ions react with the latex in solution causing a deposition on the surface of the steel parts. The newly deposited organic film is adherent yet quite porous. Thus, the chemical activators can rapidly diffuse to reach the surface of the metal, allowing continued coating formation.

The coating thickness of the autodeposition film is time and temperature related. Initially, the deposition process is quite rapid, but slows down as the film begins to build or mature. As long as the part being coated is in the bath, the process will continue; however, the rate of deposition will decline. Typically, film thicknesses are controlled from 15 to 25 micrometers (0.6 to 0.8 mils).

Autodeposition will coat any metal the liquid touches. Parts that are tubular in shape, assembled parts or parts that have intricate designs can be coated by this process. Autodeposition does not require a phosphate stage and the coating is cured at a relatively low temperature.

3.8 Powder Coatings

In the powder coating process, a dry powder is applied to a clean surface. After application, the coated object is heated, fusing the powder into a smooth, continuous film. Powders are available in a wide range of chemical types, coating properties and colors. The most widely used types include acrylic, vinyl, epoxy, nylon, polyester and urethane. Modern application techniques for applying powders fall into four basic categories: fluidized bed process, electrostatic bed process, electrostatic spray process and plasma spray process.

The electrostatic spray process is the most commonly used method of applying powders. In this process, the electrically conductive and grounded object is sprayed with charged, non-conducting powder particles. The charged particles are attracted to the substrate and cling to it. Oven heat then fuses the particles into a smooth continuous film. Coating thicknesses in the range of 25 to 125 micrometers (1 to 5 mils) are obtained. Controlling a low film thickness is difficult. A booth and collection system can be used to collect overspray for re-use.

4.0 Manufacturing Processes

A vehicle underbody is an assembly of components. The processes used to manufacture the components, and the methods used to join the components together, have a significant impact on the corrosion resistance of an underbody. Thus, it is important to have a basic understanding of manufacturing processes and joining methods.

4.1. Forming

The common processes used to convert sheet steel into an underbody component are:

- Stamping,
- Roll Forming,
- Brake Pressing,
- Hydroforming and
- Simulforming.

4.1.1. Stamping

Stamping is, by far, the most common method used to form structural underbody components. The basic stamping operation utilizes a two-piece die set inserted into a mechanical or hydraulic press. Material placed between the two dies is formed into a part by the load imposed by the press. Typically, the material being formed by the dies is held along the edges of the part by a binder. The binder controls the flow of material into the dies and is critical to the outcome of the finished part.

Most parts require several operations, each one involving a separate press and die set, to produce a final part. A typical stamping line would consist of a press with a die set to form a blank for the part, a press with a forming die set to produce a first stage shape, a press with a re-strike die set to add form to the first stage shape, a press with a piercing die set to place holes in the part and a press with a trimming die set to remove unwanted metal from the formed part. Depending on the complexity of the part, some of these operations can be combined or even eliminated.

The many factors that affect the ability to successfully stamp a part include:

- Part radii (larger radii allow the material to flow more easily),
- Blank shape,
- Binder design,
- Order of stamping operations,
- Methods of inducing form into the part,
- Selection of lubricants,
- Alignment of dies in the press and
- Maintenance of dies.

There are few limits as to the shapes that can be achieved through stamping. However, the number of operations increases, along with tooling and overhead costs, as part complexity increases.

4.1.2 Roll Forming

Cold roll forming is an ideal, low cost method of producing shapes with a uniform cross-section. A sheet or strip of metal is fed longitudinally through a roll forming mill. The mill consists of a train of pairs of driven roller dies, which progressively form the flat strip until the finished shape is produced.

The number of pairs of rolls depends on the type of material being formed, the complexity of the shape being produced and the design of the particular mill being used. A conventional roll forming mill may have as many as 30 pairs of roller dies mounted on individually driven horizontal shafts.

In roll forming, metal thickness is not changed except for a slight thinning at the bend radii. In addition, a roll formed section has lower internal stresses than the same section formed by stamping.

The roll forming process is particularly suited to the production of long lengths of shapes such as hat sections, C-sections, L-sections, Z-sections and box sections. Operations such as notching, slotting, punching, embossing, welding and longitudinal curving can be incorporated into a roll forming line to produce finished parts off the exit end of the roll forming mill. The welded tubing used in the hydroform process comes off a roll forming mill.

4.1.3 Brake Pressing

Brake pressing is a simple forming method. It involves only pure bending along straight lines. A brake press, with a set of dies, is used to place one or more parallel bends in a sheet of metal. For complex shapes, more than one set of dies is often required to achieve the final shape. Brake pressing is used to produce sections with a constant cross-section such as hat sections, C-sections, L-sections and Z-sections. The maximum length of section that can be produced is determined by the width of the brake press. Brake pressing is very economical for low volume parts. At high volumes, roll forming becomes more economical than brake pressing.

4.1.4 Hydroforming

There are two types of hydroforming - sheet and tubular. Sheet hydroforming is typically a process where only a female die is constructed and a bladder serves as the punch. High pressure water forces the bladder against a metal sheet until the sheet takes the form of the female die. Sheet hydroforming is used to produce low volume, large parts such as aircraft and bus panels.

In tubular hydroforming, a straight or pre-bent aluminum or steel tube is laid into a lower die. An upper die is then clamped onto the lower die. Next, conical nozzles are inserted and clamped into each end of the tube. Finally, water is forced at a high pressure into the tube until it takes the shape of the dies. The pressure on the tube inner wall is in the range of 2000-6000 bars. Higher pressures are used to create more complex, variable cross-section designs or to punch holes in the tube with tool inserts. If there are large changes in cross-section (15-25%), a multi-stage hydroform process may be required. In this process, an annealing stage between hydroform stations is required to permit the metal to continue to flow without failure.

Hydroforming is rapidly being adopted for structural underbody components because it offers weight and cost savings. It permits part consolidation and the elimination of engineered scrap. Box sections, consisting of two hat sections welded together, lend themselves to cost-effective

replacement by a single hydroformed part. Holes may be punched into the part during hydroforming, eliminating subsequent machine operations.

The structural integrity of a hydroformed part, made from a single continuous tube, is superior to a part made from two or more components. Weight savings of 10-20% can be achieved by reducing thickness and eliminating weld flanges.

4.1.5 Simulforming

Simulforming is a process whereby multiple components of an assembly are formed and joined in the same tool at the same time. A mechanical lock is created between mating components, thereby reducing or eliminating the need for welding. Also, simulforming results in stiff structural joints.

Simulforming reduces the cost of assembly tooling and overhead. However, depending on the application, some of the savings may be offset by the increased complexity of the simulforming operation.

4.2 Joining

The common methods used to join steel underbody components are:

- Welding,
- Mechanical fastening and
- Adhesive bonding.

4.2.1 Welding

Welding is the most common method for joining automotive components. Several types of welding are employed:

- Metal inert gas (MIG),
- Resistance (including spot),
- Laser and
- Friction.

MIG welding is used primarily on heavier gage structural underbody components. MIG welds provide a stiff, continuous joint and a more

uniform stress distribution than intermittent spot welds. In MIG welding, an electrical path is created between the workpiece and a weld wire. The wire is continuously feed through the welding tip along with a shielding gas such as carbon dioxide or argon. The weld wire, and the melted surfaces of the mating components, forms a weld fillet. It is important to maintain the proper welding speed. Too much time at a location can result in burn-through (i.e., a hole). Too little time at a location may result in a lack of penetration (i.e., a weak weld).

Spot welding is commonly used to assemble lighter gage components. It is widely used to assemble body panels, bumpers and bodies-in-white. Its main advantages are speed and low cost. A weld gun with two weld tips (electrodes) clamps together the metal sheets to be joined. Sufficient clamping force is required to ensure that a good electrical path is created from one weld tip, through the metal sheets, to the opposite weld tip. When an electrical current passes from one tip to the other, the metal between the tips melts and the clamping force causes fusion. The result is a nugget called a spot weld. The welding process is controlled by a weld schedule (a prescribed set of electrical pulses for sending the current through the metal).

Mash seam welding is a continuous form of resistance welding. The edges of two metal sheets are slightly overlapped and then fed between two roller-electrodes. The rollers melt and "mash" the two edges together to form a seam. This process is used to manufacture steel fuel tanks and tailor welded blanks.

Laser welding is finding increased usage in the North American automotive industry. It is mostly used to butt weld two sheets together. In order to achieve a sound weld, the sheets must have accurately trimmed edges. An advantage associated with a laser weld is the very small heat affected zone adjacent to the weld. Residual stresses induced by welding can lower the durability of an assembly. By keeping the size of the heat affected zone small, the effects of residual stresses are minimized. One prominent application for laser welding is tailor welded blanks.

Friction welding receives limited use in the automotive industry. As its name implies, this welding process uses the heat of friction to weld two pieces together. Generally, one of the pieces must be cylindrical to allow it to be rotated at high speed. Once it is brought up to speed, it is forced into the mating piece. The frictional energy created fuses the two pieces together.

4.2.2 Mechanical Fastening

Joining with fasteners, such as rivets, bolts or screws, is very common in the automotive industry. Such joints have very little effect on the mechanical properties of the joined parts. Thus, the assembly has good durability. Often, fasteners are used in conjunction with welding to improve the durability of what would otherwise be an all-welded assembly.

Another advantage of mechanical fastening is that joints can be disassembled readily. This feature facilitates repair work and recycling at the end of a vehicle's life.

Generally, mechanically fastened joints are more expensive than welded joints due to the cost of the fasteners. Further, mechanically fastened joints are usually less stiff and heavier than welded joints.

4.2.3 Adhesive Bonding

Adhesive bonding is now being used within the North American automotive industry. A typical use is the bonding of metal reinforcements to metal closure panels such as hoods. Adhesive bonding allows the show surface of a closure panel to be preserved.

Adhesives capable of carrying significant structural loads are slowly finding their way into the automotive industry. They have the ability to distribute a load over a large area, thereby increasing joint stiffness and durability.

In order to achieve a strong joint, the surfaces to be bonded must be extremely clean. Alternatively, the adhesive selected must be fully compatible with any pre-treatment or forming lubricants which may be on the surfaces to be bonded.

A disadvantage of adhesives is the fact they tend to fracture under severe impacts.

Furthermore, repeated impacts can cause disbonding. These concerns can be mitigated by using welds in conjunction with an adhesive (weld bonding). Often, some welds or fasteners are required to maintain dimensional integrity while the adhesive cures.

5.0 Design Considerations

During the component design process, an important consideration is access and drainage for the post-fabrication coatings. Often, openings must be placed in a component for this purpose. It is important that these openings be strategically located in order to preserve structural integrity.

A current design trend for side rails (and in some cases crossmembers) is the use of closed sections. Furthermore, there is a trend to producing these closed sections by the hydroforming process. Closed sections present more of a challenge, relative to open sections, when applying coatings for corrosion protection.

When applying electrocoat (E-coat) to a closed section, the coating distribution (throw) and thickness need to be considered. E-coating lacks the ability to throw a coating into a long, closed section. As a result, the inside of a closed section will have a thinner coating thickness than the outside of the section. One approach to overcoming this problem is to pierce holes along the length of the closed section to allow the coating to enter the inside of the section. The coating achieved depends on the location, size and frequency of the holes.

Openings (such as holes) are also required in a closed section that is to be coated with hot melt wax. The openings permit the entry of the wax during dipping and the draining of the wax after dipping. An open section, depending on the position of the section after dipping, may also require holes for draining the wax.

The application of powder coatings, similar to the application of E-coat and wax, requires openings in a closed section to ensure the inside of the section is properly coated.

The joints in an underbody structural assembly are readily coated, whether they be welded or mechanically fastened. However, joints must be properly cleaned to allow coating adhesion. In addition, the coating must be able to access the joints during the coating process.

6.0 Test Methods and Evaluation

6.1 Purpose of Testing and Types of Corrosion Tests

The selection of materials for underbody applications should be made after carefully evaluating the results from corrosion testing. Corrosion tests should simulate service conditions as closely as possible.

The major purposes of testing are:

- Selection of materials for a given application,
- Evaluation of new materials or coatings to determine their suitability for service,
- Quality control and
- Investigation of corrosion mechanisms.

The type of test and specimen geometry are generally determined by the purpose of the testing. Tests can be divided into two broad classes: accelerated laboratory tests and field service tests. Laboratory tests may include the testing of small coupon specimens or the testing of a fully assembled component. Field tests may include the testing of specimens attached to vehicles subjected to field service conditions or the assessment of a component on vehicles that have been subjected to a specified length of field service.

6.2 Test Specimens

The selection of appropriate test specimens is of major importance. The size and geometry of specimens vary, depending on the corrosion mechanism of interest, the corrosion test selected and the availability of test material. When testing, material representative of that being evaluated should be obtained and test pieces cut from it. Pieces with a smaller surface area facilitate accurate weighing and measuring of dimensions. Therefore, smaller surface area pieces are preferable when evaluating mass loss by uniform corrosion. Pieces with a larger surface area are more suitable for studying pitting corrosion because of the probabilistic nature of pit initiation on a surface. To properly evaluate crevice

corrosion, it is essential to use specimens with a well defined crevice geometry. Galvanic effects are evaluated by using test specimens that emulate the type, geometry and method of joining (including any galvanic insulation) of the dissimilar metals used in the actual component under consideration.

Specimens should be prepared in order to obtain the desired surface condition. Examples of specimens with different surface conditions include bare panels, panels with a metallic or an inorganic conversion coating, and painted panels. Occasionally, special steps (such as masking or painting) are needed to isolate the test area from the surrounding surface area. Crevice test specimens are often prepared in this manner.

6.3 Corrosion Testing

Accelerated laboratory tests are conducted on test specimens in a test chamber. The specimens are supported on non-conductive racks, using insulated fasteners when necessary. A variety of test chambers are commercially available to produce warm or ambient temperatures, and humid or dry conditions. Test conditions may also include exposure to a salt solution through spraying or immersion. Several of these conditions are combined and repeated at regular intervals in a cyclic corrosion test [Ref. 6.2.] Cyclic tests can be carried out manually, or they can be fully automated. Generally, the original equipment manufacturer (OEM) specifies the laboratory corrosion tests required to qualify a material for an automotive application.

SAE J2334 [Ref. 6.2] is a cyclic test designed to evaluate the cosmetic corrosion resistance of exposed autobody panels. This test has shown a high degree of correlation with field service conditions at selected sites in North America. It is currently being assessed as to its applicability to crevice corrosion and perforation. The applicability of SAE J2334, or any other laboratory test, should be fully reviewed before using it to predict the perforation performance of underbody structural components.

Field service tests are conducted using vehicles at a proving ground or in actual service. Test specimens can be mounted under the vehicles [Ref. 6.3 through Ref. 6.5]. The test specimens are removed after a specified interval and evaluated. Alternatively, rather than using test specimens, the actual component being evaluated can be examined at specified intervals.

6.4 Evaluation of Test Specimens

One of the most important steps when evaluating the performance of a material subjected to a corrosion test is a visual inspection of the specimens at the end of the test. A visual inspection can provide valuable information about the causes and mechanisms of the corrosion involved. Following visual inspection, and photographic recording when necessary, the specimens are cleaned to remove the corrosion products. Cleaning may use physical methods (such as scrubbing, brushing, sandblasting or air blow-off) or chemical/ electrochemical methods. Quantitative assessment of corrosion damage requires that the test specimens be thoroughly clean.

The effects of corrosion are expressed in a number of ways. The loss of metal from uniform corrosion is often expressed as mass loss per unit area over a given period of time (e.g., milligrams per square decimeter per day (mdd) or ounces per square foot per day). However, the thinning of a structural piece by uniform corrosion is better expressed in terms that can be used directly to predict the life of a given component, e.g., millimeters per year or mils per year (mpy). Corrosion rates are calculated using the loss in mass of a specimen. The density of the metal, the area of the test specimen and the duration of the test are taken into account when converting mass loss into corrosion rates.

Crevice corrosion and perforation are very important when designing and selecting materials for underbody structural components. For such components, thickness loss due to uniform corrosion is of lesser importance than crevice corrosion and perforation. A number of cyclic tests are available to determine the resistance of materials to crevice corrosion and perforation. These tests are designed to simulate the effects of field conditions of automotive service, including wet and dry environments, and exposure to de-icing salts during winter months.

Pitting corrosion that can lead to perforation is expressed as pit depth. Pitting generally occurs in crevices and under corrosion product deposits. Mass loss is of little value when assessing this type of corrosion. Pit depth is usually measured by microscopic methods or by using mechanical devices. Results are reported in terms of maximum pit depth, number of pits per unit area, average pit depth or average of a selected number of the deepest pits.

A different approach is used to evaluate cosmetic corrosion, which is an important type of corrosion for painted body panels. Prior to testing, mechanical damage is introduced to painted test specimens by a cutting tool or by blasting the tests specimens with steel shot or stones. A scribe mark produced with a cutting tool is generally required to penetrate through the paint and precoat layers into the base steel. After testing, paint delamination around the intentionally induced damage in the paint is measured to determine the corrosion resistance of the painted material. The paint delamination, in the case of a scribe mark, is measured in terms of the width of paint creep-back from the scribe mark. If paint damage is caused by blasting with steel shot or stones, delamination is expressed in terms of percent area of paint loss.

7.0 Auto/Steel Partnership Corrosion Testing

7.1 Base Case

In order to obtain a relative ranking of the corrosion resistance of steel materials for underbody structural components, the Auto/Steel Partnership is conducting laboratory tests at ACT Laboratories, Inc. in Hillsdale, MI. Eight materials are being tested in the as-delivered (i.e., without post-coatings) condition. The sheet steel materials are:

- 1010 Hot Rolled,
- 1008 Galvanneal 45A45A,
- 1008 Hot Dip Galvanized G60,
- Hot Dip Galvanized G90,
- 350 MPa Hot Rolled,
- T1-25 Aluminized,
- 409 High Chrome Hot Rolled and
- 700 MPa NUCu Hot Rolled.

The 1010, 1008 and 350 MPa materials are all commonly used to manufacture current underbody structural components. The T1-25, 409 and 700 MPa materials have been included because of their potential to offer improved corrosion resistance. The T1-25 and 409 materials are in current production. The 700 MPa NUCu material is currently under development at Northwestern University in Chicago, IL. With 1.60% Cu and 0.90% Ni, it has excellent atmospheric corrosion resistance and may prove useful for underbody components.

The SAE J2334 Lab Test Cycle (Figure 7.1) is being used to determine the relative perforation resistance and the relative weight loss of the eight test materials. A detailed description of this test method is given in Reference 6.2. Perforation resistance is being evaluated using the specimen geometry shown in Figure 7.2. Three sets of specimens are being tested. After 40 SAE J2334 cycles, one set of specimens is removed from the test cabinet and pit depths are measured. Pit depths on the second set are measured after 80 cycles and on the third set after 160 cycles.

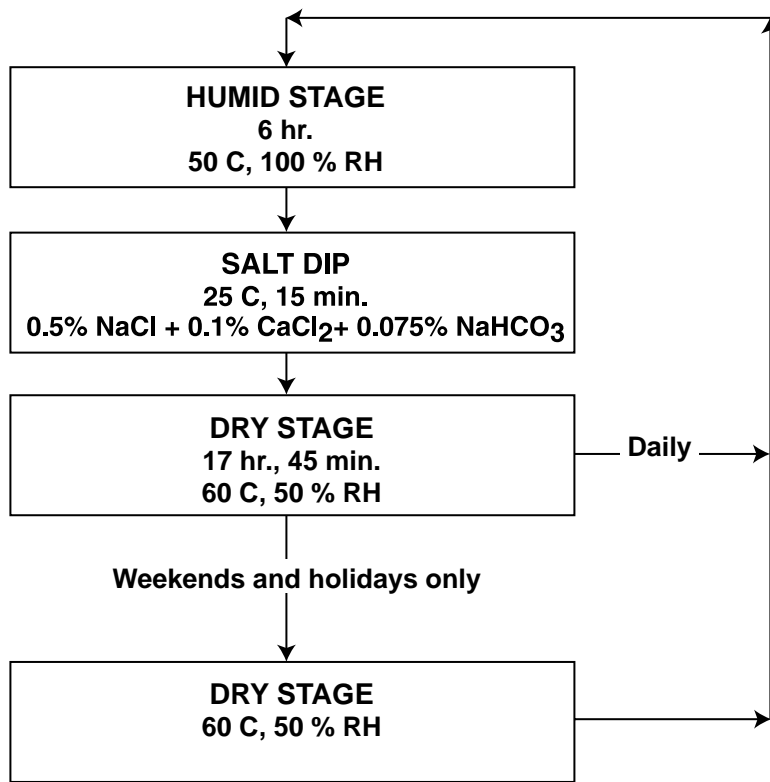


Figure 7.1 SAE J2334 Lab Test Cycle

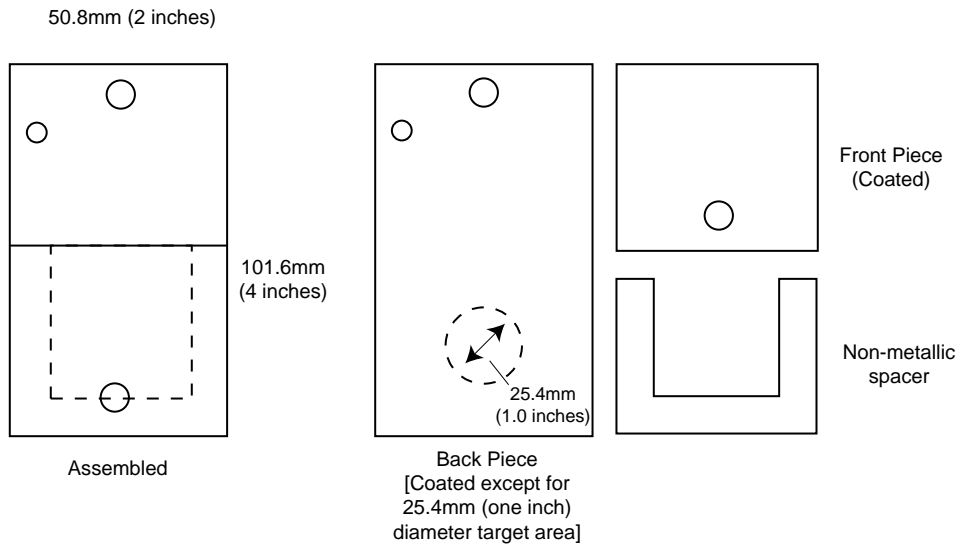


Figure 7.2 Perforation Specimen

Weight loss is being determined using the specimen geometry shown in Figure 7.3. Again, three sets of specimens are being tested. After 40 SAE J2334 cycles, one set is removed and each specimen weighed to determine weight loss. The

weight loss on the second set of specimens is determined after 80 cycles and on the third set after 160 cycles.

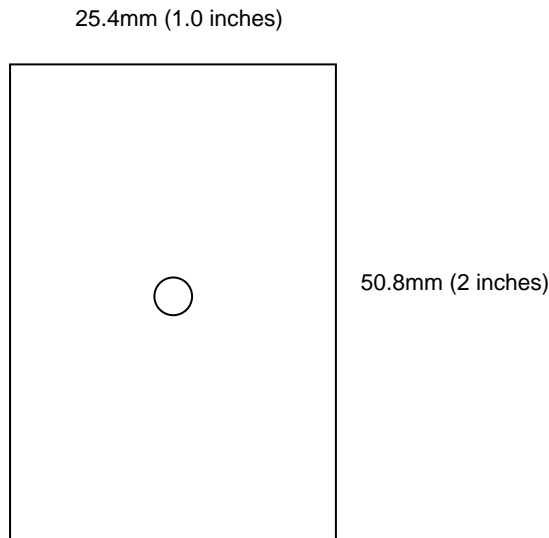


Figure 7.3 Weight Loss Specimen

It is anticipated that the Auto/Steel Partnership's base case corrosion testing will be completed in early 2000. Following analysis by the Light Truck Frame Project Team, the results will be issued as a revision to this publication.

7.2 Coated Case

The Auto/Steel Partnership is also evaluating the relative performance of post-coatings applied to the base steel materials used for underbody structural components. The coatings under evaluation are shown in Table 7.1.

Coating	Manufacturer
Conventional Wax	Henkel Thiemelt 89-5200 Daubert 1200
High Temperature Wax	Henkel Thiemelt 89-5260HT Daubert 1280HT
Electrocoat	PPG CR 590-CP 534
Polymer	Sentry Paint Alkyd Enamel
Autodepositon	Henkel Autophoretic 800

Table 7.1 Pre-Coating For Underbody Structural Components

Three tests are being used to evaluate the post-coatings:

- **SAE J2334.** The seven coatings are being tested in triplicate up to 80 cycles. A cycle is defined in Figure 7.1. The specimens are made from SAE 1010 hot rolled sheet, 2.54mm (0.100 inches) thick. Each specimen is a 101.6mm x 304.8mm (4 inches x 12 inches) rectangle, diagonally scribed after the coating has been applied. After every ten SAE J2334 cycles, the specimens are evaluated.
- **SAE J2334 Modified.** The specimens are identical to those described above for the SAE J2334 test. The SAE J2334 cycle, outlined in Figure 7.1, is being used. However, after every ten cycles, the specimens receive a bake and shot blast. One set of specimens (the seven coatings in triplicate) are baked for

30 minutes at 149 degrees C (300 degrees F). After two hours at ambient temperature, the specimens are shot blasted and then subjected to another ten SAE J2334 cycles. A second and third set of specimens (in triplicate) are tested using the same procedure except the bake temperatures are 121 and 93 degrees C (250 and 200 degrees F) respectively. The specimens are evaluated after every ten SAE J2334 cycles. Testing is continued up to 80 cycles if appropriate.

- **General Motors Corporation Trailer Test.** Panels, with the seven coatings, are mounted directly behind the wheels on a trailer. The panels are identical to those described above for the J2334 test. The trailer and panels are pulled over gravel roads (stone chipping) and through a salt splash facility (salt application). The panels are also exposed, in a booth, to high temperature/high humidity soaks. The stone chipping severity in the test is roughly representative of average customer usage in a rural environment. The test continues for ten cycles. Each cycle takes 24 hours to complete and has three phases:
 - an eight hour road test plus ambient temperature soak,
 - an eight hour booth soak and
 - an eight hour ambient temperature soak/dry off.

ACT Laboratories, Inc. is conducting the SAE J2334 and SAE J2334 Modified tests. General Motors is conducting the Trailer Test at its Milford, MI Proving Grounds. It is anticipated the coated case corrosion testing will be completed early in 2000. Following analysis by the Light Truck Frame Project Team, the results will be issued as a revision to this publication.

8.0 Lessons Learned - Review Questions

The following lists of questions may be used as checklists to ensure that corrosion concerns are properly addressed. The lists are based on "lessons learned" with respect to material, design, processing, testing and environmental exposure. While not all-inclusive, if the questions are addressed early in the development of an underbody structural component, the chances of success are greatly increased. If material, design, processing and test engineering groups pursue these questions individually as well as across disciplines, optimized component corrosion retarding will result.

8.1 Material Issues

1. Has the substrate material selection process included corrosion resistance as a criterion?
2. What are the corrosion mechanisms to which the substrate material will be subjected?
3. Are there any unique properties associated with the substrate material that make it susceptible to specific corrosion mechanisms (e.g., higher carbon content and hardness typically result in a material being susceptible to stress corrosion cracking and embrittlement)?
4. Has the substrate material been used in other applications? Were these applications successful? Can the successful applications serve as a benchmark?
5. Will the substrate material be coated? Will the coating be applied prior to fabrication or after fabrication? What type of coating will be used (e.g., metallic, wax, paint, E-coat, etc.)?
6. Is the coating selected susceptible to any unique corrosion mechanisms?
7. What factors other than the corrosion process might affect corrosion resistance (e.g., chip resistance, heat resistance, dirt retention, ozone degradation, etc.)?

8.2 Design Issues

1. Does the design selected result in the component, or specific areas of the component, being susceptible to particular forms of corrosion (e.g., crevice corrosion, galvanic corrosion, etc.)?
2. Has the design selected (or specific portions of the design) been utilized before? If so, are "lessons learned" readily available for review? Has a benchmarking study been conducted for previous, similar designs?
3. Does the design selected facilitate proper processing?
4. If E-coating is used, are adequate processing holes provided for current flow, and material access and egress? (For current flow, 25mm diameter holes are typically spaced every 300mm).
5. Does the design selected allow materials (e.g., phosphates, paints, waxes, etc.) to drain properly between process stages and/or at the end of the process?
6. Are drain holes shielded or oriented to avoid direct road splash? Are the number, size and location of the drain holes adequate to provide drainage of any contaminates?
7. Have poultice (mud, debris, etc.) traps been identified and minimized?
8. Are ample air escapes (bleed holes) provided for closed sections during processing? Are these bleed holes oriented such that they complement the intended process (e.g., to minimize air bubble size and location)?
9. Have the number of joints and exposed seams in the design selected been minimized?
10. Have stone impingement areas been eliminated or minimized?

8.3 Processing Issues

1. Does the design dictate specific processing techniques (e.g., if adequate E-coat processing holes cannot be provided because they reduce component strength, then must a wax, paint or autophoretic coating be used)?
2. Has the proposed processing technique been utilized before? If so, how does it impact corrosion resistance?
3. What impact will fabrication processes have on pre-coated material or coatings applied after fabrication? Will fabrication damage pre-coated material? Does any fabrication process create hard to clean areas?
4. Does any fabrication process leave behind processing fluids or contaminants that are incompatible with a post-coating process?
5. Has the coating process been optimized to assist in coating coverage (e.g., proper attitude of parts during the process, porpoising of frames as they proceed through tanks of paint or wax, etc.)?

8.4 Testing/Environmental Exposure Issues

1. Have corrosion validation tests been conducted on all components and sub-systems of an assembly? (A laboratory cyclic corrosion test is highly recommended. It should be modified to cover other factors such as cyclic stress, if relevant.)
2. What is the intended service life? Is the test selected to evaluate corrosion resistance appropriate for this length of service?
3. What are the in-service environmental conditions (e.g., high temperature, stone chipping, road splash, road poultice)? Have all of these environmental conditions been incorporated into a comprehensive validation plan? Has each condition been investigated individually as well as in combination with the other conditions?
4. Are specific design or material requirements dictated by the potential field environment?
5. Does customer use/maintenance have an impact on component performance (e.g., frequent underbody washing, compatibility with engine fluids, etc.)?

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Stelco Inc.
U.S. Steel Group, a Unit of USX Corporation
WCI Steel, Inc.
Weirton Steel Corporation



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