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# the Conduit

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INSIDE THIS ISSUE:



# HYDROGEN EMBRITTLEMENT IN WIRE ROPES

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## Introduction

Wire ropes are used in a variety of industries: oil and gas, pulp and paper, transportation, among others. They are critical in carrying out day to day operations such as lifting heavy equipment, moving logs, in drilling operations, etc., and due to the magnitude of the load that some of these wire ropes handle, safety is extremely important. A faulty wire rope, besides causing costly damage, may cost people's lives.

While there are many damage mechanisms that can affect the integrity of wire rope, hydrogen embrittlement is particularly critical. This article will address hydrogen embrittlement in wire ropes, how it happens, and how it can be prevented. A case study is then presented to illustrate the damage characteristics. A brief description of wire rope manufacturing is also provided, along with methods of detection and ways to avoid hydrogen embrittlement.

## Manufacturing of Lifting Cables

The manufacturing of wire rope starts with a steel ingot, which goes through several rolling stages until a wire rod is delivered to the wire manufacturing company. This wire rod then is drawn into the desired size. Once the desired diameter is reached, then the wire is baked and cleaned with acids to remove the scale that was formed during the hot rolling process. If cold drawing was used instead of hot rollers, then the cleaning step might differ from the hot rolling process, but it is still cleaned to remove any contaminants present on the

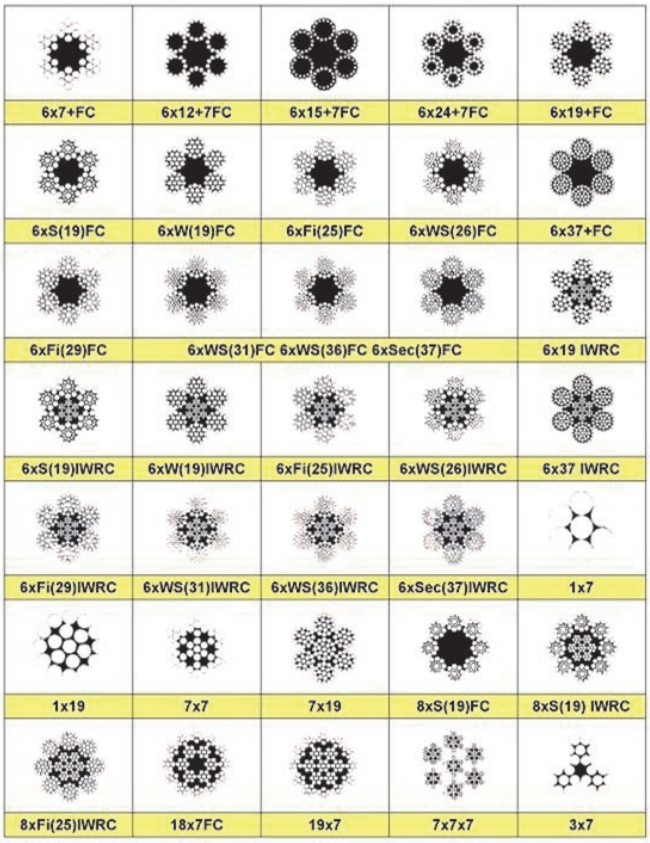


**Figure 1. Wire rope configurations (courtesy of dawson-group.com)**

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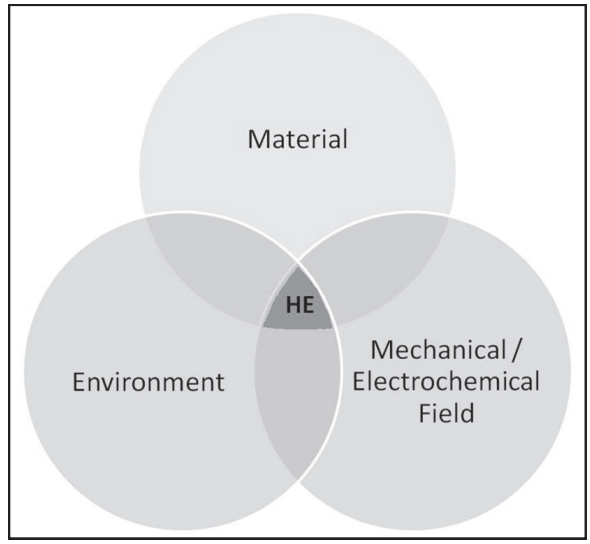
metal surface. In wire rope manufacturing, usually the individual wires are cleaned with hydrochloric acid (HCl). After the cleaning step, the wires are heat treated and annealed to achieve the desired mechanical properties, and an additional cleaning step might be added. Some manufacturers apply a corrosion inhibitor to prevent the wire strand from rusting while it awaits its final destination, whether to another processing plant or to the facility where the wire rope will be manufactured.

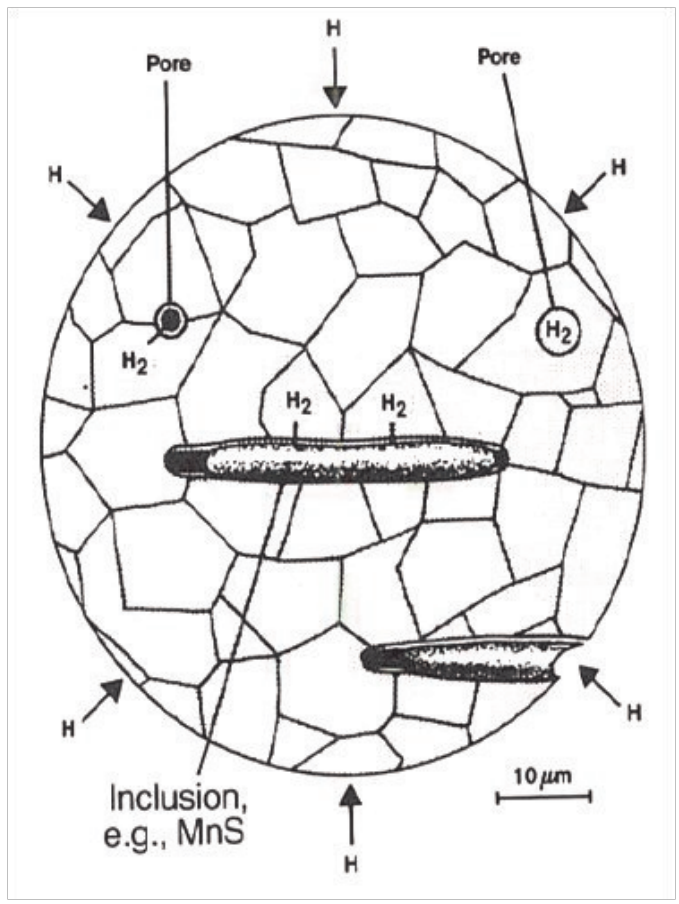
After cleaning and heat treating, the individual wires go through a plating process, where a metallic coating (usually zinc or nickel) is applied to the base metal through electrodeposition. An electric current is applied in an acidic bath where the cathode (or anode) is the coating material. This process is called electrodeposition. After electrodepositing the wires, the wires are then cleaned and rinsed, and the excess zinc (or coating) material is removed. The cleaning step that involves hydrochloric acid (HCl) is very critical and will be explained later in this article. The final step involves the plated drawn wires going through a babbit. The babbit strands and twists the wire into the final wire rope finished product. Several wire rope configurations are available as shown in Figure 1.

### Hydrogen Embrittlement Mechanism

Hydrogen embrittlement can occur when a part is exposed to hydrogen atoms, usually as the result of a chemical reaction where $H^+$ is evolved. The process involves hydrogen migrating towards the grain boundaries of the material. This causes the grain boundaries to become brittle and weak. In order for hydrogen embrittlement to occur, three conditions are needed: a hydrogen source, a material susceptible to hydrogen embrittlement, and a tensile stress (Figure 2). Materials susceptible to hydrogen embrittlement include steels with high hardness, typically above 30 HRC.

In wire rope manufacturing, the cleaning step is very important. If wires are not cleaned properly, the hydrogen from the HCl residues might diffuse into the base metal of the wire. Additionally, if the HCl residues are still present during the zinc electrodeposition step, the hydrogen migration will be aggravated and the hydrogen atoms will diffuse faster (Equation 1).




**HE—Hydrogen Embrittlement**

**Figure 2. The hydrogen molecule diffuses into vacancies and imperfections in the steel's microstructure. Such imperfections include dislocations, precipitates, cavities, grain boundaries, interphases, vacancies, and cracks[1].**

*(Continued on page 3)*

Equation 1:

$$Fe_{(s)} + HCl_{(aq)} \rightarrow Fe_{(s)} + H + \frac{1}{2}Cl_{2\,(g)} \rightarrow FeH_{(s)}$$

*During hydrochloric acid cleaning stage, hydrogen molecules can diffuse into base metal if hydrochloric acid is not removed properly.*

Furthermore, the electrodeposition process itself can cause hydrogen to diffuse into the base metal (Equations 2 and 3). The water molecules dissociate from the solution once electrical current is applied to the plating solution containing the zinc anode. This diffusion may also lead to hydrogen embrittlement.

Equation 2:

$$M + H_2O + e^- \rightarrow M + H + OH^- \rightarrow MH + OH$$

Equation 3:

$$M + H_3O^+ \rightarrow M + H^+ + \ +H_2O \rightarrow MH^+ + H_2O$$

*During electrodeposition, dissociation of the water molecule occurs and hydrogen might diffuse into the base metal during electrodeposition (electroplating)*[2].

Hydrogen embrittlement causes a loss in ductility, a loss in load carrying ability, microscopic cracking, and eventually catastrophic brittle failures. Additionally, some other effects include ease of crack initiation and propagation, and development of hydrogen induced damage (i.e. blisters and voids).

## Case Study

A fractured wire rope from a crane in a wood yard with approximately 100 days of service was received at our facility for examination (Figure 3). Most of the fracture surfaces of the wires were relatively flat, as shown in Figure 4. Additional mechanical damage, such as flat spots and inter-wire nicking, was observed on the surface of the wires of the rope (Figure 4). Metallic deposits were observed at mechanically deformed areas on the surface of several wires. The deposits had a copper color and were shiny in appearance. Other deposits had a darker appearance. Black deposits were observed that were most likely lubrication residues. Orange-colored deposits (i.e. rust) was also observed over much of the wire surface of the wire strands. Some of the wires also presented a shear lip and cup-like appearance, which is characteristic of overload.

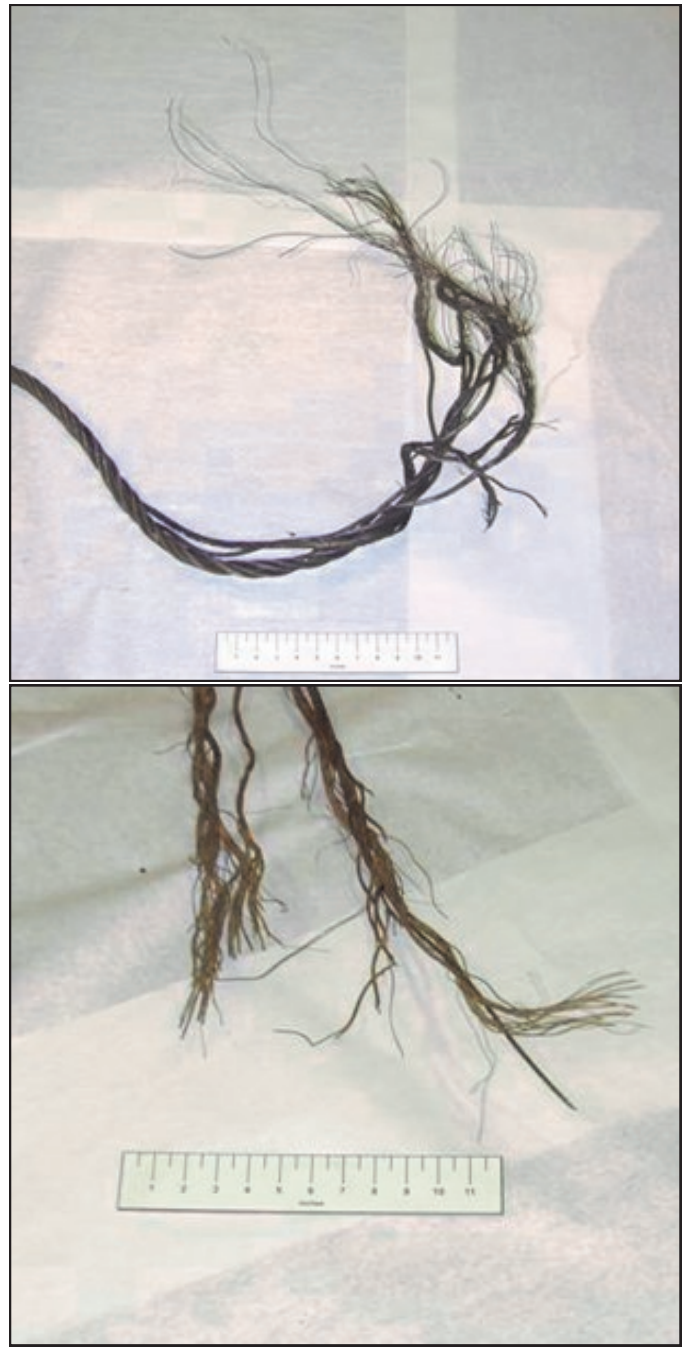


**Figure 3 Photographs show the fractured wire rope in the as-received condition.**

## Material Properties

The wire rope consisted of several outer bundles surrounding a smaller wire bundle as the core. The chemistry of the outer bundles of the rope were matched 1059 carbon steel, while the inner bundle

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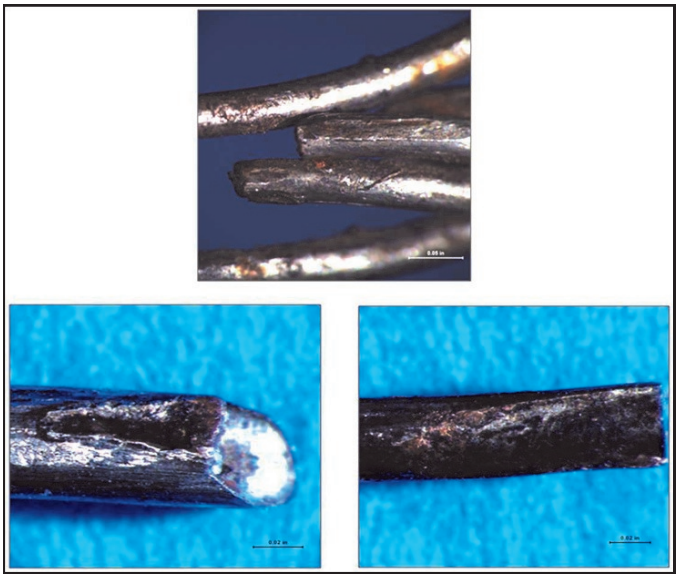

**Figure 4 Photographs show the damage observed on the surface of the wire rope.**

strands of the rope was made of 1064 steel. The average bulk hardness of both wire rope bundles was approximately 45 HRC.

## Fractography

The fracture surfaces of several wires were cleaned using a mild detergent to remove any deposits. The cleaned fracture surfaces were examined at higher magnification using a scanning electron microscope (SEM). Intergranular fracture features (a "rock candy" appearance) were observed on approximately half of the fracture surface of one wire (Figure 5). Mixed mode fracture features (intergranular and micro-void coalescence) were also observed at approximately the center of the wire. Such features (i.e. intergranular fracture) are not typical in wire rope steel. Another wire exhibited intergranular fracture features on approximately 25% of the fracture surface of the wire. Mechanical damage, most likely inter-wire nicking, was observed at the origin area.

## Metallographic Examination

Longitudinal cross sections of several wires were prepared for metallographic examination using standard laboratory procedures. The prepared sections were examined using a metallurgical microscope. The examination included evaluation of the failure features, bulk microstructure of the wires, and any anomalies.

About 30% of one of the fracture surfaces was relatively flat and blocky (Figure 6, left image), a feature usually found in brittle fractures. A white layer that did not etch was also observed along the surface of this wire, which was the galvanized (i.e. zinc) coating of the wire.

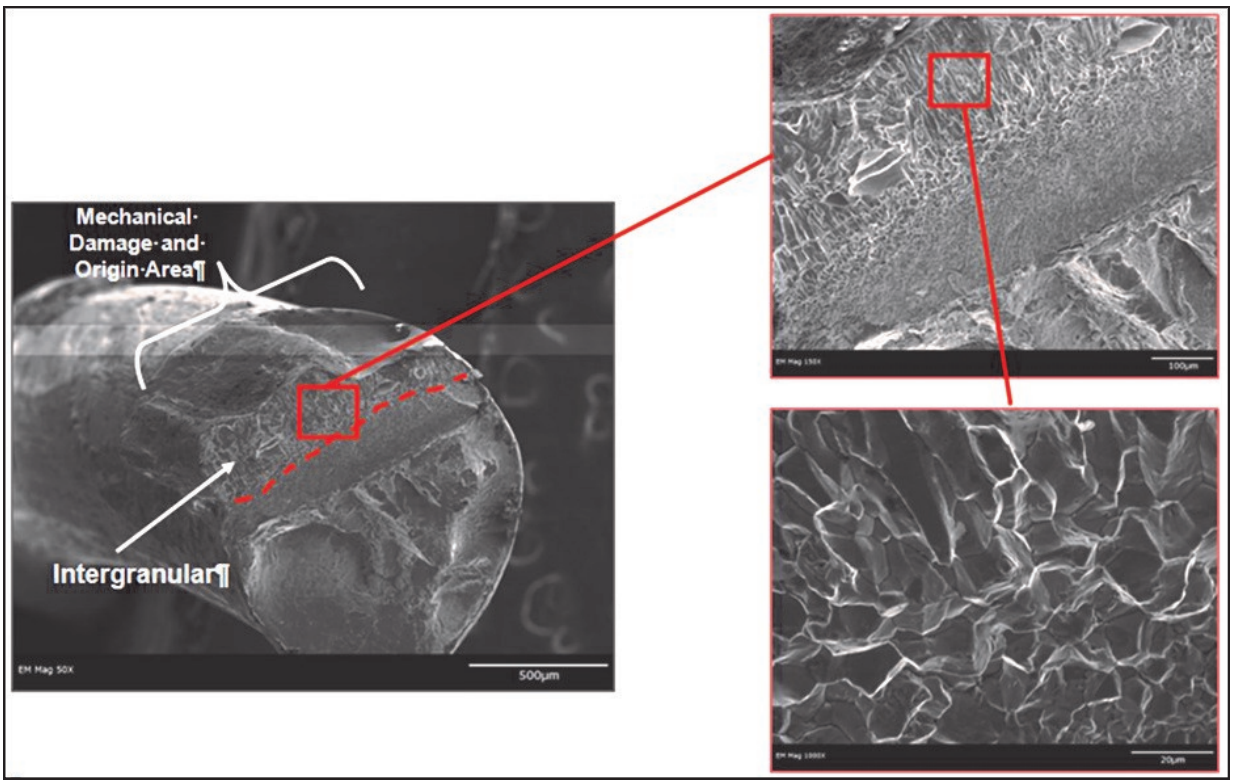


**Figure 5. Scanning electron microscope (SEM) images show the fracture surface of one of the embrittled wires. The fracture surface had a "rock candy" appearance, which is a typical feature observed in hydrogen embrittlement failures.**

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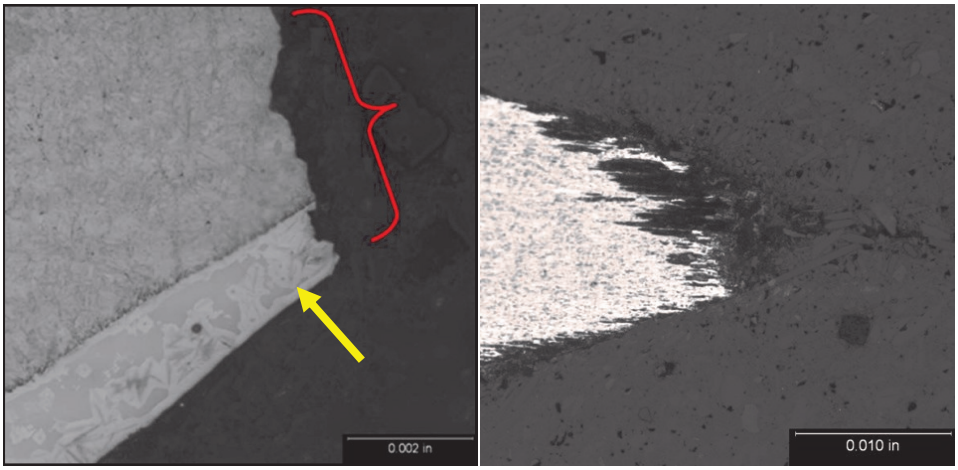


**Figure 6. The photomicrograph on the left shows the fracture surface of the wire that had a rough, relatively flat and blocky appearance (red bracket). The white layer that did not etch is a zinc coating (yellow arrow). The photomicrograph on the right shows a wire strand that failed due to overload. (Etchant: Nital)**

Another wire cross section was examined metallographically. The wire showed grain elongation, which is typically observed at the overload area (i.e. last area to fracture) and would be considered a more common mechanism of wire rope failures (Figure 6, right image).

### Case Study Summary

The wire rope failed due to hydrogen embrittlement. In order for hydrogen embrittlement to occur, there had to be a hydrogen source, a susceptible material, and a stress. The hydrogen source was most likely from manufacturing during the cleaning and/or galvanization process and no baking after electrodeposition. Improper cleaning before the electrodeposition process could leave hydrochloric acid (HCl) residues. Electrodeposition would accelerate the hydrogen diffusion into the base metal. Furthermore, the electrodeposition process itself, if not performed properly, can also cause hydrogen embrittlement. The hydrogen would dissociate from the solution and diffuse into the base metal during the electrodeposition of the zinc layer. Since this is a high strength steel with a hardness of approximately 45 HRC, and a martensitic microstructure, this material would be susceptible to hydrogen embrittlement. The stress source would be the typical loading conditions of the wire rope during operation (i.e. tensile stress/load). Fractographic analysis of the fracture surfaces of the wire rope found intergranular fracture features (i.e. "rock candy, block"), which are typically observed in hydrogen embrittlement failures.

### Avoiding Hydrogen Embrittlement

There are several steps that can be taken to avoid hydrogen embrittlement. One is reducing the hydrogen exposure by either removing the remnants of hydrochloric acid (HCl) after cleaning, or by performing a proper electrodeposition process. There are several variables, such as current, voltage, solution, and exposure time that might need to be adjusted before finding the optimal variables.

### Test Methods for Detecting HE

Using test methods such as ASTM F1459 "Standard Test Method for Determination of the Susceptibility of Metallic Materials to Hydrogen Gas Embrittlement (HE)" can determine if the material is damaged due to HE. A sample can also be cryogenically overloaded and fracture the suspected specimen, and examine the fracture surface under an SEM for the typical fractographical features. An easier way of determining if the wire rope is embrittled is to perform a bend test. If the wire bends and fractures at angles less than 45°, then there is the possibility that the wire rope is embrittled. Further testing would be recommended at this stage to verify the damage mechanism.

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[1] An Atlas of Metal Damage; Engel, Lothar; Klingele, Hermann; pg. 122; Figure 185; 1981.

[2] Embrittlement - https://www.fastenal.com/en/71/embrittlement


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# Upcoming Events

## 76th Annual International Water Conference

**November 15-19, 2015 — Orlando, Florida**


The IWC presents the latest in scientific advances and practical applications in this field, cutting across a wide range of industries, technologies and functional areas.

**David Daniels, Senior Principal Scientist** with M&M Engineering will be in attendance at the conference, as well as teaching a technical workshop following the conference on Monday, November 16th—CHEMISTRY CONSIDERATIONS FOR INDUSTRIAL AND POWER STEAM TURBINES-**in the** Crystal Room.

## Preventing Failures in Steam Generating Equipment

**M&M Engineering Associates, Inc. presents**

**5th Annual (Spring Edition)**

**February 16-17, 2016**

**Leander, Texas**

**(see next page for details)**

**Visit our News & Events page for more details:**
**mmengineering.com/news-events/**


Our clients are the greatest part of our success and we'd like to say

# Thank You!

From all of us at

M&M Engineering Associates, Inc.

# Preventing Failures in Steam Generating Equipment

## February 16-17, 2016 — Leander, Texas

**M&M Engineering will host a Spring Edition of their 5th annual workshop for producers of steam, be it used in power or process applications. The two day workshop focuses on the issues most common in steam generating systems and is applicable to many industries including: pulp and paper, refining, petro-chemical, and power generation.**

**Seating is limited - register TODAY!**

### *Day 1*

- Equipment Associated with Steam Generation – A Primer
- Utility Feedwater Heaters and Damage Mechanisms
- Water Touched Boiler Tube Damage Mechanisms
- Steam Touched Boiler Tube Failure Mechanisms
- Introduction to Nondestructive Testing & Inspection Contracting
- High Energy Piping: Damage Mechanisms and Corrections

### *Day 2*

- Introduction to Failure Analysis
- Failure Investigation Principles for Combustion Turbines
- Basic Steam Turbine Failures
- Condenser and Cooling Water Failures
- Damage Mechanisms in Deaerators
- Water and Steam Chemistry-Influenced Failures in the Steam Cycle
- Discussion and Wrap Up

* (sessions are subject to change)

The registration fee for this two day event is $800 (continental breakfast and lunch are included).
The registration deadline is February 1, 2016. For details, and to register online, visit:

http://mmengineering.com/events/event/ or simply click the ticket!


Or contact Lalena Kelly by phone or email for further information:

(512) 407-3775 or Lalena_Kelly@mmengineering.com

Event Location: 1815 S. Highway 183, Leander, Texas 78641

# Aerosol Cans and Their Failures
# Part I - Basics of Aerosol Cans

**By: Catherine A. Noble, P.E.**
**Consulting Engineer**

Personal care, home, and outdoor products come in many different types of packaging. One of the most popular types is the aerosol can due to its ability to distribute the product as tiny droplets for optimum coverage. Worldwide aerosol production is currently about 13 billion units annually.

A significant amount of engineering design and testing goes into producing aerosol cans. For one, they hold high pressures that require them to meet certain government regulations. In addition, they need to withstand a wide variety of chemical formulations for the products they contain. Products can be sprayed out as a foam, stream, fine mist, or multiple variations in between. Also, aerosol cans are manufactured and filled at very high speeds.

This article summarizes the basics of aerosol cans: history, functionality, types of cans, and manufacturing methods. Part 2 of the article in the next issue of the Conduit will discuss the various failure mechanisms for aerosol cans, which, while they are infrequent, also require engineering expertise to analyze.

### History

Aerosol packaging was first used during World War II as a "bug bomb" to protect soldiers from insects and malaria in the Pacific (Figure 1). Shortly thereafter, aerosol cans were developed for civilian applications and sold in the United States in the late 1940's. Early products included insecticides, hairspray, air freshener, deodorants, and shaving cream.

**Figure 1. Original aerosol bug bomb from World War II (circa 1943). (Agricultural Research Service, USDA)**

### How it Works

Aerosols are very fine particles of a liquid or solid substance suspended in air. For an aerosol product, the desired substance is propelled through a valve as a fine mist or foam. This allows the product to be distributed into tiny particles/droplets to get a finer, smoother coating. By pushing the valve button or actuator on the can, it opens up the pathway to allow the product to exit (Figure 2).

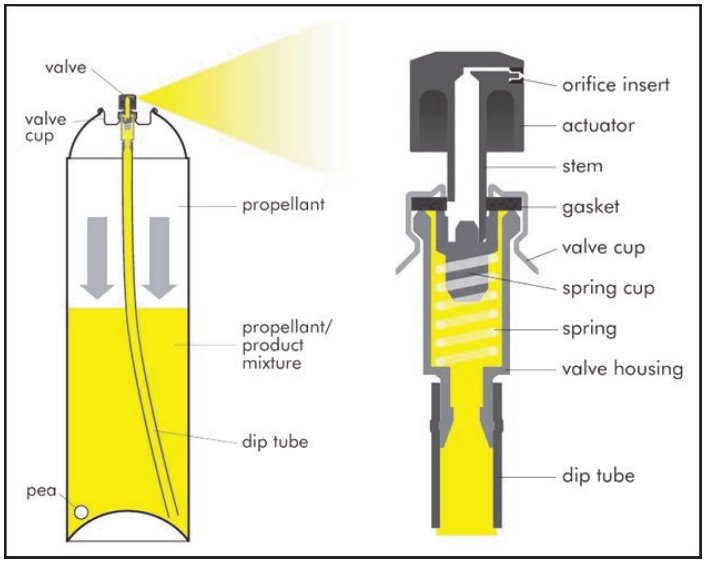



**Figure 2. Diagram of aerosol can parts (Science Inspiration). When the actuator is pressed, it allows a pressurized mixture of product and propellant through a hole in the valve, and then through the valve button's exit orifice.**

Aerosol packaging is self-contained and the product inside has three main components: active ingredients (e.g. paint), inactive ingredients (e.g. water), and propellant. The propellant is a gas that is under pressure within the aerosol container. When the aerosol is sprayed, the propellant pushes the product out into a spray or foam as it escapes.

## Types of Aerosols

The first aerosol cans were made of steel with soldered side seams. Now, there are several types of pressurized containers that can be made of various materials with differing construction. The main types of aerosol packages are:

- 3-piece tin-plated steel with welded side seam
- 2-piece laminate steel
- 1-piece aluminum
- 1-piece plastic

While each type is made of a different material and a different number of components, they all hold pressure and distribute the product in a similar manner. Also, every aerosol can has a 1-inch opening at the top that is standard to all cans. This allows a valve cup to be placed in the opening that is crimped on during/after the filling process. Cans are typically made at one manufacturing plant and shipped empty to a filling facility, so the opening must be standard.

Each type of aerosol listed above is manufactured in a different manner. Most facilities use high-speed lines that are highly automated. Below is a brief description of the most common manufacturing process for the various types of aerosol cans.

### Tin-plated Steel

The steel arrives to the manufacturing plant in coils. The material is carbon steel coated on both sides with tin, hence the name tin-plated steel. This is also the same material that most "tin cans" are made from (not actually solid tin). The steel is cut into sheets that are then coated in protective and decorative paint. Some cans are made with undecorated exteriors that are covered with a paper or plastic label at the filler.

For the can bodies (the main cylinder shape), the sheets are cut into rectangles for each individual body. The rectangle is rolled into a cylinder where the side seam is welded on a high speed line using copper wire electrodes. The top (dome) and bottom of the cans are formed separately in multi-step presses, and a sealing compound is added around the edges. The top and bottom are then double seamed onto the body (Figure 3) providing a pressure-tight seal. The dome has an opening at the top of the can for filling. Figure 4 shows some examples of 3 piece steel aerosol cans.

There are two sub-sets of tin-plated steel cans: bag-in-can and piston-in-can. Both types use a plastic part inside the metal can to separate the product from the propellant. This is done for products such as shave gel that would not keep the right product form if mixed with the propellant (e.g. shave gel would become shave foam). The bag is a rigid plastic bladder that contains the product, while the piston is a plastic cup that sits between the product and the propellant. Both types have a grommet in the bottom to allow propellant to fill from the bottom and product to fill through the top.

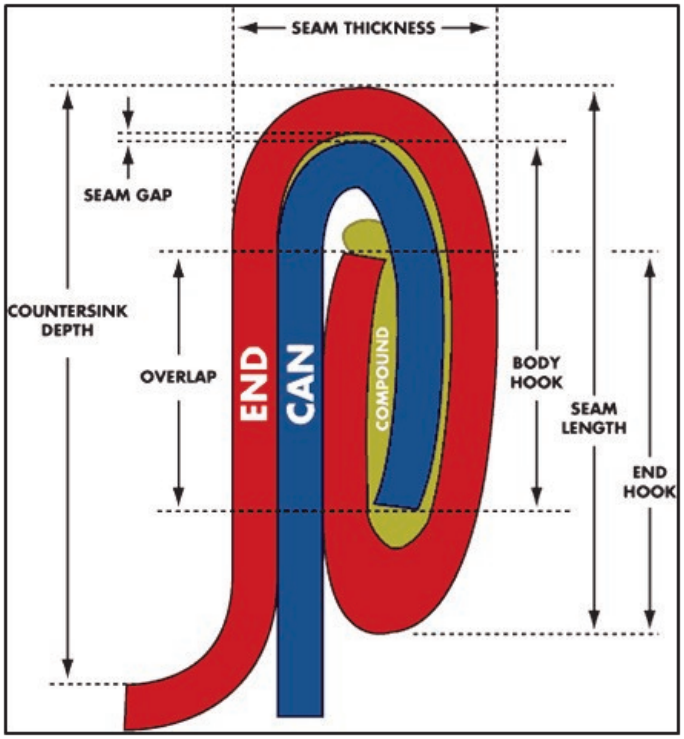



**Figure 3. Cross section of a double seam that connects the end to the can body and holds pressure in the can. (Rexam)**


**Figure 4. Examples of 3-piece tin-plated steel aerosol cans. (Packaging Alliance)**

*(Continued on page 10)*

## Laminate Steel

Laminate steel cans (Figure 5) also start out in coil form, but the coil is tin-free steel that comes pre-laminated from the steel supplier with a polymer coating on both sides. The coil is cut and a large cup is formed by a cupping press. This cup is drawn into the can shape by a second press. Can bodies are decorated at this stage of the process (or left plain for plastic labels at filling). Then the integral dome is formed on the top of the can


**Figure 5. Examples of 2-piece laminate steel aerosol cans. (Southern Aerosol)**

body by a third press. Bottoms are formed separately by a press. Just like the 3-piece can, the bottom is double seamed onto the body of the 2-piece can.

## Aluminum

Discs or slugs are punched out of a thick aluminum sheet to start the can forming process. Can bodies are then formed using the impact extrusion process by placing the slug in a forming die and striking it with a reciprocating punch. The bodies are then trimmed, washed, and dried. A lacquer is sprayed on the inside and cured in an oven; this protects the can from the product. The label is then printed on the outside and dried in a second pass through the oven (Figure 6).


**Figure 6. Examples of 1-piece aluminum aerosol cans. (CCL Container)**

Finally, the dome and valve opening are formed by several swaging steps.

Aluminum aerosols also have a bag-on-valve (BOV) option that is analogous to the bag-in-can option for tin-plated aerosol cans.

## Plastic

Plastic aerosols (Figure 7) were invented in the 1960's, but did not gain much popularity and use until the last decade or so. They are made using the injection stretch blow molding (ISBM) process to obtain the desired shape. This process was developed for plastic soft drink bottles and was then applied to plastic aerosol bottles/cans. ISBM involves molten polymer flowing into the injection cavity to produce a preform. Once it reaches the proper temperature, the preform is stretched and blown into the finished shape of the mold around it. After it is cooled, the can is ejected down a chute or removed by a robot.


**Figure 7. Examples of plastic aerosol cans. (Spray Technology & Marketing)**

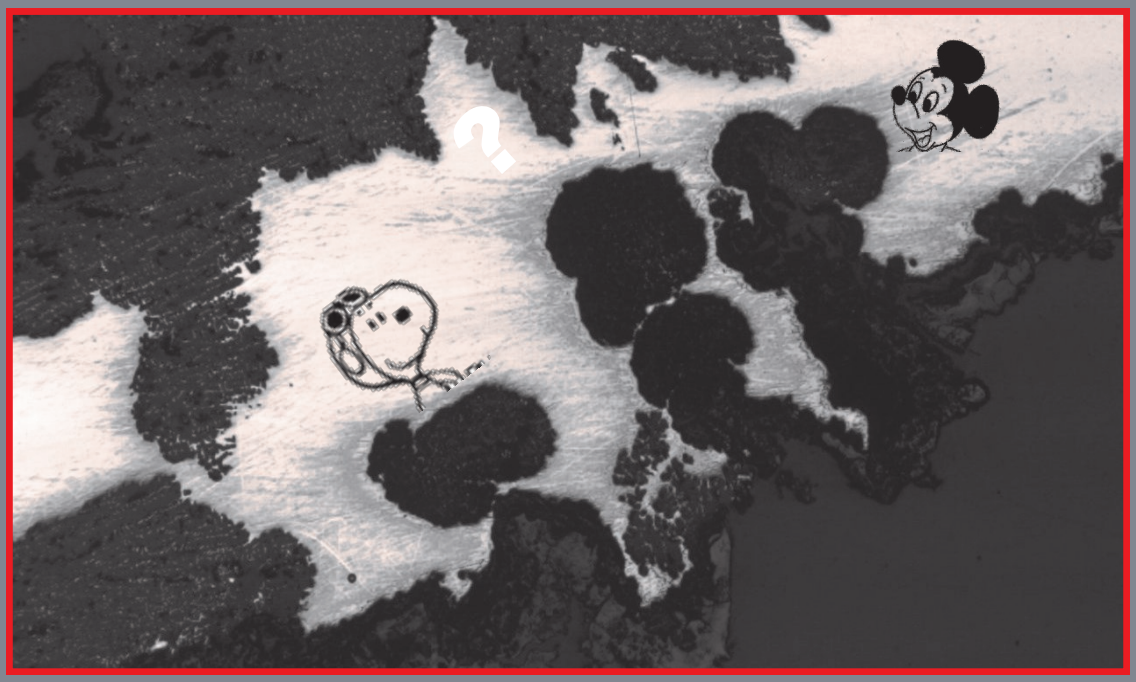
Plastic has several advantages over metal and is continuing to develop. Plastic can be transparent and multiple different shapes can be made more easily. It also can eliminate rusting that occurs on metal cans when exposed to moisture and is lighter weight.

## Can Ratings

Aerosol cans are typically given one of three pressure ratings set forth by the Department of Transportation (DOT): standard, DOT 2P, and DOT 2Q. These ratings dictate the pressures the can must withstand before buckling (deforming) at 130°F and bursting (separating so that product/pressure releases). Table 1

# A new kind of MIC?
# Nah, just Mickey and the Red Baron with their new friend.
# Who do you think it might be?"

In the last issue of *the* Conduit we had a bit of fun with our back cover photo by asking who you thought it might be. Well, you answered and we'd like to share some of those fantastic answers. Great job folks!



Pogo the Possum

Gopher
from Caddy Shack

Toad
from Mario Cart

A cartoon lemming

Patty Bouvier
from The Simpsons

By popular response,
the winner is…

Betty Boop

shows the required pressures for each rating. All of the material types listed above must meet these same requirements.

**Table 1. Aerosol Can Ratings and Required Buckle/Burst Pressures**

| Rating | Buckle Pressure (psi) | Burst Pressure (psi) |
|---|---|---|
| Standard | 140 | 210 |
| DOT 2P | 160 | 240 |
| DOT 2Q | 180 | 270 |

All aerosol cans are tested in a hot water bath at 130°F after filling to confirm that they meet the buckle pressure standards. Certain cans may also be granted an exemption from the DOT ratings if they are not able to go through the hot water bath. Whipped cream, for example, would spoil if it was tested in this manner. Exempt cans must be equipped with a pressure relief mechanism (PRM) that will vent excess pressure in the can. Each type of aerosol can will have a PRM option available. For example, 3-piece cans typically use a dome with scores on top of the double seam that vent if the dome buckles.

New regulations were developed for plastic aerosols with a "non-specified" can (akin to the "Standard can") and a "2S" bottle. These regulations include requirements for drop testing after exposure to elevated temperatures and leak testing, as well as the standard burst testing (with a required burst strength of 240 psi).

### Propellants

Propellants are used to pressurize the packaging and provide the proper product form (e.g. foam, spray, or stream). They can also act as a solvent (to keep the product mixed in the correct proportions), dilutent, freezant, or viscosity modifier. Propellants can also be used as an aerosol product themselves in the form of a refrigerant refill liquid, an electronic duster, an alarm agent (boat horn), or a specialty degreaser.

Most propellants are liquefied gases, which are compressed hydrocarbons that are liquid at room temperature when under pressure. The most common liquefied gas propellants are hydrocarbons (e.g. propane or blends of multiple hydrocarbons), DME (dimethyl ether), 152a (difluoroethane), and 134a (Freon). A few products (about 10%) use compressed gases (aka permanent gases or non-liquefied gases). These include carbon dioxide and nitrous oxide and are still in gas form when not under pressure.

A liquefied gas propellant maintains the same pressure in the container no matter how much propellant is left. This means that as the product is used up, the pressure in the can remains constant. Permanent gas pressure, however, is dependent on volume and decreases as the product is used up. These gases follow the ideal gas law where pressure decreases as the available volume increases (more volume is available for the gas as the product is dispensed) (See Figure 8).

Different propellants also have different flammability. Hydrocarbons, DME, and 152a are flammable, while 134a and permanent gases are not. Changing propellants can also alter the droplet size of the product.

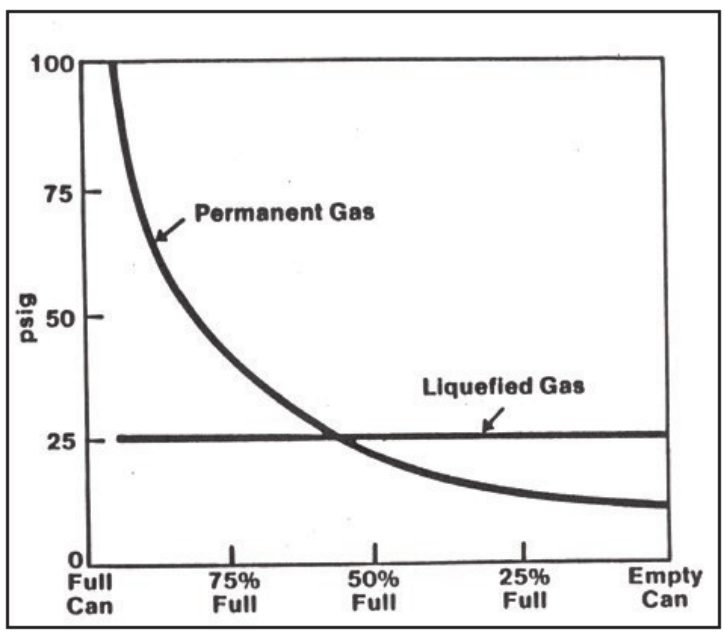



**Figure 8. Graph shows pressure inside the can versus percent full for the can to illustrate pressure changed during product discharge. (Diversified CPC)**

A large percentage of the general public still thinks that aerosol cans are "bad" for the environment and contributing to ozone layer depletion. While in fact, no chlorofluorocarbons (CFCs) have been allowed in aerosols since 1978. Propellants were switched over to fluorocarbons, which are not harmful to the ozone. In addition, volatile organic compounds (VOCs) have been reduced significantly using different blends and formulations.

### Stay Tuned for Part 2…

Part 2 of this article will present the various failure modes for aerosol cans.

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## *How to Give Metal the Look of Copper Patina*

Create the matte blue-green hues of copper left to the elements

MEGAN BAKER THIS OLD HOUSE ONLINE

Difficulty: Easy
Time: 3 hours
Cost: About $40

Shopping List:
- House numbers
- Sophisticated Finishes Copper Metallic Surfacer
- Sophisticated Finishes Patina Blue Antiquing Solution
- Clear Sealer

Tool List:
- 1-inch foam brushes (two)
- Protective gloves

Introduction:

A vivid verdigris tone can cover any paintable surface, thanks to a two-part paint application. The base paint contains copper bits, so any item can have this rich look. And oxidizer turns the paint the color of patinated copper.

Step 1: Apply The Copper Surfacer:

Mix the copper surfacer well to ensure that the metal particles are evenly distributed. Apply a thin coat using one of the foam brushes. Let dry (about an hour) before applying a second coat. Repeat until the surface has an even coverage of copper.

Step 2: Apply The Patina Solution:

While the final coat is still tacky, use the second foam brush to apply the blue patina solution, making sure to wear protective gloves. Use liberally for a more overall blue color or sparingly for a more nuanced blue patina.

Step 3: Add More Solution:

The color will start to change within 10 to 15 minutes. Add more solution for a greater color change; if the surfacer is no longer tacky, brush a new coat on the parts you'd like to color, and reapply the solution.

Step 4: Add More Surfacer:

Once dry, you can add more surfacer with a sponge brush if a less overall blue look is desired.

Step 5: Apply a Sealer:

For outdoor use, coat with a sealer, which will halt further oxidation of the surfacer.

Source: http://www.thisoldhouse.com/toh/how-to/step/0,,20691618_21314683,00.html

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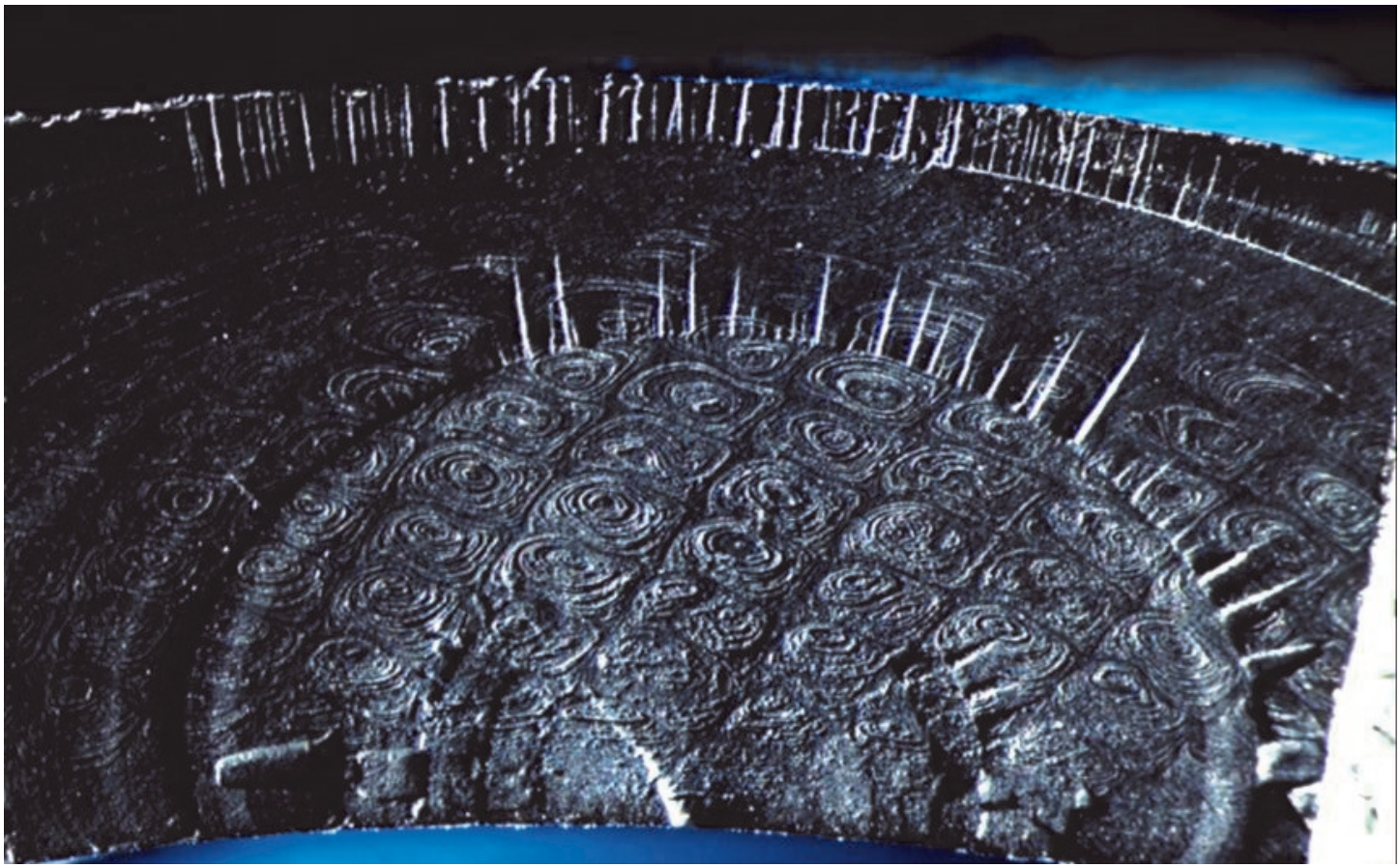

Alien crop circles in space or a CPVC fracture with incomplete mixing due to improper extrusion?