FAILURE ANALYSIS OF BRASS HOSE DIVERTER

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FAILURE MECHANICS

Abstract
In its first applications, copper and copper alloys were used for gold plating in Egyptian hieroglyphics. Today, they are used in a variety of commercial industries including the building construction industry for electrical wiring, tubing and plumbing applications. The variety of applications exposes the copper alloys to different types of environmental conditions, which can accelerate the failure process. This case study focused on the failure of a brass hose diverter used from spring through fall for three years, failing on the outer region of a female thread connection. Under SEM analysis, the failure surface revealed a section of highly localized cracks that continued radially. In addition, these cracks were perpendicular to the tensile stresses induced during the loosening of the threads. Cartridge brass, as found in the brass hose diverter of this study, is susceptible to stress corrosion cracking (SCC) in the presence of oxygen and ammonia with surface flaws acting as a site for an oxidation layer to form and subsequently crack. The ammonia was present in the fertilizer used in the lawn where the well water was pumped. The ammonia causes an oxide layer to form, causing brittle cracks to propagate into the thickness of the material until the ductile material blunts the cracks. The brass diverter failed when a SCC-induced brittle crack formed a stress concentration on a pre-existing surface flaw and propagated into the ductile material when an external force was applied. Ductile failure was indicated by microvoid coalescence. The external force was modeled as torque acting on a collar and the forces were below the yield strength of brass. Treating brass as a linear-elastic material over-predicted the critical crack length, although the stresses from SCC were not included. Using a method studied by Mackay et al [1], SCC cracks were included in the form of a J-integral. Theoretical changes in crack length were on a similar scale as the pre-existing cracks that existed in the diverter after failure (as seen by SEM), although these measured cracks did not propagate to failure. To avoid failure in the future, using a fertilizer without ammonia would be an easy solution, as well as choosing brass fittings that contain elements such as silicon, beryllium, or arsenic and to avoid a brass alloy with more than 15% zinc.

1. Introduction to Copper

The development of brass from copper was first developed by the Egyptians and used for its golden color in their hieroglyphics but used more extensively by the Romans on their helmets and ornamental jewelry [2]. In Medieval times, brass was popular for church monuments, but not until Shakespearean times was brass used as an industrial tool. Brass was used to makes pins, clocks, watches and navigational aides because of its corrosion resistance, manufacturability, and ability to machine [2]. Today, copper and copper alloys make up one of the major groups of commercial metals, behind iron and aluminum. Copper and copper alloys are most extensively used in the building construction industry, where the metal provides a wide variety of engineering capabilities, depending on the type desired, which include: wrought, cast and powder metallurgy product forms and can be used to make electrical wire, tubing, building hardware, plumbing and heating elements [3].

Today, the ability to understand how different alloys affect the structure of the brass help to determine its mechanical properties and probability of failure. Environmental conditions also become important when determining corrosion susceptibility of different alloyed coppers. This report will focus on the failure of a brass hose diverter, where environmental chemicals presumably led to stress corrosion cracking that caused brittle crack initiation on the surface of an oxide layer and consequently led to ductile failure in the form of microvoid coalescence. In addition, other explanations for failure are presented as well as recommendations for avoiding this scenario in future applications.

2. Uses and Composition of Brass Hose Diverter

2.1. Background

The brass hose fitting was purchased in 2005 to divert water from a bury hydrant to two different hoses (each approximately 50 feet long) to water the grass (Fig. 1). The diverter was approximately -45° from horizontal. The hose fitting was used during the spring through fall and stored below the cabin during the winter months to avoid freeze-thaw cycles. Recently, the grass was fertilized with with Scott's® Feed and Seed. The water was pumped from a well approximately 40 feet below the surface.

Figure 1: Brass hose diverter in its original configuration prior to failure. It was connected to a timer (which is connected to a bury hydrant) and two hoses.

On the day of failure in late September, the brass fitting was being unscrewed by hand after being on the bury hydrant since June, where it was also screwed on by hand. The interlock connecting the female threaded portion to the Y-portion of the diverter failed and the inner threads at the base of the diverter subsequently failed, pulling away from the rest of the diverter (Fig. 2).

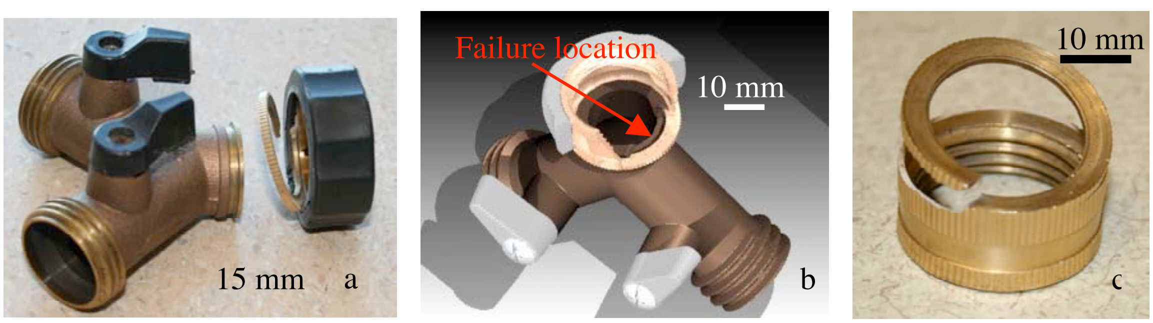
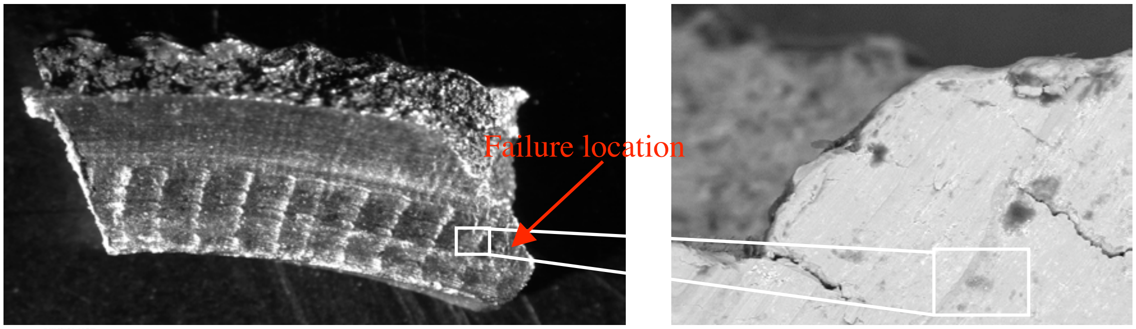


Figure 2: a) Failed brass hose diverter at the base of the Y-configuration at the first thread, b) reconstructed solid model of intact diverter with a cut-away section of failure location, c) location of failed threading.

2.2. Composition of Brass Part

Because the manufacturer of the part was unknown, the diverter was assumed to consist of cartridge brass because this material is used for most plumbing applications [3]. To verify the assumption, an unpolished surface of the specimen free of cracks was subject to Energy Dispersive X-ray Spectroscopy (EDS) (Fig. 3). EDS indicated levels of copper, zinc, and lead, which is characteristic in cartridge brass (Table 1). The oxygen could be from an oxide layer or an artifact from the SEM.



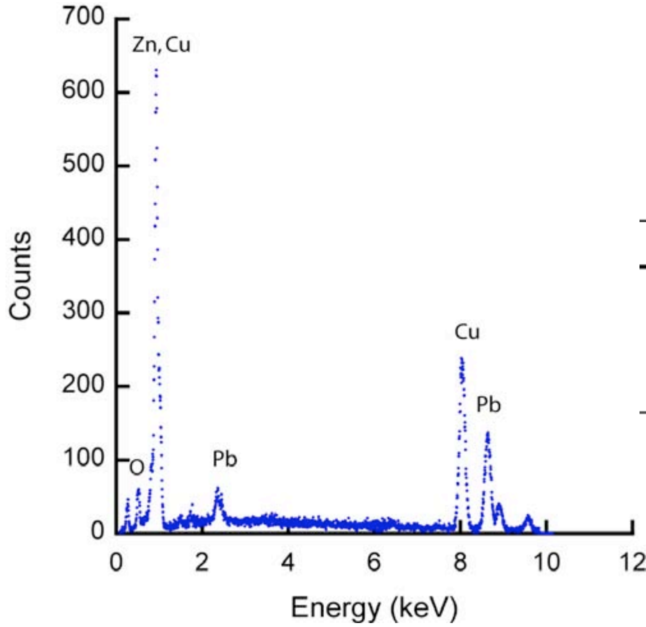


Table 1: Composition alloys of cartridge brass [1].

Element	Composition (wt %)
Copper	68.5 - 71.5
Lead	0.07
Iron	0.05
Zinc	28.4 - 31.4

Figure 3: a) Optical microscope image of surface near the fracture site and fracture surface (within the plane the view), where the white box indicating location of EDS of non-fractured brass, b) higher magnification of failure surface and corresponding EDS location, c) EDS results for brass within the white box in a) and b), verifying the material is cartridge brass.

3. Characteristics of Copper Alloys

Pure copper is extremely difficult to cast and susceptible to surface cracking and porosity. To circumvent this problem, copper is intentionally alloyed with elements such as nickel, beryllium, lead, tin, silicon, and arsenic to improve strength without greatly affecting ductility or workability [2, 3]. The workability and ductility is due to the face-center cubic structure and the twelve dislocation slip systems within the copper alloys [3] These alloys provide different mechanical properties. Copper alloys containing lead, tin or zinc have only moderate tensile strengths, indicating that the lower tensile strength found in the diverter is due to the high zinc content present. The percent of lead within a copper alloy is important when looking at bearing surfaces and boundary lubrication conditions [3], which is not important for this scenario. But the most important characteristic for this failure case involves the role of ammonia in corrosion stress corrosion cracking (SCC).

3.1. Stress Corrosion Cracking in Cartridge Brass

Copper alloys are used in various environmental conditions because of their corrosion-resistant behavior. Copper corrodes at negligible rates in unpolluted air and copper roofing in rural areas has been found to corrode at rates less than 0.4 mm in 200 years [3]. However, certain conditions do exist that will accelerate the process of corrosion, making brass more susceptible to failure. These elements include ammonia and ammoniacal compounds [3].

Ammonia can cause a distinctive brittle appearance that is associated with SCC, where the cracks are highly localized because the rate of corrosion is low [4]. This localized area of corrosion can be the result of intergranular attack, pitting, or surface flaws [4]. In many cases, SCC occurs where there is little visible evidence that the surface was corroded [5]. In the case of the diverter, the cracks can be seen in a highly localized area near the fracture surface (Fig. 4) and less than 1 mm away, the surface is virtually free of cracks (Fig. 5a). In addition, the diverter also has threads that run along the inner diameter, and under higher magnification, reveal serrated radial tick marks that could be considered a surface flaw that expose the brass to environmental conditions and allows the SCC to begin (Fig. 5b).

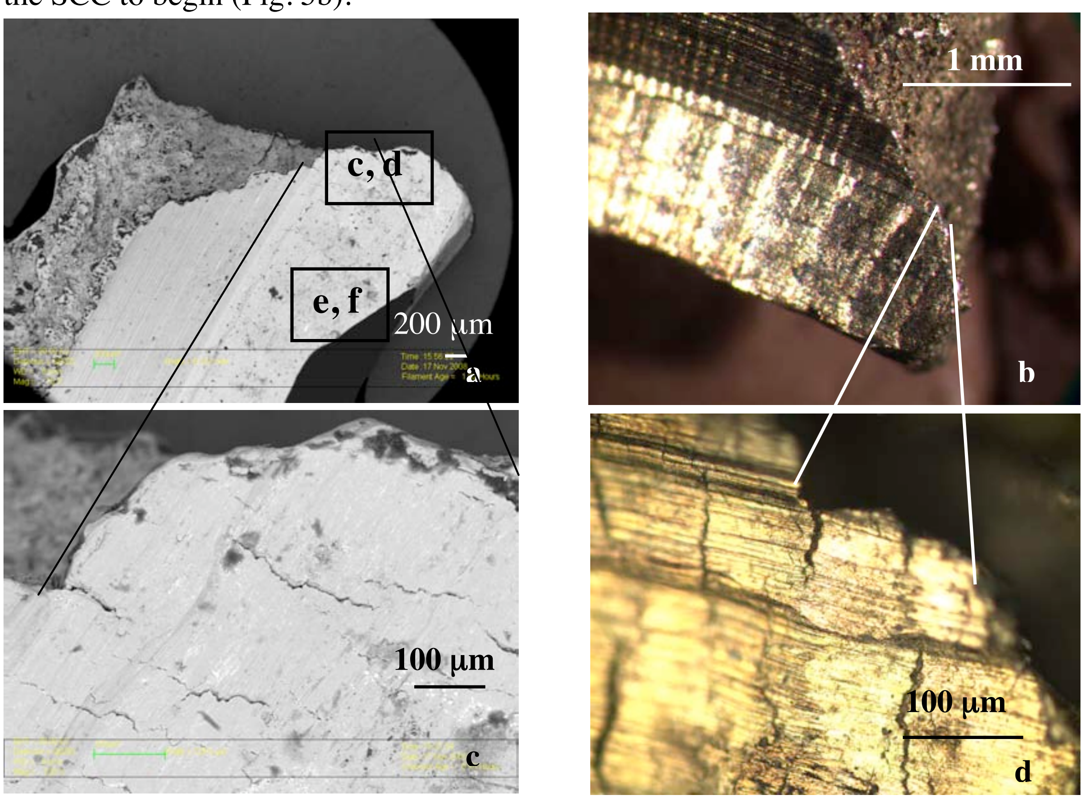


Figure 4: a) SEM image and b) optical microscope images of surface near failure site showing where higher magnification images were taken, c) SEM image and d) optical microscope image under higher magnification of highly localized brittle SCC.

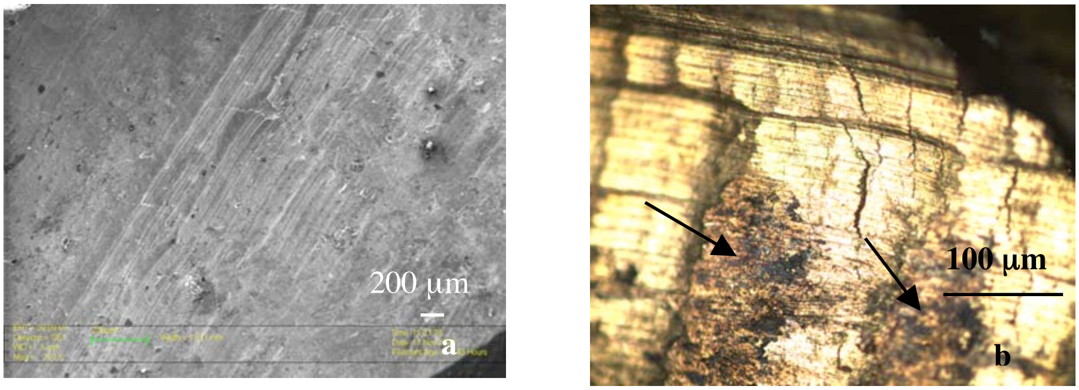


Figure 5: a) higher magnification image showing a virtually crack-free surface less than 1 mm away from the SCC region and b) optical microscope image of surface flaws from serrated radial tick marks that may have been crack initiation site.

The presence of ammonia in oxygenated solutions can lead to SCC, which causes brittle cracking of an otherwise ductile material. Moisture films on metal surfaces will dissolve significant amounts of ammonia, even at low concentrations [3]. The ammonia, in the presence of oxygen and moisture, causes a film (oxide layer) to form on the surface of the walls [6]. The reaction for this can be found in Appendix A. The high stress concentration that results at the crack tip from inherent oxide tensile stresses causes this protective oxide layer to rupture locally, exposing the underlying surface to the ammonia and the dissolution of copper begins [5]. This is called film-induced cracking [7]. This phenomena occurred in the diverter, where brittle cracks were exposed on the surface due to corrosion and propagated in a ductile manner through the thickness of the specimen, which was originally unaffected by corrosion but was subject to the stress concentration of the initial crack (Fig. 6a). Because the underlying thickness showed microvoid coalescence, the fracture happened rapidly enough because the corrosion behavior was only identified near the surface. This ductile failure is evident because of the necking behavior of the microvoids that coalesced in the presence of a high tensile stress from the untightening of the threads at the based of the diverter [5] (Fig. 6b).

Ammonia was present in the water system by use of a Scott's® Feed and Seed, a fertilizer used to promote denser grass growth [8]. The fertilizer was derived from ammoniacal phosphate and contains 5% ammoniacal nitrogen. Although the percentage of ammoniacal constituents within the lawn is unknown, low concentrations of ammonia are needed to create SCC if the stress conditions are high or if surface flaws are present [4].

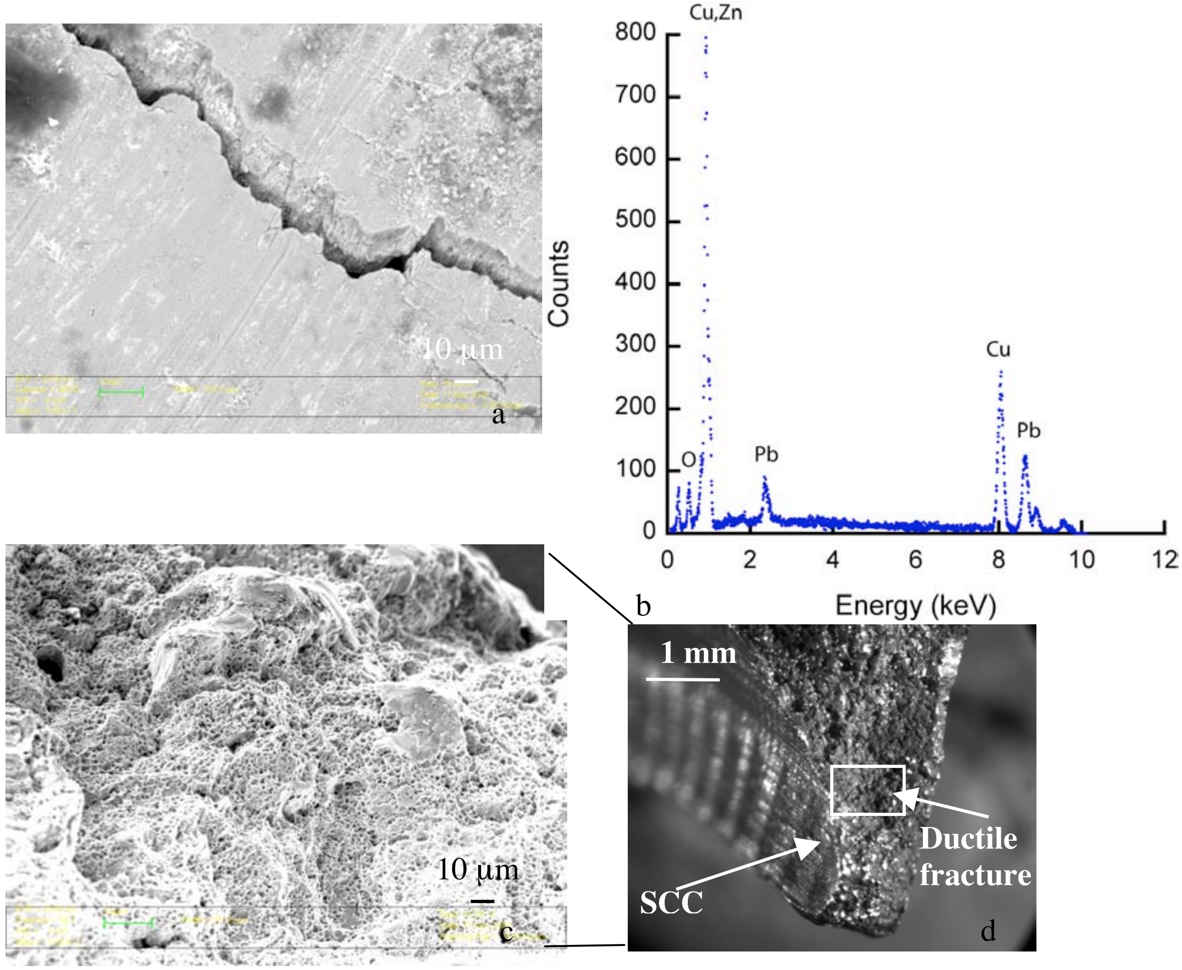


Figure 6: a) SEM image of high magnification crack caused by ammoniacal environment, b) EDS of crack surface, c) SEM image of ductile fracture, represented by coalesced microvoids that have a rim around their edges (similar to necking), d) optical microscope image of location of ductile fracture on failure surface.

4. Other Types of Failure

4.1. Corrosion Fatigue

Corrosion fatigue is the combination of cyclic stress and corrosion that results in fatigue cracks. These cracks usually run parallel to the tensile stresses and usually involve several cracks, which can be seen in the diverter failure surface. However, this type of failure was ruled out because studies have found that it is rare for more than one crack to be found in a failed corrosion fatigue part [3]. In addition, fatigue cracks usually begin at corrosion pits, which were not found on the surface at the initiation of crack sites.

4.2. Dezincification

Another important component that makes cartridge brass susceptible to corrosion is its high zinc content. In this case, zinc constitutes over 28% of the material. Alloys that contain <15% zinc have a decreased resistance to corrosion than those >15% [3]. Dezincification is a type of dealloying process where the most active metal is selectively removed from the alloy, leaving a relatively weak layer of copper and copper oxide. The result is a porous structure [3], which does not seem to be the case for the diverter.

5. Mechanical Properties of Cartridge Brass

5.1. Vickers Hardness

In the absence of tensile testing, Vicker's Hardness test (LECO Corporation, St. Joseph, MI) was conducted to determine the tensile strength, since the published values of cartridge brass range from 303-896 MPa [3]. The average Vicker's hardness (HV) was 146, based on the equation (ASTM handbook next to tester):

$$HV = 1.854 * P / d^2 \tag{1}$$

where P is the standard load for brass (kg) and d (mm) is the average diagonal from the hardness indenter. The Brinell hardness (HB) corresponding to HV was 128 (using the assumption of cartridge brass). By knowing HB, the tensile strength of the specimen can then be found from the following relationship [9]:

$$TS = 3.45 * HB \tag{2}$$

The tensile strength of this particular specimen was 441 MPa, which is within the range of published values of tensile strengths [10]. The yield strengths of cartridge copper range from 76-448 MPa. Similar to the relatively low tensile strength, the yield strength of this particular sample would probably in the range of 90-100 MPa.

5.2. *Stresses Within Cartridge Brass*

Unscrewing of the diverter from the water source resulted in external forces being applied to the surface where cracks had initiated. To find the force induced by the torque of unscrewing (which was estimate to be no more than 8 N-m), the brass was treated as a thrust collar with the failure surface as the base of the collar (Fig. 7). The torque applied and the resulting stresses of the diverter force are related by [11]:

$$F = \frac{2T}{d_c f_c} = \frac{2(5)Nm}{0.026m(0.1)} = 3846N \tag{3}$$

where T is torque, d_c is the mean collar diameter, and f_c is the coefficient of friction. The stresses on the collar are:

$$\sigma_{thrust} = \frac{F}{A_s} = \frac{3846N}{2.86e-4} = 13.4MPa \tag{4}$$

This result indicates that the stresses do not exceed the yield stress of 90 MPa. In addition, including the stresses due to internal pressure from the water results in negligible forces. As a result, 90 MPa will be used for any fracture mechanics analysis.

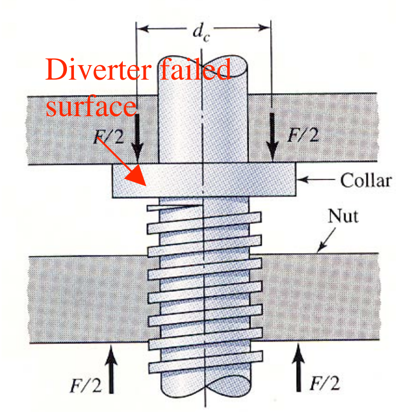


Figure 7: Diagram of forces during tightening on a collar (equal but tensile during untightening).

5.2.1. LEFM

Assuming linear elastic fracture mechanics (LEFM), the critical crack length can be calculated from [5]:

$$a = \frac{K_I^{\ 2}}{1.25\sigma_{thrust}^{\ 2}\pi} = \frac{(90MPa - m^{1/2})^2}{(13.4MPa)^2\pi} = 11.49m \tag{5}$$

where K_{Ic} for a yield strength of 80 MPa is 90 MPa-m$^{1/2}$ [12]. The critical crack length is 25 times larger than the outer diameter. However, SCC has been shown to fail at loads more than 80% of the yield strength [3, 13], indicating that the stresses from tightening the diverter may have been sufficient to cause failure of the specimen. The changes in fracture toughness due to an oxide layer in brass does not allow for further comparison for a critical crack length using LEFM and the J-integral approach should be used.

Additional stress conditions can be created through manufacturing by inducing residual stresses as well as through the formation of an oxide layer. Little information is known about the diverter, so the manufacturing processes are unclear, although tubing is usually sand cast. The residual stresses that can accumulate during sand casting are dependent upon temperature differences in the casting during cooling (since the casting is done with molten metal), phase transformation in the alloy, sand resistance to casting contraction [14]. Moreover, using only the stresses on the collar may have underpredicted K_I because cracks that develop from SCC have been shown to generate inherent large tensile stresses (perpendicular to crack) [10], indicating that crack propagation would continue with a lower external applied stress. In addition, these stresses are also dependent upon the pH of system which is based on the concentration of ammonia [10].

5.2.2. J-Integral

In recent studies, the use of the J-integral was used on testing of cartridge brass because of its low strength and high toughness, precluding the use of LEFM [1]. The J-integral represents a material's resistance to crack growth and is represented as [15]:

$$\delta = \alpha \frac{J}{\sigma_{YS}} \tag{6}$$

$$\alpha = 0.49\frac{(1+N)}{(1-\upsilon^2)}\left[\frac{2(1-\upsilon)\sigma_{YS}(1+N)}{\sqrt{3}EN}\right] \tag{7}$$

where J is a function of the crack opening tip displacement, δ, α, Poisson's ratio, ν, Young's modulus, E, and N, the work hardening exponent (N = 0.35 [1]). If a crack opens slightly and is then plastically blunted, as in the case of SCC in ductile materials, $\Delta a \approx \delta$, and equation (7) becomes:

$$J_{blunting} = \frac{\sigma_{YS}\Delta a}{\alpha} \tag{8}$$

The intersection of this result and an experimental J-curve gives J_{SC}, which represents the critical for initiation of crack growth. Using the experimental J-integral from MacKay et al [1]for specimens pre-cracked in fatigue and then exposed to an electrolyte to simulate stress corrosion cracking, a J_{SC} value was found at 4 different crack growth rates (Fig. 8).

The values of J_{SC} decreased with decreasing rates of deformation, indicating that the resistance to stress corrosion crack growth is generally reduced when the specimens are strained slowly. This may show that the diffusion of the corrosive environment cannot diffuse to the crack tip before the ductile material blunts the crack. When the deformation rate is slower, the diffusion process has more time to occur after the oxide layer has inititally cracked, which will expose more copper to the ammoniacal environment and lead to more cracking. In relation to the diverter, Figure 4c shows a SCC crack approximately 0.2 mm long that has not propagated to failure. If we assume a slow deformation rate and the current crack is the initial crack length, then the critical length is 0.215 mm, indicating the sensitivity of the material to stress corrosion cracking and its relationship to failure when exposed to an electrolytic environment like ammonia. This also assumes that the crack length will propagate through the oxide layer and not be blunted by the ductile brass. The calculated values may be a good representation for approximation of fracture toughness.

Table 2: Values of change in crack length and J_{SC} as a function of the rate of deformation calculated from equation (8) based on cartridge brass mechanical properties and experimental values of SCC cartridge brass in electrolyte solution [1].

Rate of deformation ($x10^{-4}$mm/s)	$a-a_o$ (μm)	J_{SC} (kJ/m^2)
1.2	15.4	3.45
12.0	10.4	2.31
200.0	9.1	2.04
2000.0	4.5	1.01

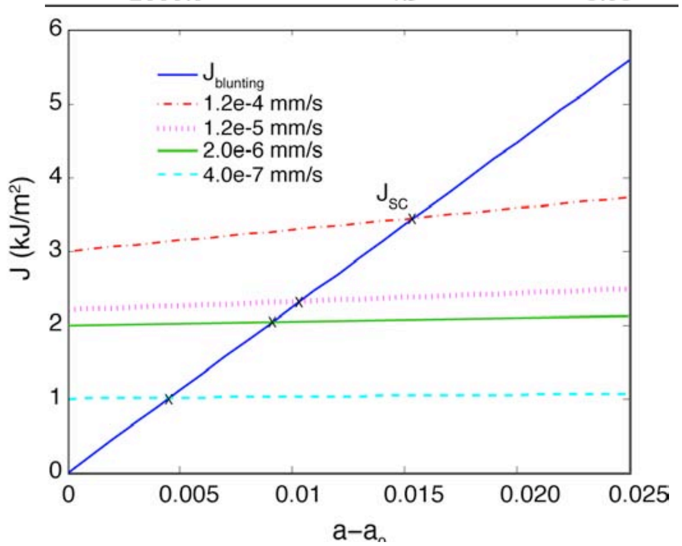


Figure 8: Crack growth resistance curves at small crack extensions with different rates of deformation. The blunting line was calculated based on equation (8) and the empirical data was adapted from [1].

6. Conclusions

Because cartridge brass is susceptible to stress corrosion cracking in an ammoniacal environment, the use of fertilizer with ammonia may have been the cause of failure. SEM images show brittle fracture beginning at a surface flaw with subsequent ductile failure through the thickness of the diverter, which is indicative of SCC-initiated fracture. The fracture occurs when the ammonia, in the presence of moisture and oxygen, forms an oxide layer on the brass. Because the oxide layer is inherently brittle and formed on a surface flaw, crack initiation began at the greatest stress concentration and propagated through the layer until it was blunted by the unaffected ductile brass. This brass was then exposed to the ammoniacal environment and the process repeats itself. Predicting the failure due to SCC requires knowledge of the stress state and the material properties of the brass. This ductile behavior caused LEFM to over-predict failure. The role of SCC was not included in those calculations. But previous experiments using J-integrals were used to provide a basis for understanding the material's critical resistance to crack propagation.

7. Recommendations

In order to reduce the likelihood that SCC does not occur in a similar brass diverter, the easiest change would be to use a different fertilizer that does not include ammonia. Another (more expensive) option could be to use a deeper water source so that the ammonia within the water from the fertilizer is perhaps more diluted, although only low concentrations are needed to cause SCC with the right stress states and environmental conditions. Because brass is consistently used throughout the plumbing industry, different types of surface finishes and alloying components are used to avoid stress corrosion cracking. Studies have shown that using copper alloys that contain phosphorus, arsenic, magnesium, tellurium, tin, beryllium, and silicon decreases the probability of cracking [3]. Decreasing the zinc content is also though to make the alloy more resistant to SCC [3].

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Appendix A: Reaction leading to SCC

The presence of ammonia in oxygenated solutions can lead to SCC, which causes brittle cracking of an otherwise ductile material, by the following set of reactions [16]:

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$$

$$Cu + 2OH^- \rightarrow Cu(OH)_2 + 2e^-$$

$$Cu(OH)_2 + 2NH_3 + 2NH_4^+ \rightarrow \left[Cu(NH_3)_4\right]^{2+} + 2H_2O$$

$$\left[Cu(NH_3)_4\right]^{2+} + H_2O \rightarrow CuO + 2NH_3 + 2NH_4^+$$