Sucker Rod Failure Analysis

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Companies may soon require their field personnel to file a form report on each sucker rod break. These report forms will be brief but the field man must be able to identify the cause of the sucker rod failure and be able to evaluate the break. One company has begun its data gathering and hopes this computerized program will find the best probable prevention program. Operators must know what to guard against before any prevention program can be successful. Obviously, a reduction in speed will not prevent the rods from rubbing the tubing, and pump pound can not be stopped by additional inhibitor. For these reasons an accurate failure analysis is most important and can lead to preventing that costly second, third, and even fourth break.

Before stepping into a lengthy break analysis, it would be prudent to check for any physical malfunction of the unit. An unintentional increase in speed could cause the pump to starve and the ensuing pound could cause the rods to start breaking. It would also be good practice to check the string design. The well may have a string that was originally designed for conditions that have since changed.

Broadly speaking, there are three categories for causes of sucker rod failures; mill and manufacturing defects, mechanical damage and corrosion. Usually, a brief inspection will place the rod break in one of these categories. The more knowledgeable an individual, the easier and more accurate his analysis will be.

MILL AND MANUFACTURING DEFECTS

After the chemical composition in steel has been fixed according to manufacturer's order, the ingot molds are filled from huge ladles (a process called "teeming"). The ingots are then placed in a soaking furnace. An eight-foot ingot weighs ten tons or more. After leaving the soaking pits, there can be as much as ¼-in. scale covering the ingot. A water ring removes this thick scale covering and the ingot is then worked through a series of rollers that subject it to tremendous mechanical pressure which reduces the ingot to a 6-in. square bloom. This rolling process refines the grain structure of the steel and also removes any scale that may have remained through the water ring. The bloom is sent to the billet mill where it is rolled into a 4-in. square. The billet is then rolled and run through forming dies until the desired diameter of the bar is reached. The hot-working improves the internal structure of the steel by closing small voids and reducing the grain size.

Inclusions are certainly detrimental to any steel and are especially critical in sucker rod steel. Visual inspection is most commonly used to find these defects but other inspection methods can be used according to the customer's standards.

Prior to rolling bars, the billets are inspected and surface defects are removed by grinding or by scarfing (removing defects with gas torches). After the bars are rolled, inspected, bundled and shipped, the sucker rod manufacturer again inspects the bars upon arrival. They are then straightened and forged. Subsequent heat treatment removes all internal stress and further refines the grain structure.

Mill and manufacturing inspection teams are responsible for the control and prevention of mill defects and this type of rod damage is outside of the direct control of the field man.

MECHANICAL DAMAGE

Mechanical damage is second only to corrosion as the cause of sucker rod failure. It would be nearly impossible to run a string of rods without some banging and abrasion but a careful crew can prevent serious damage by observing the basic care and handling recommendations of the API.

Any nick or scratch is a stress riser. The

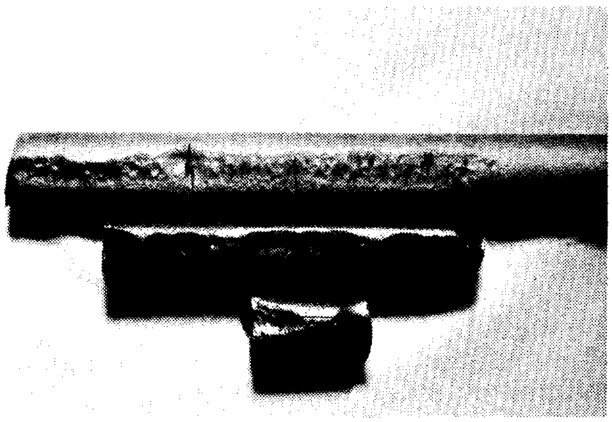
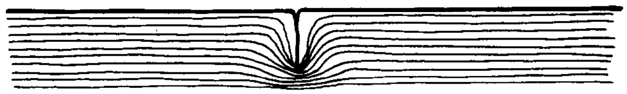


FIGURE 1

STRESS — CORROSION

ISOLATED STRESS CRACK



NUMEROUS STRESS CRACKS

FIGURE 2

STRESS PATTERNS IN CRACKED SUCKER RODS

load stress is concentrated at the tip of cracks and the deeper the crack, the greater the stress that is concentrated there. Stress is carried equally throughout the cross sectional area of a sucker rod and can be thought of as acting on many small fibers lying parallel in the sucker rod. Each fiber carries an equal share of the rod load providing the rod structure is homogeneous and the rod loads are parallel to the rod axis. Assume that a crack develops in the rod. This crack interrupts the path of the stress-carrying fibers but only for the immediate area. Because of the rigid nature of the rod, the influence of the crack is quite local and will not disturb the stress distribution for more than a few inches. See Figs. 1 and 2. However, the crack area affected will have its stress pattern greatly altered and those nearby "stress fibers" will be diverted to a path that bypasses the crack. The alternate path will be the shortest possible path which will cause the interrupted stress to be diverted around and close by the crack tip. In this manner, numerous stress paths will converge upon the area near the crack tip and concentrate high stress in this area. Such concentration of stress will cause the metal to become more susceptible to corrosion as well as subjecting it to mechanical damage.

Bent rods are not as common today as they were five years ago. Experience has taught most operators that a bent rod has been permanently damaged and must be discarded. A bent rod is a graphic example of a damaged rod. See Fig. 3. The convex side of the bar has been permanently elongated which is proof that the metal was stressed beyond its yield strength. The grains have been deformed and there is no way to make the rod serviceable again without heat-treating it. Hammering would straighten the rod but the subsequent internal complications would cause irregular stress concentration and early failure.

Over-torquing can cause immediate elongation of the undercut section of the pin if the pin stress exceeds the yield strength of the metal. An example of this type of damage is shown in Fig. 4. Simultaneously equal but opposite pressure is exerted against the pin shoulder by the coupling face. This pressure must also exceed the yield point of the pin metal and flaring occurs, as shown in Fig. 4.

A more common result of over-torque is a loose joint. Assume that a pin is prestressed to near the known yield point of the metal. There will be no permanent necking of the undercut and no flaring of the pin shoulder. But as soon as the well load is placed on the rods, the pin stress exceeds the yield point of the metal and the pin permanently elongates. The degree of elongation determines how much prestress is lost but it is assumed that all prestress is lost and the joint becomes loose. Loose joints permit eccentric loading and allow a much greater range of load than a tight joint. Eccentric load and high ranges of stress will greatly reduce both pin and coupling life.

The problem with over-torquing can be overcome by using the API recommended practice of prestressing the pin by means of circumferential displacement.

Abrasion is a type of mechanical damage that is easily identified but not often detected until the damage has been done. The broken rod will have a flat area worn on one side of the rod and the flattened surface will usually extend for several feet in both directions from the break. Rod rotaters will extend the life of the rod by spreading the abrasion over a larger area but eventually the results will be rod failure due to a reduction in cross sectional area. Rod guides will prevent this type of damage. Couplings are usually the first part of the sucker rod string to show signs of abrasion, since they have the largest diameter. Alert rod crews can head off this type of failure by discarding worn couplings.

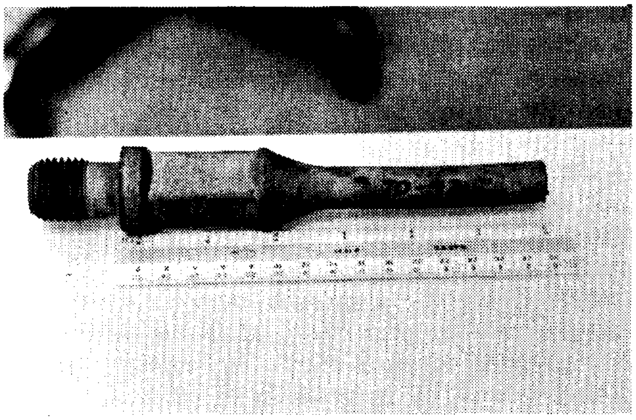


FIGURE 3

BENT SUCKER ROD

Some holes are so crooked that special procedures must be used to keep the coupling wear within acceptable limits. In most cases, the hard-surfaced couplings are used. Some couplings have quenched surfaces that are very susceptible to hydrogen embrittlement and easily cracked by accidental impacts. The more modern, hard-surfaced coupling has a flame-sprayed-powdered-metal surface that is high in nickel content and withstands impacts as well as the standard thru-hard coupling. Its high alloy chemistry makes it more resistant to all types of oilfield corrosion as well as offering a surface with a lower coefficient of friction than any of the other couplings.

CORROSION DAMAGE

Corrosion can be defined as the undesirable deterioration of metals. Actually, nature is merely trying to keep the "system" in balance by lowering the energy level of metals to a stable value. Varying levels of energy are imparted to metals as they are processed and converted from ore to sophisticated products. Metals retain a degree of this energy and thereby have a constant or continual potential to return to a lower energy state, such as their ore. Iron for example, has an ore called hematite, which has the chemical formula Fe_2O_3. Iron rust also has the chemical formula Fe_2O_3.

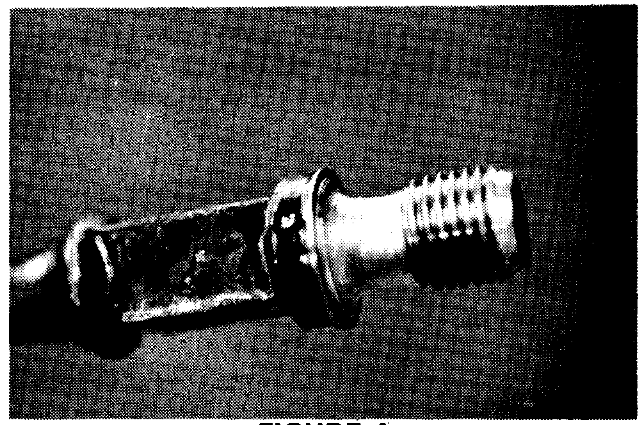


FIGURE 4

SUCKER ROD PIN SUBJECTED TO OVER-TORQUE

The energy absorbed by the metal as it is converted from the ore has been measured in the laboratory. The more energy absorbed, the easier it is to corrode the metal. For example, potassium, magnesium and zinc will deteriorate much more rapidly than will gold, platinum and silver. The relative energy levels of several metals have been recorded in the electromotive series which show which metals will corrode first when all are exposed to electrochemical corrosion.

Electrochemical corrosion is corrosion that involves a flow of electrical current. Corrosive agents are still involved but the electrical effects are now considered. The NACE uses the following illustration: A piece of zinc is immersed in HCl and bubbles of hydrogen are given off at the surface. When a strip of copper is wired to the zinc and both are immersed in acid, the bubbles now appear on the copper. The zinc is still corroding but the point where the bubbles are forming has been changed.

The corroding zinc is called the "anode" and the noncorroding hydrogen-producing metal is called the "cathode". The anode or positive electrode (Greek for "the way which the sun rises," according to Faraday), is the electrode at which current enters the cell. The cathode (Greek for "the way which the sun sets,") is the electrode at which the current leaves.

Electrons leave the iron molecule at the anode and flow through the body of the sucker rod to the cathode. The entire surface of the sucker rod will be cathodic to one anodic corrosion pit and therefore the cathode will be very large when compared to the anode. The speed of electrolytic corrosion is controlled by the relative areas of the cathode to the anode. One corrosion pit on a twenty-five foot sucker rod can be easily visualized as a fast acting, electrochemical cell.

In the cases where there is extensive pitting, a large number of pits will share the same anodic area. This will greatly reduce the flow of current because the area of available cathode for each corrosion pit will be reduced.

When two electrons leave the iron molecule, it becomes an ion or a positively charged molecule. Simultaneously, electric current flows from the anode into the electrolyte. See Fig. 5.

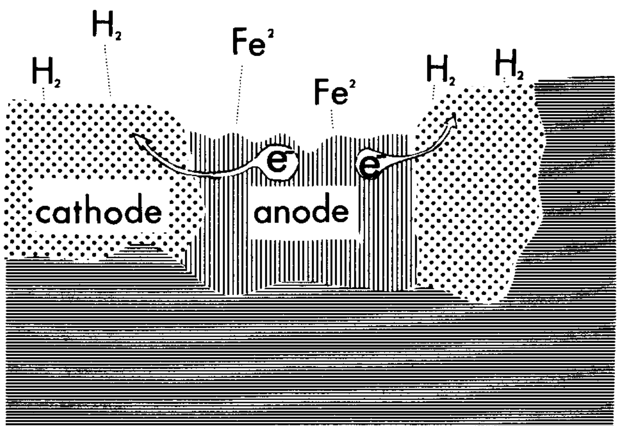


FIGURE 5

SCHEMATIC OF ELECTROCHEMICAL CORROSION

At the cathode, free electrons break the water molecules into hydrogen atoms and hydroxyl ions. Most of the hydrogen atoms will combine to form gas, but some may not combine but enter into the metal as single atoms and cause hydrogen embrittlement. The electrolyte will contain more hydroxyl ions as the reaction proceeds. These ions tend to make the electrolyte more acidic and thereby contribute even more toward the corrosive process. This is not critical in the large volumes of production fluid but if the process occurs under a scale cap then the pH of the fluid could be altered to a significant degree.

The electrochemical process depends upon the presence of an electrolyte and the flow of electrons. If either of these factors are removed or prevented, the corrosion process will stop. Nodules or tubercles are corrosion pits with scale covers. Corrosion products have built up and sealed the pit against the electrolyte. The entrapped electrolyte continues to react with the pit walls and the enclosed fluid becomes acidic. It has been shown that the fluid within some tubercles has a pH of six which probably results from the acidity formed owing to the hydrolysis of the ferrous sulphate and the neutralization of the acid by direct reaction with the iron.

Pitting is a common form of corrosion in oil well steel. This type of corrosion attack may be begun by a localized breakdown of inhibitor film. Small areas are immediately attacked by the corrosive fluid and without the immediate protection of a remedial film, a corrosion pit will soon form. Once the pit has begun, it is more difficult to inhibit. The growth of corrosion pits may be retarded and sometimes stopped by the buildup of corrosion products. Such a buildup would protect or shield the metal from the electrolyte and thereby prevent further action.

Any salt water is corrosive to steel, especially where dissolved oxygen is present. Trace amounts of oxygen have been observed to accelerate corrosion fifty-fold in salt wells located in Western Texas.

Oilfield fluids are customarily rich in dissolved gases. These gases often break out of solution in the lower part of the tubing as the fluid pressure is reduced by the pump or as the fluid ascends the tubing column. Bubbles can also be formed by vibration, turbulence and rod rotations. In areas of high bubble concentration, they will adhere to the surface of the rod and often break open. The collapsed pressure of these bubbles is extremely high. The pressure exerted by collapsed bubbles in some laboratory experiments has been found to be nearly 200,000 psi. This process occurs in one-millionth of a second and produces very high acceleration in the cavities' liquid envelope. When the walls of the cavities collide, a strong shock wave is formed which may break the inhibitor film or damage the rod's surface. A distinction should be made between an impingement attack and cavitation damage. Cavitation damage has to do with the collapse of bubbles or voids in the fluids caused by a collection of fluid vapors. Impingement concerns itself with entrained air bubbles and suspended solids. The impingement attack is common in pumps, valves, elbows, and points of high turbulence. The impingement corrosion has a distinctive pattern wherein the cavities are undercut on the side opposite the direction of flow. There is usually a critical velocity below which impingement does not occur and above which it increases rapidly.

Hydrogen embrittlement is a form of corrosion caused by the hydrogen atoms being absorbed into the steel. The hydrogen atom is quite small in relation to the steel molecules and can pass into the steel matrix with relative ease. It might be compared with a golf ball passing through hog wire. But once the hydrogen atom has combined with another atom, the resulting molecule is too large to pass through the matrix of the steel. The situation now might be compared to a basketball attempting to pass through hog wire. Most hydrogen atoms in oil wells combine to form hydrogen gas which cannot pass into the steel. However, these hydrogen atoms that do not combine pass freely into the lattice structure of the steel. When the metal is under high tensile stress, the metal is more susceptible to hydrogen embrittlement and failure occurs rapidly.

The path followed by the hydrogen atoms may be either intergranular or transgranular. The hydrogen atom usually continues into the steel until it reaches a discontinuity. Here it combines with another atom.

Stress corrosion is caused by joint action of both mechanical and electrochemical corrosion. The broken rod faces are essentially brittle in appearance and there is no sign of ductile tearing. The cracks may be intergranular or transgranular. See Fig. 6. The development of the cracks can be arrested at any time by either inhibitor protection or cathodic protection. The oil industry uses the inhibitor protection method because of the impractical requirements of cathodic protection for sucker rods. Although the crack may be protected by inhibitor, an increase in stress will cause ductile tearing and the crack will advance.

The life of the stress corrosion crack appears to have two stages: an induction period and a period of crack propagation. The beginning or induction stage is the significant portion of crack life and is the most difficult to measure since it is nearly impossible to detect the beginning or first appearance of a crack. It is the initial stage of damage to guard against because the corrosion process is accelerated as the crack deepens and fresh metal is easier to inhibit than damaged metal.

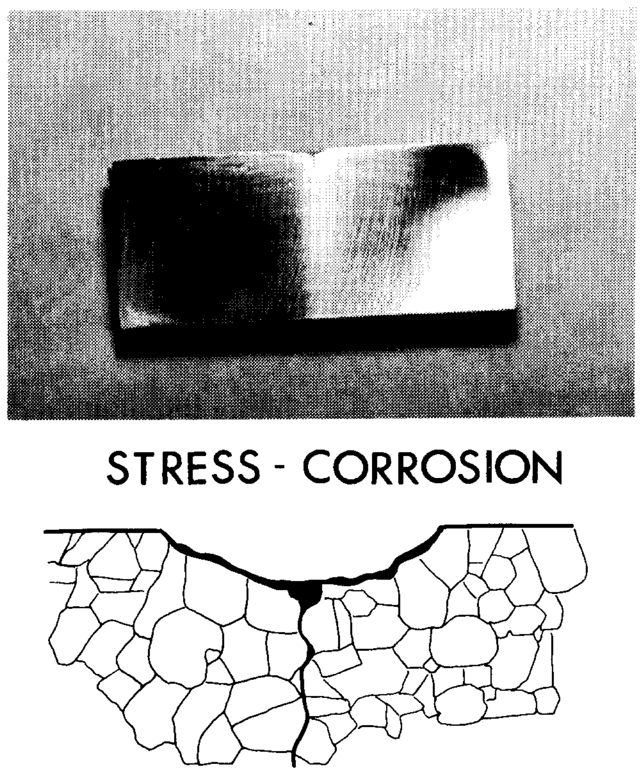


FIGURE 6

EXAMPLE AND SCHEMATIC CROSS-SECTION OF A STRESS-CORROSION CRACK

The electrochemical process begins by weakening the metal at the anodic area. Some of the metal is lost to the electrolyte (well fluid) and grain boundaries are dissolved. This process continues until a small pit is formed. The pit creates a stress riser which propagates the crack by tearing caused by the excessive stresses created by the stress riser. The crack continues by alternate mechanical and electrochemical stages which can be observed in the break face of a broken sucker rod. The "oyster shell" appearance is formed by hesitations in the cracking cycle. See Fig. 7. The mechanical stages are thought to be very brief. The relative propagation at the tip is at least one-hundred-thousand times that of the rate of propagation of corrosion on the sides of the crack. The average rate of propagation in sucker rod steels appears to be about ½ centimeter per hour.

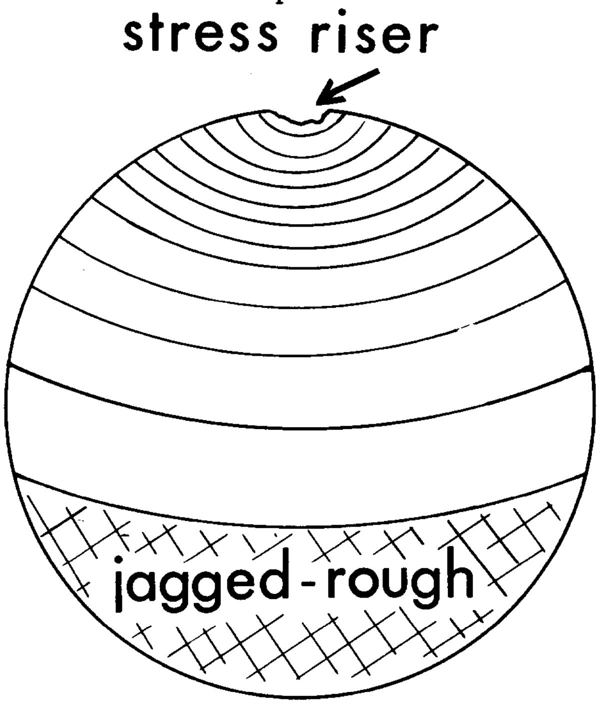


FIGURE 7
SCHEMATIC OF A STRESS-CORROSION, SUCKER ROD, BREAK FACE

Localized corrosion is accelerated by stress which causes the stressed areas to become anodic to the nonstressed area. The crack is extended by brittle fracture and the cycle then begins again and continues until fracture occurs.

Metal fatigue is the descriptive term used for crack initiation in sucker rods. Cyclic stresses enlarge these cracks which progress by stages until the cross sectional area of the rod is too small to carry the well load. At this point the rod abruptly parts. The rough texture of the surface gives the impression that the metal has become embrittled. This type of failure is sometimes erroneously called crystallization. Actually, the break merely uncovers some of the crystals that have been there all along.

CONCLUSIONS

Most sucker rod breaks will have the appearance of brittle failure. The break surface will be at right angles to the center axis of the rod body. It will have the typical, "oyster shell" pattern at one side and jagged edges on the opposite side. There will probably be a small nick or pit at the surface of the rod, located in the eye or center of the "oyster shell". This small stress riser will have started the initial crack that grew until failure occurred.

By correctly identifying the cause of the sucker rod break, the operator can effectively guard against future rod damage.

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