

Analysis of High-Collapse Grade P110 Coupling Failures

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Abstract

In recent years, environmentally assisted cracking has caused failures of many Grade P110 couplings during fracturing operations, causing enormous economic loss to the oil and gas industry. Factors that can contribute to such failures include mechanical damage, localized hard spots, improper heat treatment, and the increased use of high yield-strength couplings with high-collapse casing. Examples of such failures are reviewed and the contributing factors are discussed.

Introduction

The oil and gas industry has recently been plagued with a large number of coupling failures in high-collapse Grade P110 casing strings, most frequently during fracturing operations in shale gas wells. Metallurgical investigations have attributed many of these failures to environmentally assisted cracking, even though the production environments are either non-sour or so mildly sour that Grade P110 should perform satisfactorily, based on historical experience. The failures have occurred with casing manufactured by foreign and domestic mills and in wells drilled by a number of operators. With associated costs approaching one million dollars for some of these wells, these failures warrant additional scrutiny.

Grade P110 Casing

API Specification 5CT Grade P110 is a relatively high-strength grade of quenched and tempered oilfield casing and tubing. It has a specified yield strength of 758 -965 MPa (110-140 ksi) and Charpy V-Notch (CVN) impact toughness requirements that vary based on wall thickness. Because of its high strength, it is not considered suitable for highly sour wells, but has historically been used in mildly sour wells and is accepted by ISO 15156-2/NACE MR0175 as suitable for the mildly sour conditions described as Region 1 in that document. Its mechanical performance limits are considered relatively well-defined in API Technical Report 5C3. In recent years, a number of manufacturers have begun marketing high-collapse Grade P110 casing. Although there is not yet an industry standard for high-collapse casing, it is generally understood to be satisfactory API 5CT Grade P110 casing whose dimensions and mechanical properties have been manipulated, within the specified limits, to provide collapse resistance in excess of that predicted by API Technical Report 5C3. Although this can be accomplished by measures such as reducing ovality and maintaining a more uniform wall thickness, the collapse resistance is most commonly improved by heat treatment to the high end of the specified range for yield strength.

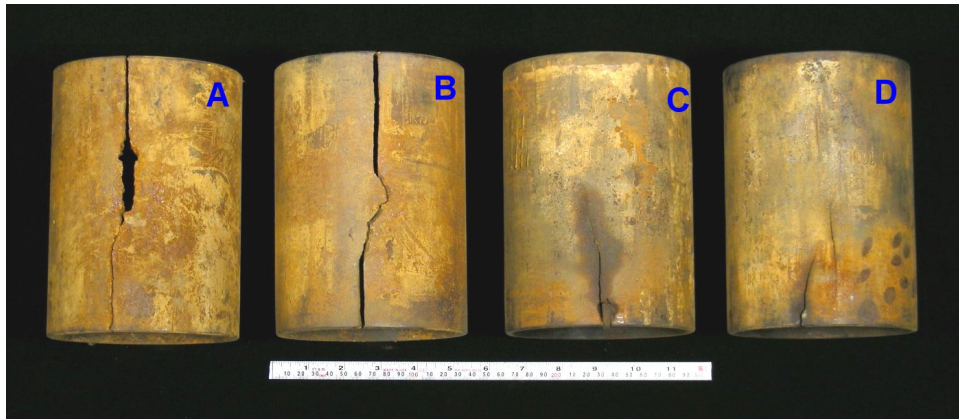


Figure 1 Four cracked couplings from a single casing string.

Common Characteristics of Grade P110 Coupling Failures

Coupling failures generally occur as longitudinal splits or cracks in the couplings. They may be present in one or several couplings in a given string. Non-destructive inspection of the couplings may or may not detect additional cracks.

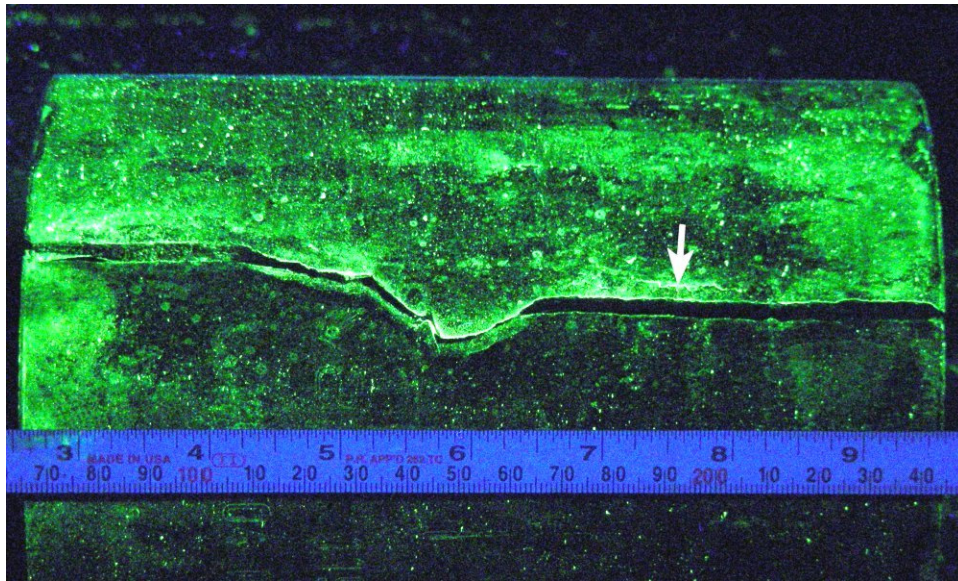


Figure 2 Wet fluorescent magnetic particle indication, arrow, at a secondary crack.

The fracture surface generally shows an area of brittle fracture radiating from a location on or near the outside surface approximately 1-inch from the end of the coupling, which is the most highly stressed location in a coupling. The fracture origin may be elsewhere, particularly if the coupling has mechanical damage or a significant metallurgical issue. The fracture surface may or may not show multiple origins. In couplings with satisfactory CVN toughness, the balance of the fracture surface is generally slanted, ductile fracture. Chemical analyses of the brittle fracture by energy-dispersive spectroscopy (EDS) rarely provides definitive evidence of iron sulfide: sulfur is either not detected or is detected in concert with barium, which only indicates contamination with barium sulfate from drilling mud. The presence of iron sulfide is understood

to be an indication of exposure to sour gas (H₂S) and would identify sulfide-stress cracking as a likely failure mechanism.

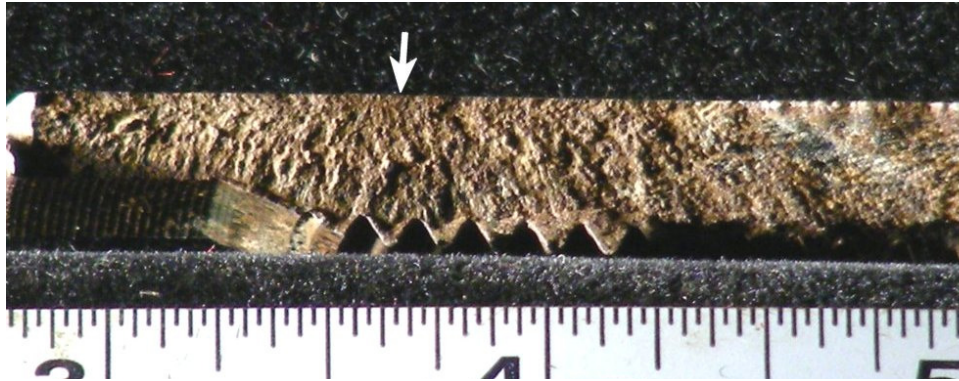


Figure 3 Typical crack surface, with an arrow indicating a crack origin.

Examination of the fracture surface with a scanning electron microscope (SEM) shows brittle fracture at the origin. The brittle fracture may be intergranular or transgranular quasi-cleavage fracture, but is most commonly a mixture of the two.

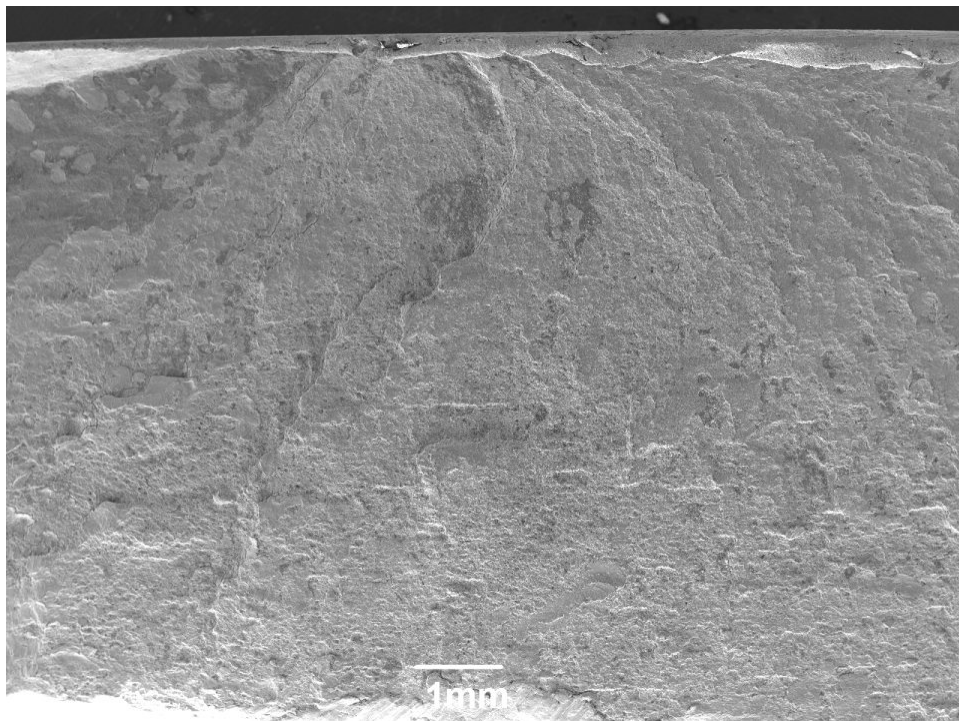


Figure 4 SEM image of a fracture origin (top).

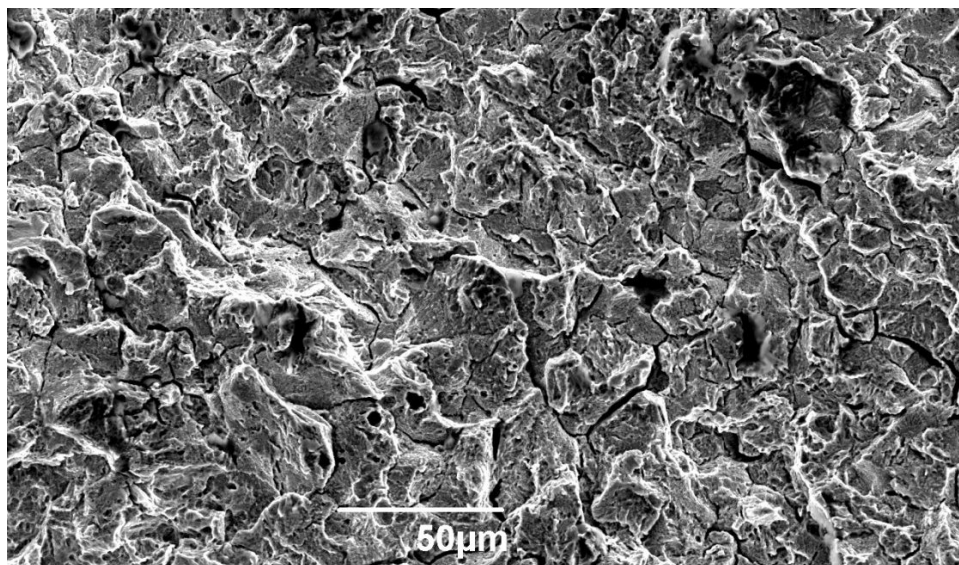


Figure 5 SEM image of brittle fracture near a fracture origin.

Metallographic examination of the fracture profile generally shows a brittle radial fracture with a shear lip on the inside surface. There may also be a shear lip on the outside surface, indicating a subsurface origin. Branched cracking may be present, but is generally quite limited.

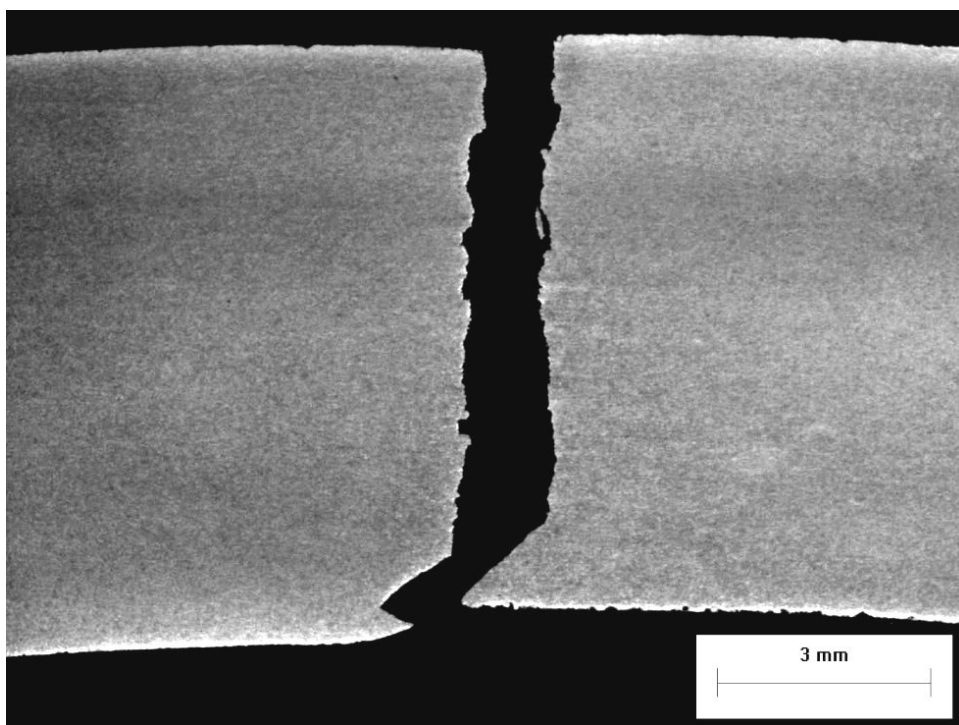


Figure 6 Transverse matched-fracture metallographic section at a fracture origin.

Mode of Failure

The characteristics described above indicate that most such Grade P110 coupling failures occur by environmentally assisted cracking. The presence of multiple fracture origins, multiple failed couplings in a single string, localized brittle fracture in an otherwise tough steel, and

failure at stresses below the yield strength (based on performance ratings for Grade P110 casing) all point to some form of environmentally assisted cracking. Even those failures that are limited to a single crack in a single coupling generally show crack features identical to those with multiple cracks or crack origins. (An exception may be noted for couplings with unsatisfactory toughness, which may exhibit brittle fracture along their entire length.) For high-strength steel in a downhole environment, the relevant forms of environmentally assisted cracking are hydrogen-stress cracking and sulfide-stress cracking. Sulfide-stress cracking is a form of hydrogen stress cracking in which the susceptibility of the steel has been enhanced by the presence of an iron sulfide corrosion film on the metal surface, so both forms of cracking may be addressed generally as hydrogen stress cracking.

Susceptibility to Hydrogen Stress Cracking

In general, the susceptibility of high-strength steel to hydrogen-stress cracking is a function of stress level, environment, and mechanical properties, specifically hardness. One troubling aspect of these failures is that many of them have occurred in satisfactory Grade P110 couplings in an environment where Grade P110 has historically performed satisfactorily and under reported loading conditions well within the rated performance properties of Grade P110 casing. For this reason, it is necessary to take a particularly close look at the stress levels, operating environment, and mechanical properties of the failed couplings.

Contribution of Stress

Couplings are subjected to axial stress from tensile loads applied to the string and may be subjected to bending loads, particularly if located in the bend radius of a horizontal well. However, the typical axial orientation of the cracks indicates that the failures are being caused by hoop stresses. Couplings are subjected to hoop stresses from two sources, internal pressure and make-up. Because API 8rd connections have tapered threads and are, by design, threaded three turns beyond the point of mechanical interference, properly assembling a casing string subjects the couplings to a sustained tensile stress in the circumferential direction. This is noteworthy because a sustained tensile stress is required to initiate hydrogen stress cracking. The most common fracture origin location, near the first engaged thread of the coupling, is the most highly stressed region of a coupling. In addition, the failures have most commonly occurred during fracturing or during a hydrotest immediately before fracturing. Although such high-pressure conditions may represent the most severe stress levels typically experienced by a coupling in its service life, operators consistently report that such failures occur at pressures well below published performance ratings for Grade P110 casing.

Contribution of the Environment

The failures have primarily occurred in shale gas wells, in part because of the high degree of fracturing required to obtain satisfactory production from those wells. Such wells are typically drilled, cased, and shut in for a period of time until fracturing can be arranged. During the shut-in period, the casing may be exposed to produced fluids, which are often corrosive. The corrosion generates atomic hydrogen, a portion of which enters the steel. Some of the wells are sour, that is, they contain enough hydrogen sulfide to significantly increase the amount of atomic

hydrogen absorbed by the steel and thereby increase its susceptibility to cracking. However, most of the wells are not sour or are so mildly sour that industry experience indicates Grade P110 should perform satisfactorily.

In some cases, well treatment fluids have caused cracking. Inhibited hydrochloric acid is commonly used to treat formations to improve production; it is sometimes included in fracturing fluids. If the inhibitor is poorly mixed, if it is absorbed by the formation before the acid flows back into the well, or if the acid remains in the well beyond the relatively short life of the inhibitor, the casing may be exposed to fairly aggressive hydrochloric acid. While Grade P110 shows satisfactory resistance to hydrogen stress cracking in many production environments, it does not always hold up well exposed to inadequately inhibited hydrochloric acid.

One factor that may be significant is that the failures often occur as or shortly after the casing is cooled by the introduction of surface water and chemicals. Under static conditions, the temperature of a casing string will increase almost linearly with depth, often to 250°F to 300°F. When the fracturing fluids are introduced into the well, the temperature of the casing may cool rapidly to near ambient temperature at the surface. Because the solubility of hydrogen in steel is a strong function of temperature, (See, for example, Figure 1.5 in N. Bailey, et al., Welding Steels Without Hydrogen Cracking, ASM, 1973), a coupling that is only saturated with hydrogen at shut-in temperatures will necessarily become supersaturated at the temperature of the fracturing fluid, and therefore more susceptible to cracking. Although the related phenomenon of cold cracking in high strength steel welds is due to a temperature-related drop in solubility of hydrogen as the weld and heat-affected zone cool from relatively high temperatures, the effect of rapid cooling from downhole temperatures has not been as extensively studied. Indeed, most environmentally assisted cracking studies have been conducted under constant temperature conditions.

Contribution of the Steel

Although many of the failures have occurred in satisfactory Grade P110 steel, a variety of metallurgical conditions can increase the susceptibility of couplings to brittle fracture and hydrogen stress cracking. These most commonly include cold work and improper heat treatment. Allowable variations in mechanical properties of Grade P110 couplings may also affect their resistance to sulfide stress cracking.

Cold work

Cold work due to mechanical damage is particular injurious to Grade P110 couplings.



Figure 7 Grade P110 coupling failure that initiated at mechanical damage, shown at the top.

Even if the damage is insufficient to cause an immediate failure, the cold-worked metal at the damaged location is much more susceptible to hydrogen-stress cracking, and superficial corrosion can generate enough atomic hydrogen to crack such highly susceptible steel.

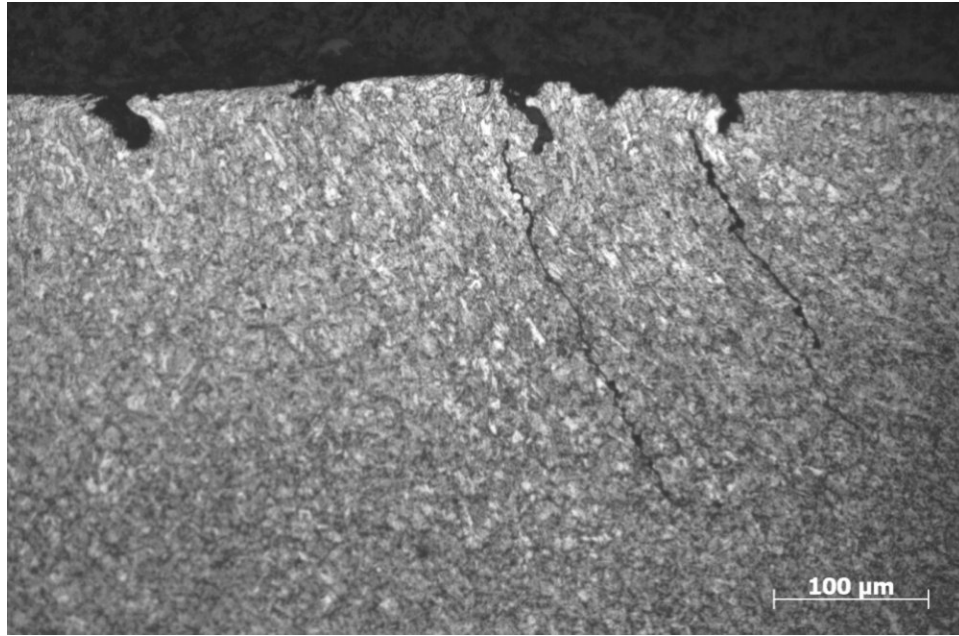
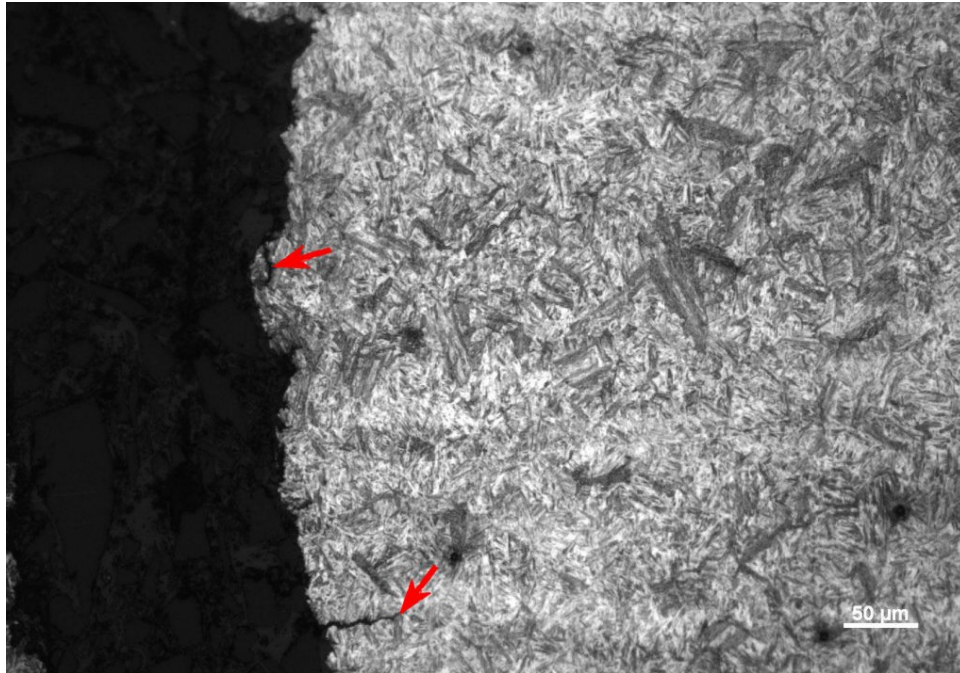


Figure 8 Photomicrograph of cracks initiating at pits in a cold-worked layer on the surface of a Grade P110 coupling.

Improper heat treatment

Failure to properly quench and temper Grade P110 can also increase its susceptibility to hydrogen stress cracking and brittle fracture. One of the peculiarities of Grade P110 is that it often contains enough alloy content to be air hardening, and normalized coupling stock may exhibit satisfactory yield strength and tensile strength, and typical hardness for Grade P110. However, the Charpy values of a coupling inadvertently machined from coupling stock that has not been quenched and tempered will be quite low, as will be its resistance to hydrogen-stress cracking. Likewise, failure to temper a coupling will result in a hard microstructure with very high susceptibility to brittle fracture and hydrogen-stress cracking.



*Figure 9 Photomicrograph of untempered martensite in a cracked coupling.
Arrows indicate secondary cracks.*

A less obvious heat treatment error is inadequate austenitization. If the coupling stock does not get hot enough during austenitization, or is not held at temperature long enough, residual ferrite may remain, resulting in a mixed microstructure upon subsequent quenching and tempering. It has been well-established that, at a given strength level, a uniform microstructure of tempered martensite shows optimum resistance to environmentally assisted cracking.

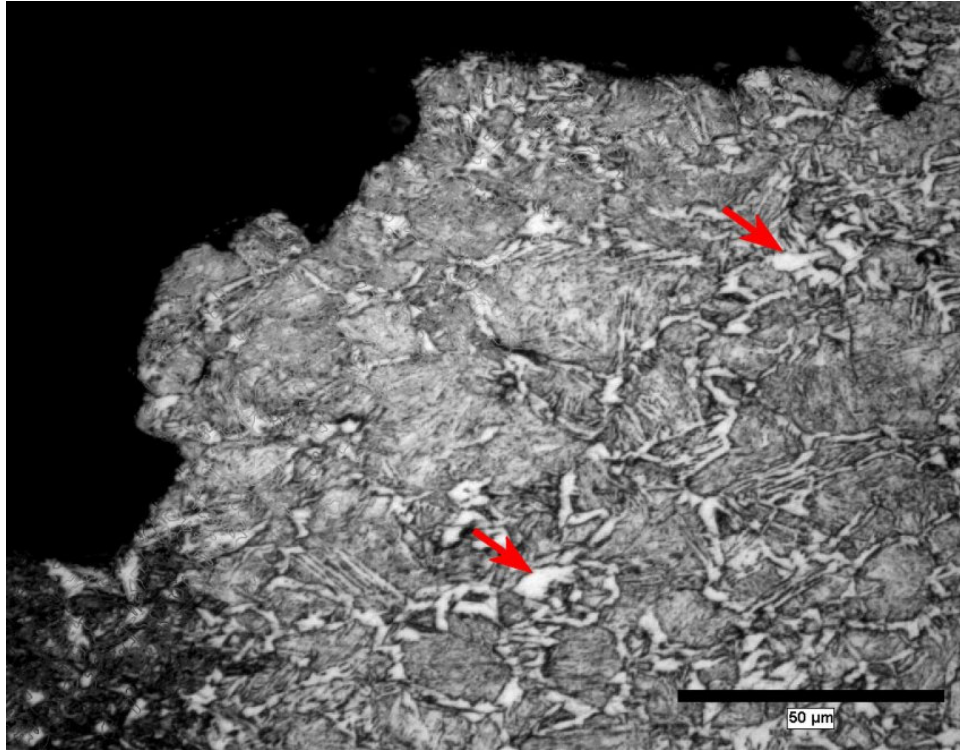


Figure 10 Photomicrograph of ferrite, arrows, in a cracked Grade P110 coupling.

Local variations in microstructure and hardness, due to localized heating, may also affect the susceptibility of a coupling to hydrogen stress cracking. Specifically, hard spots show higher susceptibility to environmentally assisted cracking and may fail in environments where satisfactory Grade P110 might ordinarily perform satisfactorily.

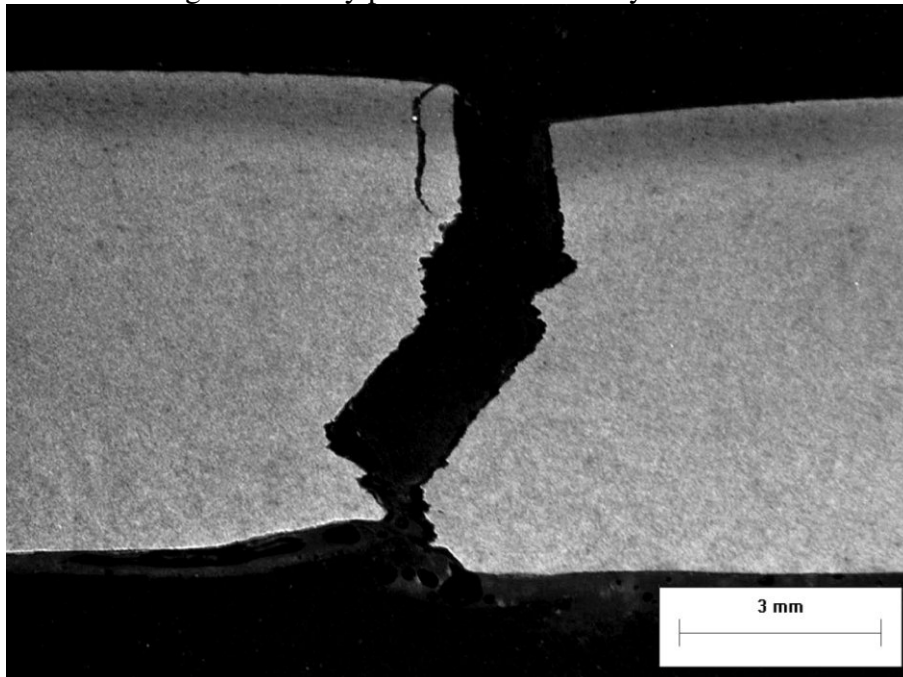


Figure 11 Photomicrograph of cracking initiating in a hard spot.

Although improper heat treatment may not generate unsatisfactory yield strength or tensile strength, it nearly always results in unsatisfactory CVN impact toughness. That said, it should be recognized that API 5CT calls for mechanical testing of a coupling blank from each heat before machining and it is not possible to extract the specified size of mechanical testing specimens from a machined coupling. The marginal failure of subsize specimens that have been machined from a failed coupling to satisfy yield strength or CVN requirements may be the result of normal material inhomogeneities, and may not necessarily indicate improper heat treatment.

High-collapse couplings

Nonetheless, many coupling failures have occurred in satisfactory Grade P110 steel under relatively benign conditions. Tellingly, however, such failures have occurred almost exclusively in Grade P110 couplings with a measured yield strength in excess of about 920 MPa (133 ksi). Since the susceptibility of high-strength steel to hydrogen-stress cracking generally increases with hardness and strength, relatively high-strength Grade P110 couplings can be expected to show a correspondingly increased susceptibility to hydrogen stress cracking. These couplings have generally been installed on high-collapse casing with similar mechanical properties.

Given the process control capabilities of modern casing mills, it is unlikely that the relatively high yield strength is accidental. However, the rationale for heat treating couplings to the high end of the specified strength range is unclear. Although increasing the yield strength of the casing will increase its collapse resistance, increasing the yield strength of the couplings provides no such benefit. The couplings are much stouter than the casing and are not susceptible to collapse. Nonetheless, many manufacturers, domestic and foreign, have apparently chosen to manufacture “high-collapse couplings” to go with their high-collapse casing. This has undoubtedly contributed to the rash of recent coupling failures.

Summary and Recommendations

Although some of the failures in Grade P110 couplings may be attributed to defective steel, mechanical damage, or unusually aggressive environments, many of the failures have occurred in satisfactory steel in benign environments. One factor common to nearly all of the failures in satisfactory steel is a coupling heat treated to the high end of the yield strength range specified for Grade P110. Although most of these couplings fully satisfy all requirements of API 5CT for Grade P110, their relatively high strength results in a correspondingly increased vulnerability to hydrogen stress cracking. It should be possible for manufacturers to improve the performance of their couplings by heat treating to the low end of the specified range of yield strength values. Purchasers of high-collapse casing should take particular care to make sure that they are not also receiving “high-collapse couplings.” In cases where an especially high degree of reliability is required, it may be prudent for purchasers to consider couplings of a sour service grade, such as Grade C110, that has been carefully formulated and heat treated for improved resistance to environmentally assisted cracking. Environmentally assisted cracking failures do occur in high-collapse Grade P110 casing, but with far less frequency than the recent spate of coupling failures, making the use of sour service casing less critical. Nonetheless, high-collapse casing should be ordered only for those wells where the well design requires the marginally increased performance.