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Failures Related to API 5CT High Strength Steels

American Petroleum Institute (API) 5CT high strength steels are extensively used for casing strings in wells subjected to high cyclic hydraulic fracturing loads. While non-sour grades of API steel such as P110 casing strings have been used satisfactorily for well construction, standard API P110 connections have seen higher rates of failures than pipe body failures in shale wells that require hydraulic fracturing. P110 pipe body and connection failures have also been experienced in cases where poor manufacturing practices have been employed to produce P110 steel casings and connections used in wells subjected to these high hydraulic fracturing loads.

Important Material Properties

The following material properties are important when understanding the limitations of API 5CT high strength steels: yield strength (YS), Charpy V-notch (CVN) impact energy, hardness and tempering.

API Specification 5CT/ISO 11960 defines the YS by drawing a vertical line at an elongation of 0.5% to 0.65% depending on the material grade (0.6% for P110) and where it intersects the stress-strain curve in a tensile test is the YS. The ASTM method draws a line parallel to the linear portion of the stress strain curve starting at 0.2% elongation and where it intersects the stress-strain curve on the stress axis is defined as the 0.2% offset YS. Both methods generate very similar results. This value obtained from tensile testing is used for determining if a material meets the API specified minimum yield strength (SMYS) requirement, which is critical for load case considerations and determining design safety factors.

CVN Impact Energy or "toughness" is the energy required to initiate and propagate a crack in the material. Toughness is a valuable property as it enables a material to arrest a crack rather than allowing the crack to grow until pipe failure. Toughness has a strong correlation to temperature and can be very high at bottomhole temperatures; however, some high strength steel materials will become more brittle at cooler, surface temperatures.

Hardness Testing measures the ability of a material to resist deformation from a known compressive force applied to an indenter. The higher the strength of the steel, the less deformation will occur; hence, the higher the hardness value obtained. Since there is a correlation between hardness and tensile strength, the hardness test can be used as a non-destructive small scale quality assurance test to determine the approximate strength level of the steel. Another important associated consideration is that materials with higher hardness and yield strength are more vulnerable to environmentally assisted cracking.

Tempering is a thermal process where steel is heated to a predetermined temperature for a certain period of time after being hardened by quenching from a relatively high temperature. As quenched, carbon steel is very hard and behaves in a brittle fashion; however, the tempering process lowers the hardness/yield strength and restores the toughness of the steel back to a more acceptable level, based on the time and temperature used during this process.

Current P110 API 5CT Specifications

API Specification 5CT requires P110 grade steel to have a yield strength range between 110 ksi and 140 ksi. Due to the high strength of this material, it will inherently have a very high hardness, making it vulnerable to environmentally assisted cracking, especially as it gets closer to 140 ksi. Many high strength steel materials have a maximum hardness requirement to address this issue; however, P110 steel lacks this requirement.

Furthermore, all high strength sour grade oil country tubular goods (OCTG) steels have a minimum tempering temperature requirement to ensure hardness is reduced, and sulfide stress cracking (SSC) resistance increased along with toughness. However, P110 is required to be quenched and tempered, but lacks a minimum tempering temperature requirement. Some basic P110 specification requirements are shown in Table1.

The advancements of today's standards in steel making and processing technologies enables the steel industry to produce cleaner and tougher steels; however, this is not reflected in the current edition of the API 5CT specification. Additionally, P110 pipe body material does not have a defined toughness testing requirement unless specifically invoked by the end user. Even when toughness testing is required, the minimum CVN impact value requirements in API 5CT (for pipe body and coupling stock) are too low.

Grade	P110
Yield Strength	110-140 ksi
Tensile Strength	125 ksi minimum
Heat Treatment	Quenched & Tempered

Table 1: Basic API 5CT P110 Requirements

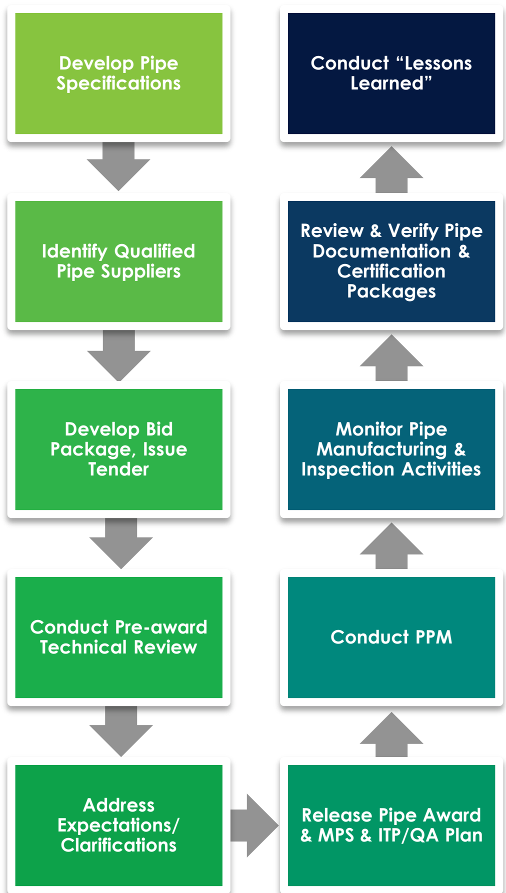

Figure 1: Generic Pipe Purchasing Process

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Due to these low CVN toughness value requirements and/or the lack of toughness testing requirements, the end user must acknowledge if there is a need for higher-than-standard toughness material to be used in their well designs.

Typical Failures in Onshore Wells

While P110 steel tubulars perform adequately in many wells, it is more susceptible to failure in wells requiring high cyclic fracturing loads. Most of the documented failures occur at the connections where the fracturing cyclic stress levels are the highest due to make-up stresses overlaid on the high applied internal pressures. Additionally, even the presence of very low concentrations of H_2S not considered sour by NACE and/or frack fluids may generate enough hydrogen to embrittle high strength steels such as P110 and cause it to fail when subjected to these high frac loads. In other cases, failures have also occurred due to manufacturing defects in the electric resistance welding (ERW) seam welds and/or due to seamless pipe defects such as seams, laps, scabs, and/or cracks.

Failure Mitigation

When evaluating an onshore well design requiring high cyclic fracking loads, three important parameters must be considered: (1) stress level, (2) environment and (3) material susceptibility to cracking due to the environment and/or high cyclic loads.

Since the highest stresses are always expected to be at the connections, the stress levels can be reduced by using a connection with low make-up stresses. Depending on the economics of the well(s), a standard API connection with high make-up stresses may be substituted by a connection with lower make-up stresses such as a low thread interference connection having a metal seal near the end of pin (i.e. metal to metal seal proprietary connection) and/or any other type of connection having lower stresses upon make up (i.e. modified API connections).

Since non-producing environments during fracking on some of these offshore wells can be unpredictable, it has become standard practice by some operators to specify P110 casing material with some restrictions on the maximum allowable yield strength. Depending on the manufacturer, restricted P110 material may have different designations such as restricted yield (RY), or mild sour (MS), just to name a few. The typical maximum allowable yield strength for this RY P110 material is 125 ksi. Reducing the maximum allowable yield strength decreases the susceptibility to environmental cracking and, at the same time, increases the toughness of the material since the tempering times and temperatures utilized produces a softer, tougher material.

Another important aspect in mitigating casing failures in onshore wells is having a robust QA/QC program and pipe purchasing process. Figure 1 shows a generic recommended pipe purchasing process schematic that can help avoid failures due to pipe manufacturing issues. Customized QA/QC programs can then be developed depending of the operator's needs.

Example of Defective Pipe Failure

A 7" ERW P110 casing joint has failed on an onshore well during the 23rd frack stage. The well was scheduled to undergo 40 frack stages.

CVN impact testing was specified for this pipe by the vendor. CVN impact testing performed at the laboratory revealed that the toughness of the ERW seam weld was slightly below API 5CT requirements for ERW pipe. The combination of high cyclic frack loads and a low toughness material caused a crack to initiate and propagate causing the pipe to burst and lose pressure containment. Even though the transverse ERW CVN impacts were just slightly below the minimum 15 ft-lbs required by API 5CT adjacent to the failure area, the material exhibited greater levels of brittle behavior than ductile behavior (i.e. only 10% shear area). This was also observed in material that was just slightly tougher than minimum API 5CT requirements and tested further away from the failure location (i.e. only 20% shear area). Material test reports (MTR) from the manufacturer reported CVN impact values 4 times greater than the ones obtained at the laboratory during the failure investigation.

Metallographic and scanning electron microscope (SEM) analysis performed on cross-sections of ERW through-thickness samples revealed that the material contained large amounts of mid-wall centerline segregation (shown in Figure 2). Excessive centerline segregation may lead to poor fusion line (FL) toughness, lack of fusion, FL embrittlement due to metallurgical effects and/or a detrimental increase in FL hydrogen embrittlement and/or SSC susceptibility when exposed to producing or non-producing environments.

In addition to all of these findings, the manufacturer revealed that this ERW pipe was tempered at a temperature approximately 500°F lower than what was reported in the MTR. Tempering the casing at the higher MTR reported temperature could have helped prevent the casing from behaving in such a brittle fashion. However, API 5CT does not have a minimum tempering temperature requirement for P110 casing steel material which allows the manufacturer to temper the material at a temperature that can yield low toughness properties. The operator of this well did not have a robust casing purchasing program that could have helped control the quality of tubulars being used in their wells. Buying off the shelf casing strings having no specific fit for purpose requirements can help reduce costs, but it just takes one failure to wipe out all the savings and jeopardize the profitability of a well.

Conclusion

Having a robust connection design selection analysis process, QA/QC program and pipe purchasing process, in addition to material specifications with more rigorous fracture toughness fit-for-purpose requirements, can avoid failures in applications where high cyclic frack loads are applied.

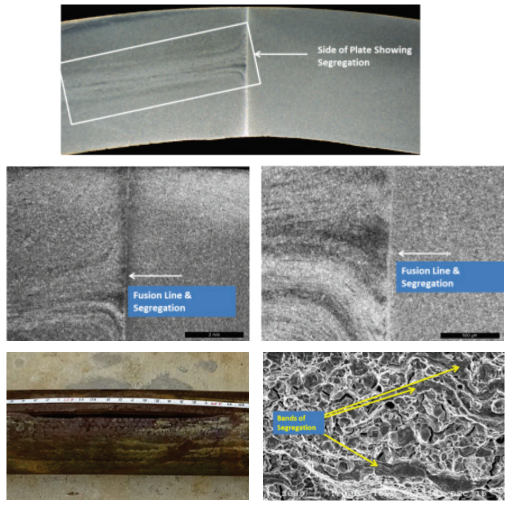

Figure 2: P110 ERW Fusion Line Brittle Fracture Failure

References

1. API Specification 5CT, Specification for Casing and Tubing
2. NACE MR0175/ISO 15156