THE AMERICAN OIL & GAS REPORTER®
SEPTEMBER 2006
The "Better Business" Publication Serving the Exploration / Drilling / Production Industry

Supplementary Specs Key For N-80

By Samit Gokhale
and Sean Ellis

HOUSTON–N-80 casing is a preferred casing grade for production casing strings. N-80 casing is usually ordered to API Specification 5CT without specifying the appropriate supplementary requirements. However, casing strings that meet the minimum strength requirements of API Specification 5CT have experienced sudden failures during normal workover and well stimulation operations.

This article presents a case study and lessons learned from the analysis of such a casing failure in a well in East Texas. It is based on the results of metallurgical analyses performed during the investigation, and details the standard manufacturing operations and heat treatment processes performed for N-80 casing ordered to API Specification 5CT, and the result of these operations on the casing's final material properties.

By re-heat treating the failed casing with supplementary requirements in mind, the casing material properties were improved substantially. In fact, if the casing initially had the properties of the re-heat treated steel, the failures on the subject well likely would have been avoided.

After completing logging operations on the well, 5½-inch, 17 pound/foot normalized type N-80 LT&C casing (N-80 grade casing) was successfully run to a total depth of 10,262 feet. The casing was ordered to API Specification 5CT ("Specification for Casing and Tubing," Sixth Edition, American Petroleum Institute, October 1998). While cementing the casing, pump pressure suddenly dropped from 2,400 to 400 psi. Subsequently, a split in the casing was located at ±3,980 feet based on pressure tests, a spinner/temperature log, and a casing inspection log.

The burst joint was to be pulled out of the hole for failure evaluation. However, during the recovery operation, the 5½-inch casing string parted in the first joint below the slips. Additionally, the third joint from the surface had a longitudinal split located 26 inches from the end of the coupling.

Based on the fracture surface morphology and the appearance of the longitudinal split, the failure mechanism was identified as a brittle fracture with rapid crack propagation. It was suspected that the casing material had poor fracture toughness. The exposure of material with poor fracture toughness to the operating loads, coupled with localization of stresses at the slip cut, had led to crack initiation followed by rapid propagation of the crack front, resulting in a brittle fracture. Operational load analysis indicated that the tensile and pressure loads were well below the casing's rated capacities. To investigate the cause of the failures, both the parted joint and the split joint immediately below the parted joint were analyzed. The burst casing joint at 3,980 feet

TABLE 1

Material Property Requirements for API 5CT N-80 Grade Casing

Major Material Property Requirements	N-80 Grade Casing Ordered to: API 5CT	API 5CT w/ SR16
Chemical analysis	Yes	Yes
Tensile test (for yield strength, tensile strength, percent elongation)	Yes	Yes
Charpy V-notch impact test (for fracture toughness)	**No**	**Yes**
Hardness test	No	No
Fine-grain practice (grain size ≥=5)	Yes	Yes

TABLE 2

Conformance of Failed Casing with API Specification 5CT (With and Without SR16)

Material Property	Meets API 5CT?	Meets API 5CT with SR16?
Chemical composition	Yes	Yes
Material strength (tensile test)	Yes	Yes
Charpy V-notch impact energy (for fracture toughness)	—	**No**

was not recovered and was not available for examination.

Metallurgical Analysis

Metallurgical analysis of both the parted and the longitudinally split casing joints was performed to identify the factors contributing to failure. Material testing was performed to determine whether the material properties met the requirements of API Specification 5CT and identify the material attributes that contributed to the failures.

Chemical composition, material strength, hardness and fracture toughness are the major material attributes that affect a material's ability to sustain loads and resist initiation and propagation of cracks. API 5CT mandates tensile testing and chemical analysis for N-80 grade casing.

The API specification does not require Charpy V-notch impact energy testing unless agreed to by the manufacturer and purchaser. Charpy V-notch impact energy values generally are indicative of the fracture toughness of the material. Because API does not mandate this test for normalized N-80 grade casing, manufacturers do not routinely perform supplementary testing to verify impact energy values to qualify N-80 grade casing.

This additional test normally is performed only if the supplementary requirement SR16 of API Specification 5CT is specified. Table 1 summarizes the major material property requirements for API Specification 5CT N-80 grade casing, with and without supplementary requirement SR16. Tensile tests, chemical analysis and Charpy V-notch impact energy tests of the failed casing joints were performed. Table 2 presents a review of the conformance results of the failed casing material with API requirements.

The failed casing met the mandatory material property requirements of API Specification 5CT, namely chemical composition and minimum strength requirements. The casing material had poor fracture toughness, as indicated by the low-impact energy values, and did not meet supplementary requirement SR16. However, because the casing was ordered to API Specification 5CT without specifying SR16, supplementary tests to verify impact energy values were never performed by the manufacturer to qualify the N-80 casing string. Had the supplementary tests been specified in the purchase order, the casing string would have been rejected, and the failures likely would have been avoided.

Fracture toughness is the material property that quantifies a material's resistance to crack propagation from existing cracks and/or imperfections. Because the test to measure fracture toughness is difficult and expensive, Charpy V-notch impact energy values are used as an approximation of fracture toughness. Low impact energy values generally indicate the material has poor fracture toughness.

Material with low-impact energy values has a limited ability to accommodate dynamic loads and advancing crack front, is sensitive to crack initiation and propagation, and usually fails by brittle fracture and/or has reduced fatigue performance.

Figure 1 graphically shows the relationship between material toughness and its ability to accommodate existing cracks under varying stress levels. Tougher materials can tolerate larger defects for same stress or higher stress for same size defects (i.e., a tougher material shifts the curve to the right, allowing the material to withstand both larger defects–stress risers, notches, existing cracks, etc.–and higher stresses).

Microstructural Evaluation

Examining the fracture surface and material testing confirmed that the failures were caused by the material's poor fracture toughness. To evaluate the factors contributing to the poor fracture

FIGURE 1

Relevance of Fracture Toughness of Material

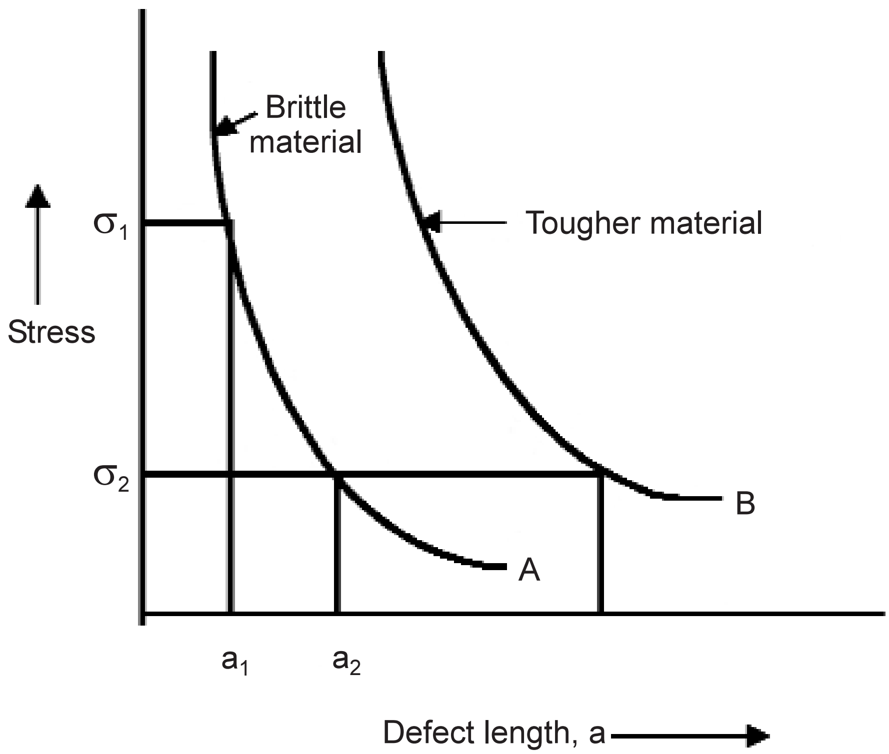


TABLE 3

Longitudinal Impact Energy Test Results of Re-Heat Treated Sections

Property	As Received	Re-Heated Treated (1,436°)	Re-Heat Treated (1,472°)	Re-Heat Treated (1,508°)
Impact energy (ft-lbs)	**8, 9, 9**	36, 36, 34	34, 35 31	32, 32 33
% shear	10, 10, 10	99, 99, 99	99, 99, 90	99, 99, 90
Lateral expansion (mils)	12, 14, 13	57, 54, 50	45, 51, 42	49, 52, 52

toughness, the material microstructure was evaluated, and the manufacturing and heat treatment operations were studied. API 5CT requires N-80 grade casing to be made to fine-grain practice (grain size ≥=5 as determined in accordance with test methods outlined in ASTM E112). It also requires the pipe to be normalized, or at the manufacturer's option, to be normalized and tempered or quenched and tempered full length.

The failed casing material presented a coarse structure of ferrite and pearlite. The grain structure consisted of coarse pearlitic grains surrounded by fine ferrite daisy chained around prior austenitic grain boundaries. The pearlitic grain size measured 2.0 to 3.0, while the ferritic grain size measured 13.0. The overall grain size measured 5.5, which met the API Specification 5CT grain size requirements. However, the coarse appearance of the pearlitic grains and the nonuniform microstructure suggested that the casing joints were either in as-rolled condition, or the normalization procedure was improperly performed.

The relative sizes of ferrite and pearlite are determined by the prior austenitic grain size of the steel. During air cooling, temperature and cooling rate greatly influence the fineness (grain size) of pearlite. Lower exit temperatures, improper soak time or improper cooling rates could have contributed to the coarse pearlitic grain structure.

To evaluate the normalization heat treatment procedure, the mill's manufacturing process was studied. The N-80 grade casing was processed using a hot stretch mill process. Hot rolling of the tubes was initially performed to obtain the required wall thickness. Next, the tubes were processed through a hot calibration process, where the correct outside diameters were obtained. Before the hot calibration process, the tubes were re-heated from a 1,472 degrees Fahrenheit (800 degrees Celsius) exit temperature after the hot rolling step to 1,652-1,688 degrees. The tubes lose temperature during the hot calibration process, resulting in a hot calibration exit temperature of 1,472-1,508 degrees. The exit temperature normally is monitored using infrared pyrometers. After the hot calibration process, the tubes are air cooled.

In this manner, a conventional normalization heat treatment–where the finished components are heated above the austenitic transformation temperature and subsequently cooled in still or slightly agitated air–is not performed. However, section 5.2.1 of API Specification 5CT states that "All pipe processed through a hot stretch mill shall be considered normalized, provided the exit temperature is above the upper critical temperature for the steel being processed and the pipe is air cooled."

The minimum phase transformation temperature on the carbon-iron phase diagram dictates that the exit temperature has to be greater than 1,436 (780 Celsius) degrees for the failed casing. The theoretical exit temperature after the hot calibration process is 1,472-1,508, which means that pipe processed through the hot calibration process and air cooled would be considered normalized, per API Specification 5CT.

FIGURE 2A

Failed Casing Joint Microstructure As Received (x100)

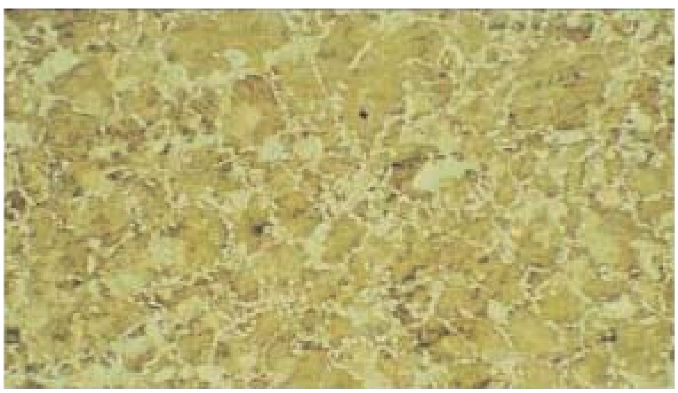


FIGURE 2B

Failed Casing Joint Microstructure After Normalizing at 1,436° (x100)

FIGURE 2C

Failed Casing Joint Microstructure After Normalizing at 1,472° (x100)

FIGURE 2D

Failed Casing Joint Microstructure After Normalizing at 1,508° (x100)

When performed properly, the hot stretch mill process results in a good combination of mechanical strength and fracture toughness. However, as the hot calibration exit temperature is very close to the minimum required transformation temperature, the temperatures have to be continuously and accurately monitored. Any deviation from the narrow temperature tolerance zone, or inaccuracies associated with the temperature measuring instrument, will result in improper normalization heat treatment.

Lower exit temperatures, improper soak time or improper cooling rates could result in the type of material properties observed on the failed casing joints in the East Texas well. Such joints may meet the minimum strength and elongation requirements of API Specification 5CT, in spite of possessing poor fracture toughness.

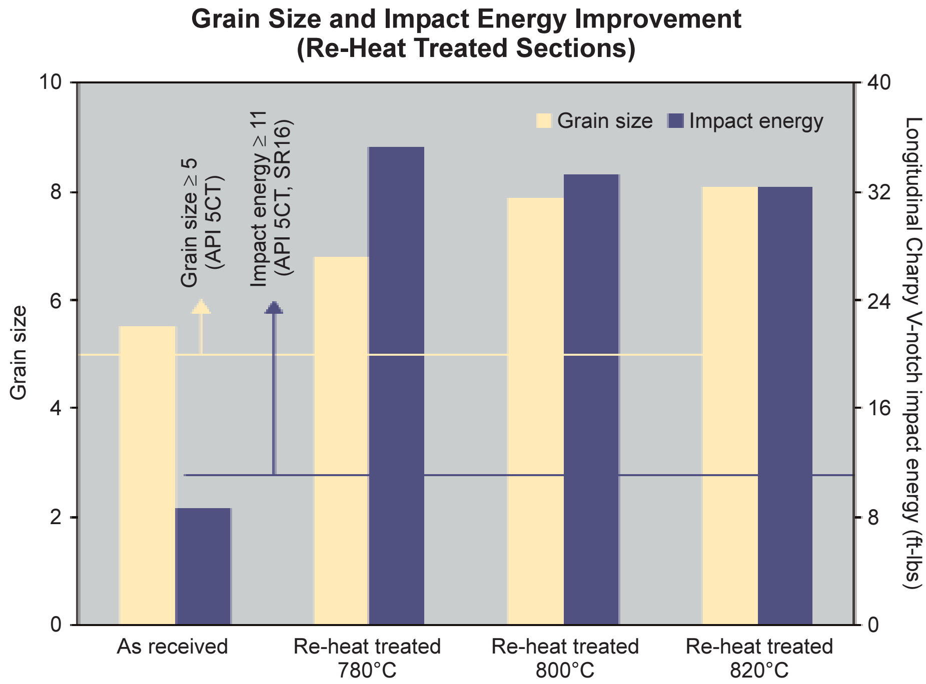
Re-Heat Treatments

To confirm the theory that the failed casing joints were improperly normalized, and that this led to the poor fracture toughness of the material, sections from the failed casing joint were re-heat treated (normalized) at 1,436, 1,472 and 1,508 degrees Fahrenheit. These temperatures represent the minimum temperature for normalizing this material according to API Specification 5CT, and the specified temperature range for normalizing this material according to hot stretch mill process.

After normalizing the sections from the failed casing at these temperatures, the microstructures were examined and the grain size was measured. Charpy V-notch impact tests also were performed on half-size specimens machined from the re-heat treated sections. The overall grain sizes of the original and re-heat treated sections of the failed casing were 5.5 as received, 6.8 after re-heat treating at 1,436 degrees, 7.9 after re-heat treating at 1,472 degrees, and 8.1 after re-heat treating at 1,508 degrees. The microstructures are presented in Figures 2A-2D. Table 3 presents the impact energy values of the re-heat treated sections.

The re-heat treated sections presented a fine structure of ferrite and pearlite. Significant refinement in the overall grain size was observed. Unlike the coarse pearlitic structure (pearlitic grain size of 3.0) and fine ferrite structure (ferrite grain size of 13.0) of the original material, the re-heat treated structure was more uniform.

FIGURE 3



Significant improvement in the impact energy values also was observed. The average impact energy of the re-heat treated sections was greater than the minimum required value specified in the supplementary requirement SR16 of API Specification 5CT. The improvement in the grain size and the impact energy values is depicted in Figure 3.

The significant refinement of the microstructure and increase in the fracture

SAMIT GOKHALE

Samit Gokhale is manager of mechanical and materials engineering at T H Hill Associates Inc. in Houston. He has been with the company since 2001, and has worked on and managed numerous failure investigations and projects involving drill string design, deepwater landing string design, fatigue design and stress analysis. Gokhale also manages the research and development department, and is an instructor for drill string design, fatigue design and failure prevention courses. Prior to joining T H Hill Associates, he worked as a design engineer at Tata Motors Limited. Gokhale holds an M.S. in mechanical engineering from the University of Florida.

SEAN ELLIS

Sean Ellis joined T H Hill Associates Inc. in Houston in 1998 as a project engineer, and has since worked within the organization as manager of mechanical design and failure analysis, vice president of research and development, and vice president of sales and marketing. Throughout his career at T H Hill Associates, Ellis has been involved in developing new technology to assist in failure prevention and in the design and design review of many drill stem components used in challenging wells. He holds a B.S. in mechanical engineering from the University of Florida.

toughness for each of the re-heat treated sections, as compared to the microstructure of the original material, confirmed that the failed casing was improperly heat treated, and this resulted in the poor material fracture toughness. The casing material may have been heated to a temperature less than 1,436 (780 Celsius) degrees.

The analysis confirmed that N-80 grade casing ordered to API Specification 5CT may be improperly normalized at the end of the hot stretch mill process. Such casing joints still may meet the minimum strength as well as the grain size requirements of API Specification 5CT, but will possess poor fracture toughness. If the supplementary requirements SR16 of API Specification 5CT are not specified, then additional tests to verify Charpy V-notch impact energy may not be performed, resulting in acceptance of these casing joints. Such casing joints may burst or part unexpectedly in a brittle manner during normal workover and well stimulation operations.

Consequently, when ordering N-80 grade casing of the normalized (N) or normalized and tempered (N&T) type, operators are advised to specify supplementary requirement SR16 of API Specification 5CT. If an existing stock of API Specification 5CT N-80 grade casing is available, the casing string can be selected if it is quenched and tempered (Q&T) type. If the available stock is N or N&T type, then additional Charpy V-notch impact energy tests should be performed to ensure that the casing material meets the supplementary requirement SR16 of API Specification 5CT. ❐

Editor's Note: For additional information on N-80 grade casing and API Specification 5CT, see SPE/IADC 92431, a technical paper originally prepared for presentation at the 2004 Society of Petroleum Engineers/International Association of Drilling Contractors Drilling Conference.