Specifications for Special Tubular Products

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ABSTRACT

Traces development of requirements for special tubular products for wells. Describes manufacture, heat treatment, testing and inspection of tubular goods for use in critical well services requiring high strength materials or involving corrosion, corrosion cracking or embrittlement in the presence of hydrogen sulfide. Discusses yield strength and hardness limits. Proposes specifications for special tubular products.

Steel tubular goods find a wide range of applications in the oil and gas producing industry. These versatile products serve as pressure piping for gathering lines and transmission lines and for acidizing and cementing operations: as mechanical tubular components in oil field equipment such as packers, valve seats and pump cases to name but a few and as combined pressure-resisting-mechanical components, such as casing, tubing, drill pipe, and couplings for the whole gamut of producing conditions. The tubular goods for most of these applications are worthy of note as specialized products, made to specification from various steels in a range of sizes. However, this discussion will deal only with specialized tubular goods, and mainly with special seamless tubing used for producing oil and gas. But before proceeding with a discussion of specifications for special tubing, it will be helpful to review the development of requirements for special tubular products for wells and some highlights of their manufacture.

The first use of tubular goods in wells was for casing, and the use is nearly as old as is the discovery of oil. The first casing was conveniently available water pipe which satisfactorily met the need to prevent sand and soft earth from caving into the shallow holes drilled by cable tools. At the same time, it also served for producing the well. From these humble beginnings, the usage of tubular products in wells grew to over two million tons in the United States in 1959. Then, as wells became deeper, rotary drilling was developed, and, for drill pipe, tubular goods proved ideal because of its torsion strength-weight ratio and a bore which permitted circulation of drilling fluids.

Deeper wells also generated a need for a string of tubing for producing the well in order to take pressure off the casing, simplify clean-out, facilitate pumping, combat corrosion, reduce hazard, and increase control over wells. The first well tubing was, again, common pipe. This origin is reflected in the continuing use of standardized pipe OD sizes for tubing although it now differs considerably from ordinary carbon steel pipe. Actually, seamless tubular goods can be readily produced in almost any conceivable combination of diameter and wall thickness. The retention of pipe OD sizes has the advantage of standardization for joining. However, today even OD sizes are undergoing some modification because of the requirements for multiple completion wells.

The demand for pipe and the variations in products supplied by producers vying for the new business inevitably led to a need for specifications and standards to insure quality and consistency in tubular goods. As a result, API Specification 5 was prepared in 1924 and revised as 5A soon afterward and frequently since then. From this point, the tubular shape remained a basic component for producing wells, but change followed upon change. A brief history of the development of needs for tubular goods of higher strength is given in the steady progressing of grades in the API specifications. As wells got deeper and pressures increased, F-25, H-40, J-55, and N-80 grades came into being. In 1960, the API published a new tentative standard, Specification API 5AX, covering the high strength grades, P-105 and P-110. In view of current problems in the use of P-105, P-110 and higher strength grades, it is easily forgot that the transitions from H-40 to J-55 and then to N-80 were also fraught with problems for the technologies of earlier times. These higher carbon and alloyed steels used to obtain greater strength responded differently to heat treatment, machining, welding and the effect of notches than their pipe steel predecessors. But knowledge and experience conquered these difficulties so that today we retreat to N-80 materials as "safe" and "sure".

Beginning in World War II the tremendous development of natural gas production to fulfill the demand for petrochemicals and the post-war demands for gas heating brought new materials problems to the producing industry. For example, gas wells tended to have a profusion of problems of high pressures and new corrosion. Corrosion in gas condensate wells led in the late 1940's to field tests by the Cotton Valley Producers Association and the National Association of Corrosion Engineers. These tests showed that increased corrosion resistance was obtained with nickel or chromium alloy steels in sweet gas condensate service.

While oil country goods had previously been furnished mainly by the pipe mills, these new developments brought into the field specialty manufacturers to supply the demand for corrosion-resisting, high strength alloy tubing. Steels with 5 and 9 per cent nickel were early favorites and continued so until the Korean War when nickel was placed on defense allocations. However, the nickel shortage, stress corrosion cracking failures in some 9 per cent nickel strings and the development and wide use of inhibitors for controlling corrosion caused an abrupt decline in the use of alloy steel tubular goods in the early 1950's, but this trend was strongly reversed in the late 1950's. Too, deeper gas wells brought requirements for tubular goods at minimum yield strengths of 105,000 and 110,000 psi and increased the demand for heat treated alloy steel tubular products. Also, sulfide stress cracking problems in sour gas condensate wells and the relation of this problem of metallurgical characteristics created a need for special tubular products with closely controlled properties and heat treatment as preventatives. Furthermore, corrosive gas condensate wells making large quantities of carbon dioxide cracked N-80 and 4340 tubing but were successfully produced with 9 per cent chromium tubing. And, most recently, the producing industry has made wide application of the multiple completion technique using "macaroni tubing" in small sizes. New techniques to increase the recovery of oil, such as "in situ combustion" are expected to bring new materials problems in production. Consequently, it is apparent that the oil and gas industry will have continuing need of these special tubular products.

At this stage, it is important to differentiate between the special tubular products under discussion and other oil country tubular goods. This differentiation can perhaps best be made in terms of manufacture and specifications. Oil country tubular goods are usually produced like pipe in large tonnages in a restricted number of sizes, grades and chemical compositions that meet standard API specifications but have relatively broad definitions of finish, inspection, and mechanical properties. By contrast, specialty products may be produced in an almost unlimited range of sizes, grades and chemical compositions, including highly alloyed and corrosion resisting steels, but with restricted specifications on finish, heat treatment, mechanical properties and inspection methods. These specifications are generally negotiated for individual requirements.

Assuming that a special tube is ordered, one may find it may be helpful to consider some of the operations involved in making it. First, the manufacture of special tubular goods begins with the melting, blooming and rolling of steel to a solid round bar. The steel may be open hearth or electric furnace quality although for quality reasons the higher alloys such as 9 per cent chromium are always made in the electric furnace. At this stage, blooms and later bars are carefully cropped, inspected and ground or scarfed to remove defects, while Etch tests are used to check for unsound steel which must be discarded. Secondly, the seamless tubing is formed by rotary piercing mills from solid bars. Here, adaptability and flexibility are keynotes of piercing specialty tubing, and the mills are built for rapid changeover and permit short as well as long runs of different sizes to be made economically and readily. This adaptability represents a difference from normal pipe mill practice. Finally, while most well tubing is furnished hot finished, it can also be made by cold drawing a hot finished product. Cold drawing provides a practical way of furnishing longer lengths, up to about 45 ft. This process allows a reduction in the number of joints and is worthy of consideration because of lower joint costs.

After cropping, inspection and removal of injurious defects and hydrostatic testing, the tubes are upset at the ends, an action which gathers stock to permit machining of threaded joints which are themselves usually of the special and proprietary type. Heating tube ends to forging temperatures for upsetting causes a heat transition zone which is between temperature extremes and which is always weaker and often less corrosion resistant than the rest of the length. In gas condensate wells, for example, the difference in metallic structure caused by this heating has led to preferential corrosion in a band behind the upset and has been termed "ringworm corrosion." To restore strength and corrosion resistance, the metallic structure of the tubing is homogenized by a full length normalizing* heat treatment which is done in a continuous furnace. However, the practice of full length normalizing after upsetting is not mandatory in API specifications for J-55 and lesser grades. Consequently, for some applications of J-55, for example, it is necessary to specify normalizing of upset tubing to insure against "ringworm corrosion".

Today it is commonplace for special tubing to carry a specification for restricted strength and hardness properties. Close control of these properties is normally obtained by application after normalizing of a second heat treatment called "tempering". However, because steels differ in their capacities for hardening as functions of composition and section thickness, in actual practice, control of properties begins with the selection of the type of steel and often with selection of an individual heat or heats of steel. It is necessary that the steel harden, through the section thickness (including the thickened upset zone) on normalizing, with something to to spare to allow for controlled softening during tempering. Because of the inherent variations in heats of steel, it is necessary to conduct laboratory tempering trials on mill normalized tube samples representing each heat on each order. These trials are made to establish the exact tempering temperature needed to achieve the specified properties. Then, pilot trials are performed by mill tempering tubing representing each heat at the selected tempering temperature. After the mill heat treatment hardness and tensile properties are determined. If the tests indicate adjustments in tempering temperature are needed to meet property specifications, additional pilot runs are made until the results are satisfactory. The order is then tempered in accordance with the practice for each heat dictated by the trials.

At this point, it might be noted that in some cases a minimum tempering temperature (after normalizing) and controlled yield strength have been specified for tubing to be used in sour gas condensate wells. These applications have been successful according to the user, while other users have utilized maximum hardness limits to specify tubing for this type of service with satisfactory results. However, while tubing can readily be produced to a heat treatment requirement, this type of specification has serious limitations. First, it is subject to misinterpretation unless clearly stated: for example, temperature can be interpreted as furnace temperature rather than as metal temperature, and these temperatures are not necessarily the same; second, there is no convenient test or method of inspection to ascertain compliance with a requirement to apply some specified temperature. For these reasons, the stipulation of tangible and measurable properties is to be preferred for specification criteria.

The upset and heat treated tubes are then inspected. All tubing is visually inspected for injurious defects, dimensions, and tolerances. Beyond this point, inspection varies according to the specifications agreed upon at the time of purchase. For instance, some type of nondestructive test is often specified at the purchaser's option. At present the most common mill inspection test is the magnetic particle test (using fluorescent or non-fluorescent applications); however, some use has been made of the ultrasonic test, which is very commonly applied today for the nondestructive inspection of boiler, superheater, chemical plant, nuclear and other specialty tubing for critical services where failure involves special hazards. The ultrasonic test lends itself to continuous, automated inspection and has the important advantage of being sensitive to defect depth. A lack of this defect depth sensitivity is a shortcoming of magnetic particle and borescope tests for inspection of tubular products. But one disadvantage of ultrasonic inspection is that it must be done before upsetting to allow smooth travel on the conveyors. The upset ends then require inspection by other means such as magnetic particle testing.

Specifications for many types of nondestructive tests of tubular goods have not yet been defined by the recognized specification-writing organizations. As interim specifications, B&W Specifications NDT-1 and NDT-2, describing ultrasonic testing and magnetic particle or fluorescent penetrant testing, respectively, have served many tubular products consumers. These specifications define test methods and also notch calibration standards for ultrasonic testing. Defect limits are customarily negotiated for each purchase. Typical notch depth standards for ultrasonic inspection of some kinds of

*Normalizing is the heating to a temperature above the critical range to homogenize the steel followed by air cooling.

specialty tubing are shown below:

Condition	Notch Standard Per Cent of Wall Thickness
Hot Finished	10
Cold Finished	7.5
Cold Finished, specially processed	3% or .004" whichever is greater

One of the distinguishing features of special well tubing specifications is the limitation of yield strength and/or hardness. The demand by users for maximum and minimum yield strength limitations has been recognized recently by the API in API 5AX Tentative Specification for P-105 and P-110 grades. For example, P-105 tubing in API 5AX Tentative is now specified with 105,000 psi minimum and 135,000 psi maximum yield strength, a 30,000 psi range between limits. There is no maximum on yield strength in API 5A specification, nor do the API specifications contain hardness limits. However, the oil and gas producing industry has considerable interest in restricted yield strength and/or hardness limits for the medium strength materials (yield strengths of 55,000 psi minimum up to 80,000 psi minimum) and the high strength materials (over 80,000 psi minimum yield strength). And, if required, special well tubing can be supplied to 15,000 psi yield strength range between limits (medium strength materials) and 20,000 psi yield strength range between limits (high strength materials).

A very common problem encountered today with special well tubing is the incompatibility of limits being specified for hardness and yield strength on a given materials requirement. For example, the specification of tubing to have hardness of Rc22 maximum and 105,000 -125,000 psi yield strength is an obvious incompatibility. The essence of the problem is that the ideal tubular product for well service should have the strength of hardened tool steel and the toughness of a rubber hose. Unfortunately, it is not in the nature of steel to develop high strength simultaneously with great toughness. High hardness goes along with high strength and lower toughness; however, specifications usually reflect the desire for maximum strength and minimum hardness. In the last decade there has been much work done by both manufacturers and users with notched tubular specimens (C-ring tests) in an attempt to develop a convenient test for measuring the notch sensitivity (toughness) of tubular products. But to date, a completely satisfactory test has not been found.

Hardness tests first entered well tubing specifications because of the general correlation between the degree of hardness and the tendency to crack in hydrogen sulfide stress-cracking tests. Later the hardness test began to be generally used as a quick, nondestructive method for checking uniformity of heat treatment. These are valid reasons for specifying hardness tests. However, the specification of unrealistic hardness limits and the use of hardness testing as a substitute for tensile testing to determine yield strength are unsound. Some of the specification difficulties being encountered result from communications deficiencies, lack of standards, and ambiguous terms — all compounded by an intensely competitive market condition.

Fundamentally, the problem has to do with the relationship between hardness and yield strength. Most materials engineers recognize that hardness of metals and strength correlate to a significant degree; however, some do not stop to consider that the relationships which exist are not absolute. But the correlation between hardness and tensile strength is considered better than that between hardness and yield strength.

Since hardness tests are relatively new in oil field tubular goods specifications, some comments are in order. Hardness is commonly determined by measuring a material's resistance to indentation by a hardened ball or diamond point under a known load. Of these tests Brinell or Rockwell tests are the most common, but, while several years ago Brinell testing was used for well tubing, it has been supplanted by Rockwell testing: the latter makes a smaller impressing under a lighter load; thus permits its use for thinner tube walls than does the Brinell test. Hardness testing is affected by surface conditions such as roughness, scale or a soft decarburized surface layer from heating during manufacture and heat treatment. Proper surface preparation is important for hardness testing and is usually accomplished by grinding.

In some cases, a commercial importance has been attached to one point of Rockwell hardness, a point that is greatly disproportionate to its engineering significance. Rockwell hardness machines are commonly calibrated against test blocks which are only accurate to ± 1, i.e., within a two point range. Hence, a machine is considered accurate if it reads Rc 24, 25, or 26 on a Rc 25 ± 1 test block. Two different machines checked against the same test block may read Rc 24 and 26, respectively, and both are considered accurate. Yet it is easy to see the commercial significance on a requirement for Rc 25 maximum if these machines were in use by two different suppliers or by a supplier and a consumer. Realistic appraisal of the limitations of hardness testing is the only engineering answer to this problem. For this reason, B&W specifications for special well tubing contain a two point Rockwell hardness tolerance for check tests performed outside our plant. On the other hand, properly defined specification limits must be considered as unequivocal and not as "aims" or "approximations". Any other approach, express or implied, defeats the purpose of a specification.

Hardness values obtained on the outer surface of of finished tubing may be slightly greater than are those taken on the mid-wall of tensile or ring samples because of the effects of straightening. Experience has also shown that hardness values tend to be lower on upsets than on bodies* of carbon-manganese or some low alloy steels because of section size effects during normalizing. On the other hand, on higher alloy tubing such as 9 per cent chromium steel, the opposite tends to be true because upsets come to tempering temperature more slowly than on the thinner wall in the remainder of the tube. However, the latter effect is minimized by long tempering times.

Yield strength, as determined for most steel products including tubular goods, is an arbitrarily defined property which can vary with the method of measurement, i.e., .2 per cent offset; .5 or .6 per cent total extension, etc. Furthermore, yield strength and its relationship to hardness are sensitive to composition, heat treatment and microstructure. In other words, for a given steel composition and heat treatment, a scatter of hardness of 3-6 points Rc among test specimens having the same measured yield strength is not abnormal. Conversely, yield strength also scatters for a given hardness level. A computer programmed statistical study of mechanical properties of well tubing recently conducted at Babcock & Wilson facilities indicated that only about 55 per cent of the variation of yield strength measurements is explainable by hardness measurements.

In considering this subject, metallurgists and materials engineers are prone to think and speak of hardness-

*The term "body" is used to describe that portion of tubing between upsets.

strength relationships in terms of averages but to write specifications in terms of maximum and minimum values. However, these averages and values are not the same because averages neglect normal scatter which is of great practical import in meeting specifications. Nothing here is intended to imply that average properties are suitable criteria for specifications because they are not. This lack of suitability has not, however, kept them from being used. As an example, if high strength special tubing is specified to meet Rc 28 maximum average hardness and if that hardness tests at several locations along the length, then the tests are to be averaged for determining the hardness of the piece for acceptance. But such a specification is actually inadequate. It conceivably would accept material Rc 36 on one end and Rc 20 on the other (average Rc 28), although such non-uniform material (exaggerated for illustration) would be unwelcome in the field.

Property specifications are frequently loosely stated and subject to varying interpretation. Materials engineers have a right to know and should satisfy themselves how their requirements will be interpreted, and this knowledge and satisfaction should be gained at the inquiry stage and before contracts are let. Marked variations in response to property specifications on bids may be an indication of varying interpretations since metallurgical behavior of materials is likely to be much the same regardless of manufacturer.

The hardness and yield strength limits shown in Table I have been developed from manufacturing experience and offer a reasonable guide for specifications. Since it is impractical to attempt to cover all possible property levels, representative combinations are listed from the many available.

Special tubular products as herein discussed have not been defined by any of the standard specification writing agencies. To fill this gap, the company with which the author is associated has prepared two specifications, WL-1 and WL-2, covering special tubular products for oil and gas wells. Specification WL-2 covers 9 per cent chromium steel tubing and WL-1 covers other steels at various strength and hardness levels. These specifications incorporate features of inspection and testing which have been discussed herein. Additional specifications can and will be prepared as the need arises.

This presentation has served mainly to describe the special tubular products available to those concerned with the production of oil and gas. No attempt has been made to define how these materials should be used because producing conditions differ widely among wells, formations, and regions of the globe. Where producing conditions indicate a need for special tubular products, successful selection and application can be best assured by good communications between the engineering staffs of the user and the manufacturer.

TABLE I

Some Representative Mechanical Properties Available in Special Tubular Products As Described Within the Paper

Grade	Yield Strength(a) psi	Rockwell Hardness Maximum
J-55	55,000 min	-
-	55,000 min	C20
-	55,000-70,000	C20
-	65,000-80,000	C22
-	75,000-90,000	C23
N-80	80,000 min	-
-	80,000 min	C24
-	80,000-95,000	C24
-	90,000-110,000	C28
-	100,000-120,000	C30
P-105	105,000-135,000	-
-	105,000-125,000	C33
P-110	110,000-140,000	-
-	110,000-130,000	C34
9 Cr-1/2 Mo or 9 Cr-1 Mo	75,000-90,000	C23
"	80,000-95,000	C24
"	90,000-110,000(b)	C28
9% Nickel	90,000-110,000(c)	C28

Notes:

(a) Yield strength determined by extension under load using .5 per cent with J-55 or N-80 types or with materials having specified maximum yield strengths at or below 110,000 psi and .6 per cent with specified maximum yield strength above 110,000 psi.

(b) Achievement of yield strengths above approximately the range 90,000-110,000 psi may involve tempering at temperatures which could embrittle 9 per cent chromium steel. While higher yield strengths can be obtained, the utility of these higher strengths should be carefully examined.

(c) The tempering of 9 per cent nickel steel is restricted because of the low transformation temperature of this alloy. The yield strength which can be achieved without probable detrimental to other properties is shown.