Advancements in Steel Making and The Effect On Pipeline Specifications

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Abstract

This paper will go through the history of the steel making process and how these changes have affected the quality of steel. The process has changed dramatically from early processes to methods used today. Development of these methods resulted in more cost effective manufacturing. One of the methods developed was to use chemistry to enhance the steel. The chemistry of micro alloyed steels will be explained in detail and the benefits and drawbacks of specifying these types of steel for pipeline projects will be discussed. The elements that make up the steel composition, such as Carbon, Manganese, Sulfur, Columbium, and Vanadium, will be discussed and the effect on the steel will be explained. Actual steel making data will be presented and discussed. Pressure vessel quality steel and what the term means will be evaluated. Controlled rolling practices will be explained and how they can be used to affect the steel properties.

The paper will take the information about steel and discuss how these changes should or could be used in the design and specifications for pipelines. Finally the cost benefit of these steels will be discussed.

Introduction

When designing steel pipe there are two major requirements of the material. It must be strong enough to withstand the internal pressure and it must be able to withstand any external loads. AWWA[(2)] design of steel pipe is based on the yield of the steel to withstand internal pressure. The formula is:

$$P = 2st/D$$

Where

P = design pressure
s = allowable design stress (for working pressure this is 50% of yield)
t = thickness of the steel
D = diameter of the pipe

Yield strength is also used to control thrust, stresses at supports, reinforcing for fittings and numerous other design criteria.

Steel pipe is designed as a flexible conduit and relies on this flexibility to withstand the external loads of the soil when installed in a buried condition. Therefore the steel pipe must be ductile in nature. This ductile nature also is important during fabrication and handling of the finished pipe.

The two characteristics of steel that I will discuss in this paper will therefore be yield/tensile strength and ductility. Yield strength is defined as the stress caused by a load creating a 0.5% extension of the gauge length. Tensile strength is defined as the stress required to cause the material to rupture or fail. There are two tests that give representative values for ductility. Elongation, the % increase of a given length prior to fracture during tensile testing, is the most representative of ductility. Charpy V-notch impact testing, the resistance to fracture in the presence of a notch, is more representative of resistance to impact load.

Steel Making

The basic oxygen steel-making process is as follows: Molten iron from a blast furnace is poured into a large container called a ladle. A lance is lowered into molten iron and magnesium is added to the molten iron in the ladle. The magnesium reduces sulfur impurities to magnesium sulfide in an exothermic reaction. The magnesium sulfide is then raked off. The BOS vessel is filled with steel scrap and molten iron from the ladle is added or "charged" until the vessel is full. A lance then blows 99% pure oxygen onto the steel and iron, causing the temperature to rise. This melts the scrap, lowers the carbon content of the molten iron and helps remove unwanted chemical elements. Fluxes are fed into the vessel to form slag that absorbs impurities. Near the end of the cycle, samples are tested and a computer analysis of the steel is obtained within 6 minutes. The steel is then poured or "tapped" into a giant ladle. In the ladle adding alloying elements that give the steel the desired properties further refines the steel. The steel is then removed from the ladle.

Steel making is a process that many people have seen to some degree. It is a staple of many action films to show a steel mill with the villain meeting his demise in the vat of molten steel. It is the ultimate blue collar manufacturing process embodied in the Pittsburgh Steelers football team. The paradigm to this impression is that it is imagined to be a process with very little change. Over the last 50 years there have been numerous advances in the steel making process that has resulted in lower cost, higher quality steel being produced. Technology and manufacturing process have been developed and implemented that result in cleaner and stronger steel at no increase in cost. I will discuss some of these changes that directly relate to yield and ductility and therefor to steel pipe design.

Continuous Cast Steel

Until 1960 most steel in the United States was made by pouring molten steel into an ingot and processing it into finished product after reheat and rolling. These ingots were very thick and the temperature used was high. This produced a grain size that was usually ASTM No 5 or lower. Grain size is represented by a value related to the number of grains per unit area at a magnification of 100 x. Controlling grain size directly relates to the strength and ductility of a material. Fine grain size (higher than ASTM No. 5)[(3)] is a desirable property in steel for water pipe manufacturing.

Current practice for almost all steel made in the United States today is to continuously cast the steel. In this process the steel material is introduced into the caster and is continuously removed from the bottom of the caster in a long and thinner strand of steel. This strand of steel is then cooled and cut to the desired length to be processed. The advantage to this process is that the temperature of the strand is better controlled through the use of computers and finer grain sizes can be produced, particularly when charged directly to the hot roll mill while the steel is above 1000 ^{o} F. These strands are much thinner than the ingots. Prevention of reoxidation of the liquid steel is more easily accomplished via the continuous casting process. These strands are much thinner than the ingots. The cooling temperature is lower and the process allows for rolling them into finished product with less temperature and pressure on the material. The end result is better steel.

Chemistry

Most people have heard of alloyed steels. There are many reasons to use alloying elements in the steel making process, but to understand the important reasons for their use for steels used in pipe manufacturing we need to understand what each element is and does. ASTM A-1018(4) is a relatively new steel standard and has limits on numerous chemicals. It has both structural grades and high strength low alloy steel (HSLAS) grades. I will list the elements from this standard as a representative list and define their use.

A 1018/A 1018M – 02

TABLE 1 Chemical Composition[A] For Hot Rolled, Heavy Thickness Coils

Designation	C	Mn	P	S	Cu[B,C]	Ni[B]	Cr[B,D]	Mo[B,D]	V	Cb	Ti	N
	Designations SS, HSLAS, and HSLAS-F % Heat Analysis, Element Maximum unless otherwise shown											
SS												
Grade 30 [205]	0.25	1.50	0.035	0.04	0.20	0.20	0.15	0.06	0.008	0.008	0.008	0.014
Grade 33 [230]	0.25	1.50	0.035	0.04	0.20	0.20	0.15	0.06	0.008	0.008	0.008	0.014
Grade 36 [250]	0.25	1.50	0.035	0.04	0.20	0.20	0.15	0.06	0.008	0.008	0.008	0.014
Grade 40 [275]	0.25	1.50	0.035	0.04	0.20	0.20	0.15	0.06	0.008	0.008	0.008	0.014
HSLAS[E]												
Grade 45 [310] Class 1	0.22	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	...
Grade 45 [310] Class 2	0.15	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	0.020
Grade 50 [340] Class 1	0.23	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	...
Grade 50 [340] Class 2	0.15	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	0.020
Grade 55 [380] Class 1	0.25	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	...
Grade 55 [380] Class 2	0.15	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	0.020
Grade 60 [410] Class 1	0.26	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	...
Grade 60 [410] Class 2	0.15	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	0.020
Grade 65 [450] Class 1	0.26	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	0.014
Grade 65 [450] Class 2	0.15	1.50	0.04	0.04	0.20	0.20	0.15	0.06	0.01 min	0.005 min	...	0.020
Grade 70 [480] Class 1	0.26	1.65	0.04	0.04	0.20	0.20	0.15	0.16	0.01 min	0.005 min	...	0.014
Grade 70 [480] Class 2	0.15	1.65	0.04	0.04	0.20	0.20	0.15	0.16	0.01 min	0.005 min	...	0.020
HSLAS-F[F]												
Grade 50 [340]	0.15	1.65	0.025	0.035	0.20	0.20	0.15	0.06	...	...	...	...
Grade 60 [410]	0.15	1.65	0.025	0.035	0.20	0.20	0.15	0.06	...	...	...	...
Grade 70 [480]	0.15	1.65	0.025	0.035	0.20	0.20	0.15	0.16	...	...	...	...
Grade 80 [550]	0.15	1.65	0.025	0.035	0.20	0.20	0.15	0.16	...	...	...	...

[A] An ellipsis (. . .) indicates that no limits have been set for that element.

[B] The sum of copper, nickel, chromium and molybdenum shall not exceed 0.50 % on heat analysis. When one or more of these elements are specified by the purchaser, the sum does not apply; in which case, only the individual limits on the remaining unspecified elements will apply.

[C] When copper steel is specified, the limit for copper is a minimum requirement. When copper is not specified the copper limit is a maximum.

[D] The sum of chromium and molybdenum shall not exceed 0.16 % on heat analysis. When one or both of these elements are specified by the purchaser, the sum does not apply. In the case where only one of the two elements is a specified, the individual limit on the remaining element shall apply.

[E] For HSLAS steels, columbium and vanadium may be added singly or in combination.

[F] These steels shall also contain one or more of the following elements: vanadium, titanium, columbium (niobium), or molybdenum. Other alloying elements may be present, but are not required.

Carbon (C): Carbon has historically been the principle element used to increase strength and hardness. Increased levels decrease ductility and it has a moderate tendency to segregate.

Manganese (Mn): Manganese is also used to increase strength. It has the benefit of helping to control the negative effects sulfur has on the steel.

Phosphorous (P): Phosphorous increases strength and hardness but decreases ductility and toughness.

Sulfur (S): Sulfur is a naturally occurring element that is considered harmful to steel unless machinability is a consideration. It decreases ductility, toughness, and weldability. It has a strong tendency to segregate.

Copper (Cu): Copper is mainly used where there is a concern for atmospheric corrosion.

Nickel (Ni): Nickel is used to increase strength and toughness.

Chromium (Cr): Chromium increases strength and aids where there is a concern for atmospheric corrosion.

Molybdenum (Mo): Molybdenum combines with carbon to increase strength.

Vanadium (V): Small quantities of Vanadium are used to increase strength.

Columbium (Cb): Small quantities of Columbium are used to increase strength.

Titanium (Ti): Titanium is added to restrict grain size growth.

Nitrogen (N): Nitrogen will increase strength and hardness.

Reading through the above chemicals it is apparent that there are numerous combinations of elements that can be used to obtain varying characteristics. For steel water pipe we have identified strength and ductility as the properties we are looking for.

In the past, strength was obtained by increases in carbon. The limit in most steel to a maximum amount of carbon is because adding carbon will also decrease ductility. There are now much better formulas for steel that will also keep the grain size small and therefor keep the ductility where we desire it. Carbon is still a very important element in the steel but is not the only or best way to obtain strength. For structural grade steel in the 30,000 to 40,000 psi yield ranges, carbon will be one of the main elements for strength. In steels with required yields over 40,000 psi there are numerous alloying elements that will be used to obtain the strength. Vanadium, Columbium, and Titanium are all elements that can be added in small quantities to increase strength. These steels will often be classified as HSLAS.

In the process for making steel with a continuous caster the steel will be "killed". The term killing with respect to steel is the deoxidization of the steel. The term is descriptive of the way the steel just lays in the caster and does not move from release of gases. The two elements most commonly used to kill steel are Aluminum and Silicon. Aluminum has the added benefit of controlling grain size and therefor producing better ductility. The majority of modern steel currently produced is killed with Aluminum. ASTM A 1018 HSLAS Class 2 requires killed steel made to a fine ferric grain practice for steel with improved formability

Rolling Practices

After the strand of steel is cast from the continuous caster and made into a slab it must still be rolled from the thicker slab to the thickness of the final product. To roll the slab heat must be added. The amount of the heat is critical to the final properties of the steel. Rolling practices have been refined and now the initial temperature of the slab and the rate of cooling are much more controlled. This lower initial temperature and controlled rate of cooling tend to keep the grain size smaller. Higher temperatures allow the formation of undesirable larger ferrite grains. Segregation of the other elements is also diminished with the lower temperatures. Much more is now known about the effects of the rolling temperature to the final physical properties than has ever been known.

Specifications

How does this information affect the specifier of steel for water pipe? American Water Works Association (AWWA) has written numerous standards to deal with water and products used in the water industry. AWWA C-200 is the standard for steel water pipe. This standard lists numerous ASTM steel and pipe standards that are allowable for the fabrication of steel pipe to meet the requirements of C-200. These currently include ASTM A-53, A-134, A-135, A-139 for pipe and ASTM A-570, A-36, A-283, A-572, A-1011, and A-1018 for plate, sheet, and coil. These materials all have characteristics that will work well in normal water applications of 150-psi pressure and 100 degree F or less temperature. The lower grade materials with yields of 35,000 to 42,000 will usually be very cost effective.

Often times a requirement will dictate a higher pressure for the working or transient design for the steel pipe. In these cases the use of higher-grade steel will be more cost effective. Around 40,000-psi yield the steel will typically become HSLAS steel. As the steel yield increases in strength the elongation will decrease or become less ductile. This should not normally be a concern. If the conditions require that the steel retain a higher degree of ductility because of handling, depth of cover or other conditions, then there are ways to insure that the steel used on your project retains a good ductility or elongation. The easiest is to require that the steel is continuous cast steel and Aluminum killed. The specifying agency can also specify an elongation that is more in line with the lower grade steels.

When specifying steels it is important to know what affects your cost. Steel is charged for by the pound. If the steel can be kept to the thinnest wall to meet all the requirements then this is normally the cheapest. In the standard pressure design for AWWA, the thickness of the steel is directly proportional to the pressure and the yield of the steel used. For working conditions over 150 psi it is often best to use a yield of 40,000 or higher. The specifying of a continuous cast steel that is Aluminum killed will cost very little or nothing. The steel manufacturers in America today are almost exclusively manufacturing their steel to this practice. For higher pressures, it is the opinion of the author, that specifying continuous cast steel that is Aluminum killed will always be a good specification.

For deflection at deep covers, the installation practice is usually the best method to control overall project costs. With the above requirements the steel will be ductile. The deflection can then be controlled with compaction, selection of backfill and installation practice.

Conclusion

For steel pipe manufactured to meet AWWA standard C-200 the important characteristics of the steel are strength and ductility. When the pressure is over 150 psi it is economically advantageous to investigate using higher yield steels. The old concern with higher yield steels is that this will result in steels that are less ductile. With the advent of continuous casting of steel, microalloying, and controlled rolling practice, this concern has been minimized. Specifications can be written that will use the advantages of these newer processes so that the strength and ductility expected of a steel pipe for water transmission usage will be as good or better than necessary.

Elongation properties of these newer steels can be specified to the same values as the lower older grades of steel. A 21 to 25% elongation is very reasonable to expect. As a point of reference this is over two times the requirement of ductile iron pipe. Specifying any of the materials listed in AWWA C-200 with the provision that the steel is continuously cast and Aluminum killed will give you a very good steel for this application.

These newer practices allow the steel companies numerous combinations of process and chemistry to obtain the desired results. There is no need to tie their hands with additional requirements to obtain desirable steel. Some of these practices affect the steel differently than others. The yield to tensile ratio may be closer than what was considered proper in the past but with the present practices the negative effect of this lower ratio can be minimized. Specifying the elongation you desire along with a continuous cast Aluminum killed steel to any of the AWWA C-200 steels allowed, will result in a very conservatively designed, cost effective pipeline.

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2. American Water Works Association, Standard AWWA/ANSI C-200 Steel Water Pipe-6 in. and Larger, 6666 W Quincy Ave, Denver Colorado 80235

3. ASTM A6 General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling using Test Method E112, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428

4. ASTM A 1018-02 Standard Specification for Steel, Sheet, and Strip, Heavy-Thickness Coils, Hot-rolled Carbon, Structural, High-strength Low-Alloy, Columbium, or Vanadium, and High-strength Low-alloy with Improved Formability, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428