Comparison of the Mechanical Properties of Steel and Ductile Iron Pipe Materials

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ABSTRACT

Water infrastructure engineers commonly evaluate a variety of pipe materials to determine the most appropriate solution for a particular application. Occasionally engineers inappropriately apply identical structural design criteria for both steel and ductile iron pipe (DIP). While similarities do exist, there are substantial differences in the material properties that make their structural designs unique. The applicable AWWA standards and design manuals are evidence of such variances.

To demonstrate the distinguishing mechanical properties of steel and ductile iron, large diameter samples were gathered, cut, and subjected to mechanical property testing. A review of the results will validate the existence of distinct material properties and clearly indicate the need for unique design practices that should not be modified or comingled. The mechanical property differences between steel and ductile iron and the implications to applicable AWWA design criteria are discussed.

INTRODUCTION

Engineers are, today more than ever, pushed to simplify and standardize designs and design procedures. At times, for the sake of perceived technical or commercial "fairness," these considerations get inappropriately used in the structural design of different pipe products, as has been seen in some pipe specifications produced. Although certain aspects of pipe design can be standardized such as equal performance requirements based on design pressures, there are limits to what can be done with the structural design once performance limits are established. Different products have different inherent physical characteristics that must be uniquely accounted for in their particular design.

This paper evaluates the similarities and differences in mechanical properties of two common pipe products used in water transmission pipelines, ductile iron pipe and steel pipe. History of the base materials used is explored, from a view point of their structural functioning. Mechanical testing results for the two pipe materials are reported. Discussions on the differences in application of the AWWA structural design criteria for each material are presented to show why the differing approaches are appropriate.

HISTORY AND CLASSIFICATION OF CAST IRON AND STEELS

History - The production of iron and steel has a long history, with the first recorded working of iron dating back to 1500 BC. The iron was heated, hammered and worked, but by itself iron was softer than bronze. By 1100 BC, it had been discovered that by reheating the iron in a furnace with charcoal, some of the carbon was transferred to the iron, resulting in hardening of the metal. The

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metal was hammered and worked to remove cinders and slag, and the material compacted. This produced wrought iron (wrought meaning worked) and had a carbon content of just 0.02 to 0.08 percent (Spoerl 2004). Quenching the metal in water further increased the hardening. These processes eventually replaced copper and bronze as the preferred metal for weapons because the metal was harder, yet the edge of a blade could still be honed and sharpened. This new material was the origins of steel. It was also the start of the Iron Age, but furnaces were not yet hot enough to actually melt iron; this would take another 500 to 600 years to accomplish.

Around 500 BC, the Chinese created a furnace capable of melting iron which required about 2800° F. Up to then, furnaces could melt copper at temperatures of about 2000° F, but were incapable of reaching the higher temperatures needed for iron. At these high temperatures, iron also would draw in large quantities of carbon into the matrix, creating cast iron with carbon ranging from 3 to 4.5 percent. This high carbon content made cast iron hard but brittle and it could not be forged (heated and shaped by hammer blows). It would be over another thousand years before the western world would develop the process to melt iron. By then the Chinese were using cast iron as structural elements. Up to the 1700's, casting iron was still a limited process, whereby large quantities of charcoal were needed to produce the iron. It was then discovered that coke (coal baked to remove impurities) could be used instead of charcoal. The result was a major improvement in cast iron production.

Other innovations were occurring as well. The blast furnace had been developed, a chimney-like structure where the combustion was intensified by blasting air pumped through alternating layers of charcoal, flux, and iron ore. Molten iron was poured through a series of lateral sand troughs, which resembled piglets suckling, giving it the name *pig iron*. By the late 1700's, pig iron was being refined in puddling furnaces, which allowed for excess carbon to be oxidized out of the mix. As the carbon oxidized out, the melting point of the iron would rise and bits of hardened metal would form on the surface. Skilled workers called Puddlers would remove the bits and place them together to be hammered in a forge. The wrought iron was then run through a rolling mill to produce sheets or rails.

Development of Steel Manufacture - Steel has a carbon-content lower than cast iron, but at the time, it was much harder to make due to the difficulty of controlling the carbon content during processing. Wrought iron has little carbon, enough to make it harder than pure iron, but still malleable. Cast iron has much more carbon which makes it much harder, but also brittle and not workable. Steel landed in between making it harder than wrought iron, but unlike cast iron, malleable and flexible. This made steel desirable, but controlling the carbon was extremely difficult and expensive. In the mid 1800's, the Bessemer process was developed. The Bessemer process used compressed air forced through molten pig iron to unite carbon and oxygen. The process was refined with the addition of a compound of iron, carbon, and manganese to reduce the oxygen content and keep the carbon content at desirable levels. Basic materials such as lime were later added to reduce the phosphorous to desirable levels. The Bessemer process created a revolution in steel making, allowing manufacturers to produce steel for costs substantially less than ever before. Other methods soon were developed to produce similar results as the Bessemer process and the steel industry as we know it was born.

Classification - Under current classification systems, the general definition of steel is an alloy of iron, carbon (under 2%) and other alloying elements capable of being hot and or cold worked into various shapes. Cast iron is an alloy of carbon (over 2%) and other elements and is not normally malleable or flexible and is used in its cast form.

CAST IRON

Cast irons are grouped by the appearance of their fracture surface, their microstructure or their material properties. One of the oldest classifications of cast irons is gray iron and white iron, which describe the color / appearance of their fractured surfaces. Mottled iron is a mixed appearance of gray and white. The variation of color is due to the formation of graphite flakes, which when formed, gives the fractured surface a gray color, Figure 1. Gray iron has almost no ductility, but is easily cast into complex shapes. White iron does not have graphite flakes; instead an iron carbide network is formed. White irons are extremely hard and abrasion resistant but also have little or no ductility.

Malleable iron is produced by heat treating white iron to break down the iron carbide into a tempered carbon, a form of graphite. Malleable iron exhibits some ductility due to the absence of iron carbide and the irregular shaped nodules of graphite that form.

Ductile Iron is also known as nodular iron and spheroidal graphite cast iron. The nodules are not as irregular shaped as malleable iron and are formed during solidification rather than by heat treatment, Figure 2. The graphite spheroids are formed by inoculating magnesium or cerium into the mix. Ductile iron pipe typically will use magnesium in the manufacturing process.

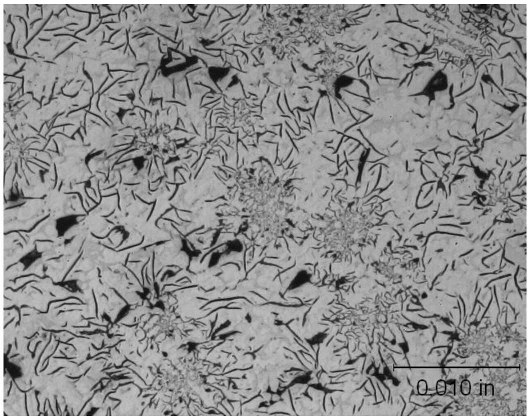

Figure 1: Micrograph of Gray Cast Iron

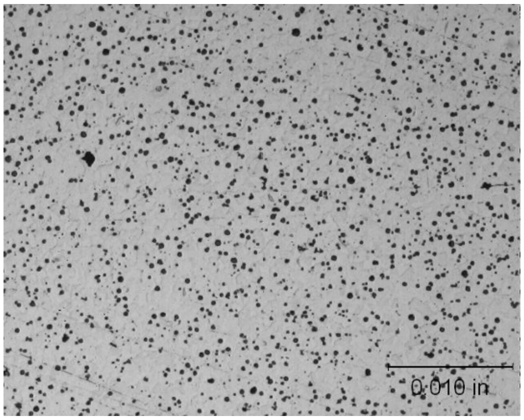

Figure 2: Micrograph of Ductile Iron

STEEL

There are currently thousands of steel compositions available in the world. Generally, steels are classified by their chemical compositions. Alloy steels are broken down into low and high alloy steels, with a break point of 8% of alloying elements being the determining factor for the classification. Plain carbon steels are further broken into three main groups: low carbon (under 0.2% carbon), medium carbon (0.2% to 0.5% carbon) and high carbon (above 0.5% carbon). Plain carbon steels are the most common steels produced and offer a wide range of characteristics and properties. Steels commonly used in the production of steel water pipe have carbon content from 0.08% to 0.25%, Figure 3.

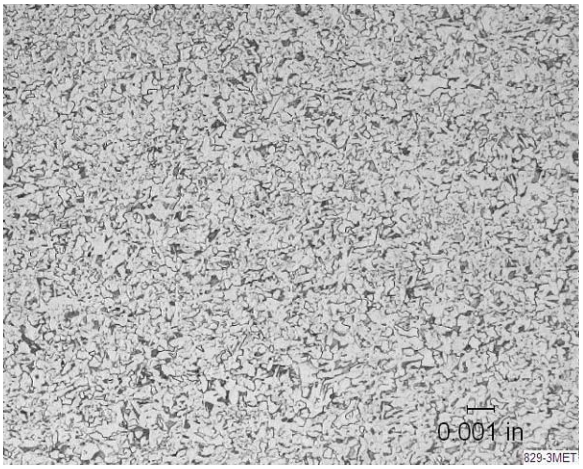

Figure 3: Micrograph of Plain Carbon Steel

Low alloy steel types include: High strength low alloy steel (HSLA), a group of low to medium carbon steels that use a low amount of alloying elements to increase yield instead of raising the carbon content to achieve yield strengths above 50ksi. High temperature steels used in applications such as turbine rotors. Improved corrosion resistance steel, also called weathering steel that usually contains additions of copper, nickel or chromium. Improved formability steel is designed for drawing quality it usually has a specific aluminum content or is "interstitial" free; free of interstitial elements that degrade deep drawing.

Examples of high alloy steels are corrosion resistant steels (stainless steel), heat resistant steels and wear resistant steels. There are many types of stainless steels including austenitic, ferritic, martensitic and duplex. Heat resistant steels are used in elevated temperature applications. Examples wear resistant steels of are tool steel and austenitic manganese steel.

IMPORTANT CAST IRON AND STEEL MECHANICAL PROPERTIES

Yield strength is the approximate point on the stress strain curve, Figure 4, where a material transitions from elastic to plastic. Up to the yield point, Hooke's Law is applicable as the stress strain relationship is linear. Load can be applied to a material; when the load is released, the material returns to its original shape. The slope of the line is the modulus of elasticity, E. Yielding occurs when the stress strain curve starts to deviate from a straight line.

In elastic metallic materials, the point that deviation starts to occur is difficult to determine as the material undergoes strains after the proportional limit is exceeded. An arbitrary yield stress is determined by the offset method (Gere1997). Yield is typically set when the deviation equals 0.2% strain of the measured length, shown by a line offset from the linear-elastic region of the curve. This is known as the 0.2% offset method and can be seen in Figure 4. In brittle materials, little or no plastic deformation will occur and the material will fracture near the end of the linear elastic portion of the curve. Yield strength is routinely used as a basis of design for many products, including steel and ductile iron pipe.

Tensile strength or ultimate tensile strength is the maximum stress reached during a tension test. In ductile materials the ultimate measured strength commonly will be reached before fracture, with a lower stress level recorded at the point of fracture. Yield and tensile are measured along the stress side of the graph. In some structural designs, allowable stress is calculated from the tensile strength of a material, but for steel and ductile iron pipe it is not; yield should be used. It should be noted that the ratio of yield to tensile stress only shows the stress relationship and does not account for strain. It does not indicate the ability of the material to elongate or resist fracture.

Elongation is a measurement of ductility. It is a measurement of the strain side of the graph and is usually measured as a percentage of permanent growth over a set length of the test specimen at fracture.

Yield, tensile, and elongation are all measured during a tensile or tension test. A standard sized and shaped sample is pulled and the associated stress and strains are recorded. The elongation is determined once fracture has occurred by measuring the increase in length of the sample.

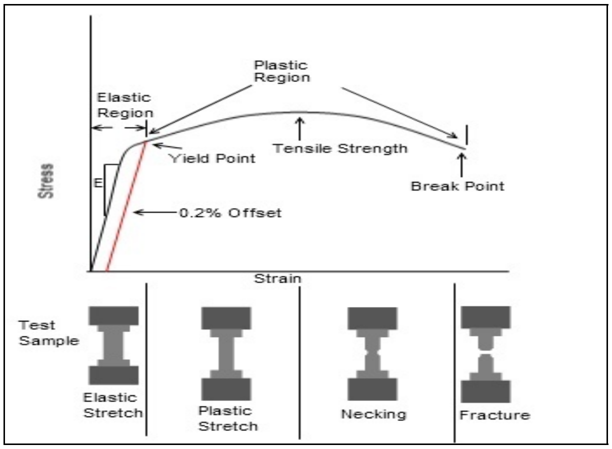

Figure 4: Typical Steel Stress Strain Diagram

Toughness is the ability of a material to deform plastically and absorb energy in the process before fracture. Toughness can be measured by taking the area under the stress strain curve. This is called the "material toughness", see Figure 5. It can be seen that a material with low strength and high ductility does not have high toughness, and similarly a high strength low ductility material also has low toughness. It takes a combination of ductility and strength to achieve a high toughness.

Although not a direct measurement of toughness, impact testing does represent a material's relative toughness. Impact tests are also not directly used for fracture mechanics calculations. The transition curve that is generated when impact tests are completed at different temperatures will show a material's transition temperature. Below that temperature, a material shows brittle tendencies; above it, ductile behavior.

Steel and ductile iron pipe use Charpy impact testing to determine the relative toughness of the pipe material at a given temperature. The values of Charpy testing give the energy absorbed by the sample during fracture at the tested temperature.

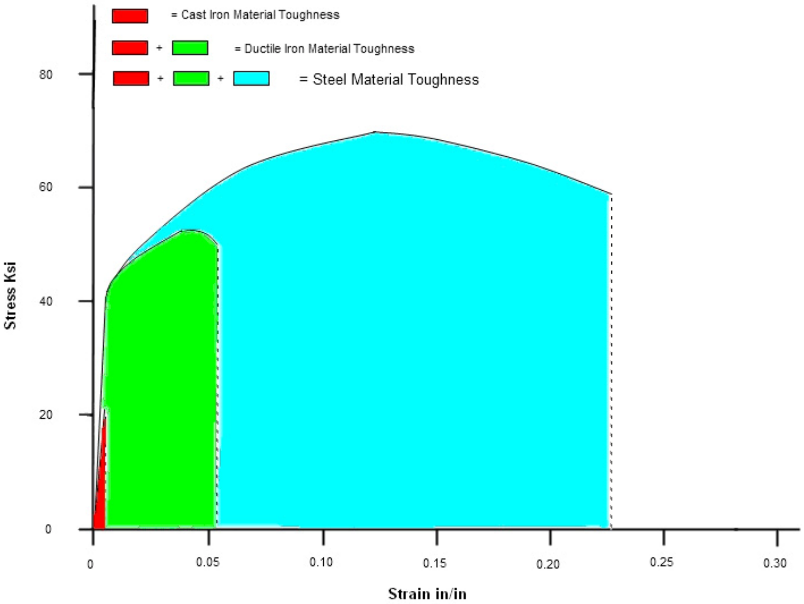

Figure 5: Cast Iron, Ductile Iron, and Steel Material Toughness

Bend test is a measurement of a material's ductile properties. Ductile materials will bend without breaking or cracking, brittle materials will crack or fracture during a bend test. A common bend test is to deform a sample 180 degrees around a mandrel of a set radius to determine if the material can resist the bending without cracking or fracture. Table 1 lists important physical/mechanical properties of ductile iron and steel pipe.

Table 1: Typical Minimum AWWA DIP and Steel Pipe Properties

Property	Ductile Iron Pipe	Steel Pipe
Yield	42 ksi	33 – 55 ksi
Tensile	60 ksi	50 – 70 ksi
Elongation	10%	18 – 30%
Impact	5 ft-lb @ 70 deg. F	15 ft-lb @ 32 deg. F
Bend	Not required by AWWA	180 degree

TESTING PERFORMED

In order to properly evaluate the mechanical properties of steel and ductile iron pipe, samples of three large diameter pipe types, steel, ductile iron and cast iron were acquired. The cast iron samples were tested to offer a historical perspective of the material. There were a total of 6 properties that were evaluated: yield strength, ultimate tensile strength, percent elongation, Charpy impact toughness, bend test and micrograph analysis.

The tests were completed in accordance with the following standards:

Yield strength, ultimate tensile strength, percent elongation, Charpy impact and bend tests – ASTM A370 (2010).

It should be noted that the tensile tests were all performed with full thickness flat bar cut from the actual pipe wall and not machined rods, Figure 6. Machined rods remove the normal inside and outside surfaces of the sample, thereby only sampling the mid section of the pipe body, which is not a true representation of the finished product. Hence actual pipe wall samples were used to produce results closer to what would be expected in actual application.

Figure 6: Prepared Test Samples

Micrographs were completed in accordance with ASTM A247 (2010) and ASTM E112 (2010).

All ductile iron samples were from 42-60-10 DIP that requires 42,000 min. yield, 60,000 min. tensile, and 10% min. elongation. Dimensions and other parameters for DIP samples and steel pipe samples are shown in Tables 2 and 3, respectively.

Table 2: DIP and Cast Iron Pipe (CIP) Samples, All US Origin [1]

Diameter, inches	Thickness, inches	Class	Diameter, inches	Thickness, inches	Class
30	0.380	200	16	0.380	CL 51
30	0.406	250	24	0.340	200
24	0.420	350	18	0.445	CL 53
30	0.560	CL 53	30	0.400	250
24	0.415	350	16	0.625	CIP

[1]Classes shown are based on material thickness

Table 3: Steel Sample Specified Properties

Material Specification	Diameter, Inches	Thickness, Inches	Design Operating Pressure, psi	Min. Specified Yield, ksi	Min. Specified Tensile, ksi	Min. Specified Elongation, %
ASTM A 1018 SS Gr 36	60	0.428	250	36	53	21
ASTM A 1018 HSLA Gr 45	84	0.625	325	45	60	22
ASTM A 1011 SS Gr 45	30	0.207	165	45	60	19
ASTM A 1011 SS Gr 36	30	0.149	300	36	53	22

RESULTS

The results of the testing on the various pipe materials are presented in Table 4.

Table 4: Testing Results for DIP, CIP, and Steel Pipe

Material Type	Thickness	Yield	Tensile	Elongation	Charpy [4]			
					-40 F	0 F	30 F	65 F
42-60-10 DIP	0.380	46,766	58,680	5.7	5.1	5.7	6.0	6.2
42-60-10 DIP		43,771	55,350	5.4				
42-60-10 DIP		44,865	55,930	6.1				
42-60-10 DIP	0.406	40,083	54,000	5.3	5.3	6.0	6.9	6.9
42-60-10 DIP		40,345	54,790	5.4				
42-60-10 DIP		41,325	55,490	7.4				
42-60-10 DIP	0.420	41,073	58,610	8.0	6.0			6.7
42-60-10 DIP		39,772	54,920	5.9				
42-60-10 DIP	0.560	44,768	57,120	5.6	3.2			6.0
42-60-10 DIP		44,175	50,540	4.3				
42-60-10 DIP [1]	0.374	47,820	62,830	5.5				
42-60-10 DIP	0.415	43,821	52,530	4.3	5.3			6.7
42-60-10 DIP		42,972	52,210	3.3				
42-60-10 DIP	0.380	41,227	53,490	6.1	4.7			7.3
42-60-10 DIP		40,868	51,120	5.2				
42-60-10 DIP	0.340	41,870	51,160	5.5	6.0			7.0
42-60-10 DIP		42,097	53,520	7.7				
42-60-10 DIP	0.445	46,060	56,820	5.8	4.4			6.7
42-60-10 DIP		45,380	54,960	5.8				
42-60-10 DIP	0.400	43,228	51,100	6.5	5.3			6.7
42-60-10 DIP		46,870	54,680	6.3				
Cast Iron Pipe	0.652	NA [5]	23,856	NA [5]	[2]			[2]
Cast Iron Pipe	0.652	NA [5]	21,069	2.2	[2]			[2]
Steel A1018 GR36 [3]	0.428	41,355	67,880	40.2	7.1	41.7	58.7	90
Steel A1018 GR36 [3]		42,634	68,840	41.1				
Steel A1018 GR36 [3]		42,205	68,240	42.9				
Steel A1018 GR45 [3]	0.625	52,200	65,700	32.0			262.5	
Steel A1018 GR45 [3]		53,200	65,900	32.5			262.5	
Steel A1011 GR45 [3]	0.207	56,400	75,900	29.0			75.7	
Steel A1011 GR45 [3]		54,300	76,200	28.0			74.0	
Steel A1011 GR36 [3]		50,400	72,100	29.0			48.0	
Steel A1011 GR36 [3]		53,800	72,900	28.0			54.7	

Notes for Table 4:

[1] DIP tensile sample was machined smooth to see the change in properties.

[2] Cast Iron Charpy specimens could not be machined without fracturing.

[3] Testing was reported previously by Keil (2010)

[4] Charpy results are corrected for subsize samples.

[5] Due to material characteristics, values were not measurable.

Results show the DIP samples' yield, tensile and elongation fell below the minimum required for this material. This variation may be because the samples were not machined to give them a smooth surface and removing interior and exterior surface irregularities that are part of the pipe wall thickness and normally found on DIP. DIP samples used for acceptance by the AWWA standards would be machined rods. The testing done for this paper gives results that would be expected in actual application since the inside and outside surfaces are left in their as-cast condition.

The tensile results for the DIP appear to match closely with the burst tensile strength published in the Handbook of Ductile Iron Pipe (1984) of 53,320 psi.

The steel results also appear to be typical of those encountered in actual application, where the yield, tensile and elongation exceed the specified minimum. It is typical to see yields exceed the specified minimum yield by 5,000 to 10,000 psi.

The Charpy results show DIP to have low relative toughness at all the temperatures tested with no value above 7 ft –lbs, indicating that at room temperature and below, DIP is a relatively brittle material. It is expected that DIP will not exhibit higher results at any higher temperatures. The steel exhibited a transition somewhere between -40 degrees F and 0 degrees F, showing a transition from brittle behavior to a ductile behavior. The steel samples exceeded the industry standard of 15 ft lbs at 32 degrees F.

The bend test results showed steel to be capable of withstanding a mandrel bend of 180 degrees without cracking or fracture. At approximately 30 degrees of bending, nearly all of the ductile iron samples fractured, with one sample fracturing at about 45 degrees. The results again indicate that steel is substantially more ductile when compared to DIP. Figure 7 shows some of the samples after the bend test.

Figure 7: Bend Tests: DIP, Steel, and Cast Iron Pipe

CURRENT AWWA DESIGN CRITERIA

AWWA design standards for steel and ductile iron pipe start with a similar approach to pipe wall design, but due to significant differences in material properties, deviate in the allowable stresses used. Both start with a simple hoop stress analysis to determine a minimum wall thickness needed for pressure considerations. Additional checks for both products are made to verify that wall thickness is adequate for other considerations such as minimum wall for handling, and earth loads. Steel pipe is designed and manufactured in accordance with AWWA C200 (2007) and AWWA M11 (2004). DIP is designed and manufactured in accordance with AWWA C150 (2008) and AWWA M41 (2009).

For example, both use the Hoop Stress equation,

$$t = \frac{PD}{2S}$$ **Equation 1**

Where: t = pipe wall thickness
P = pressure, psi
D = outside diameter, in
S = the allowable stress

The difference between the two materials is how P and S are handled in the equation. For steel, there are two different calculations utilized, one where P is the operating pressure and S is 50% of the minimum specified yield strength. The other equation is for transient pressure conditions where P is the transient pressure and S is 75% of the minimum specified yield strength due to the highly ductile nature of steel.

With DIP, there is one equation used that includes an allowable transient pressure that exceeds working pressure by no more than 100 psi, where P is maximum of operating pressure plus 100 psi surge or transient "allowance" and S is 50% of the minimum specified yield strength. The hoop stress equation is then manipulated for DIP design by multiplying the pressure P in the numerator and the allowable stress S in the denominator by 2. At first glance, this gives the appearance of the design being analyzed at "double" the pressure, but it also uses 100% of the design yield strength. This is represented as a "Factor of Safety of 2"; in reality the net effect is that 50% of the minimum specified yield is used in the design against the maximum or transient pressure P. Considering the actual physical properties of full thickness DIP samples demonstrated in this paper, the use of 50% of the yield strength for surge or transient pressures are appropriate values.

Examples:
Assume a 48-in nominal diameter pipe that will operate at a pressure of 150 psi and may encounter a pressure during a transient condition of 250 psi. Both materials will be considered to have a minimum yield of 42,000 psi.

For steel pipe:

Operating condition:

$$t = \frac{150 \times 49.875}{2 \times 21000} \quad \therefore t = 0.178\text{in}$$

Transient condition:

$$t = \frac{250 \times 49.875}{2 \times 31500} \quad \therefore t = 0.198\text{in}$$

The greater of the two values is 0.198in, so that would be the minimum specified wall thickness for steel pipe. Due to the mechanical properties and consistency of the material, no additional allowances or tolerances are added to the thickness. Additional checks would be analyzed based on the conditions in which the pipe will be used such as: Handling, buckling and deflection due to earth load.

For DIP:

$$t = \frac{[2\times(150+100)]\times 50.80}{2\times 42000} = \frac{2}{2}\times\frac{250\times 50.80}{2\times 21000} = \frac{250\times 50.80}{2\times 21000} \therefore t = 0.302\text{in}$$

With DIP, a service allowance of 0.08-in and the casting tolerance of 0.08-in are required, giving a minimum specified wall thickness of 0.454-in. For DIP, additional checks would be analyzed based on the conditions in which the pipe will be used, such as: handling, deflection due to earth loads, ring yield strength and ring ultimate strength. It is important to note that the additional checks for the two pipe materials may look similar in the equations used, but the factors required in the calculations will be different.

CONCLUSIONS

Steel and ductile iron are both ferrous materials that are created from iron that is melted and mixed with carbon and additional alloys. Due to the manufacturing process and carbon content of the two materials, they exhibit markedly differing final characteristics. When steel and ductile iron mechanical properties are compared, steel exhibits substantially better ductility and toughness. Steel pipe will typically exhibit tensile elongations 2 to 4 times higher than DIP. Steel pipe will typically exhibit Charpy impact values at normal water pipe operating temperatures 3 to 30 times higher than DIP. Steel pipe will typically exhibit substantially higher material toughness than DIP. Steel for steel pipe in bend tests will pass a 180 degree mandrel bend without cracking; DIP will fracture at about 30 degrees.

Yield and tensile testing results showed that steel will commonly have actual values 5 to 10 ksi above the specified minimum. DIP, when tested with full thickness bars, may have values below the minimum.

Ductile iron is cast and contains carbon in excess of 2%. Because ductile iron is further processed as compared to other cast irons, it exhibits better ductility when compared to those cast irons. Due to the casting process, ductile iron will have surface irregularities. These likely account for the values from testing of yield, tensile and elongation of full section tests being below the minimum specified for DIP.

The unique AWWA designs used for each of the materials appear to be appropriate considering the mechanical characteristics of the two materials. DIP exhibits relatively brittle characteristics; the AWWA design methodology appears to take that into account. Also, given the results of the testing, it appears that the AWWA design method for steel pipe is conservative and also appropriate.

There is no technical justification to substitute or comingle AWWA methods of design, equations or factors of safety. Likely justifications for comingling are commercially based with an eye to increase the cost of one material over the other. It is recommended that specifiers provide and or design with the established and equitable parameters of working, transient, and test pressures and utilize the AWWA Design Manuals for each product.

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