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Grey Cast Iron Water Pipe Metallurgy

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Abstract:

The results of a metallographic study of grey cast iron water pipes are reported. These pipes had been installed between 1885 and 1973 in eight different water systems. Each pipe had been extracted during scheduled maintenance or failure repairs to provide data for a larger study to produce a methodology for determining the residual life of grey cast iron pipes. This metallographic study was conducted to determine the causes of variations in the mechanical properties of these pipes.

Pit cast and spun cast pipes were found to have distinctly different types of graphite flakes, flake sizes and metallic matrices. These differences were directly responsible for the variations in the mechanical properties between the two types of pipes, with the larger flake sizes of the pit cast pipes in particular producing weaker material. Examples of anomalous pipes that did not have the standard appearance of either type of manufacture were also found and the reasons for their appearance identified.

The results of the study show that the metallurgy of the pipes may be a major contributing factor along with external forces such as corrosion or poor installation practices. Metallographic analysis can therefore assist water utilities in making decisions on repairs, rehabilitation and replacement.

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Introduction:

Although grey cast iron pipe is no longer manufactured for use by the water industry, these pipes are the most common form of piping in service throughout North America (Kirmeyer, Richards and Smith, 1994). The age of grey cast iron pipes in use in the ground ranges from more than 120 to less than 30 years old. As a result of the aging of these pipes and their extensive use, there is considerable interest in understanding how and why they fail. A complete understanding of the failure process would enable the operators of water systems to predict pipe breakages and aid in the scheduling of repairs and replacement. Pipe failures are a complex process that depends on corrosion, applied external forces and pipe metallurgy and mechanical properties. The external factors causing pipe failures have been described elsewhere (Rajani, B., Zhan, C. and Kuraoka, S., 1996), as has the typical appearance of those failures (Makar, 1999a, 1999b). While knowledge of the failure process is still incomplete, it is known that the metallurgy of these pipes plays an important role in their failure mechanisms. Grey cast iron is brittle in nature and the types of failures typically encountered by water system operators (longitudinal breaks, splitting at the bell, circumferential breaks) reflect that brittleness (Makar, 1999b). However, all grey cast irons are not the same. The quality of the pipe depends both its age and source. In addition, two different manufacturing methods (pit or vertical and centrifugal or spin casting) were used to make in-service grey cast iron pipes (Cast Iron Pipe Research Association, 1952).

Previous workers (Allen, 1933, La Que, 1964, Sears, 1968, Jakobs, 1985, De Rose and Parkinson, 1985) have investigated the metallurgical properties of grey cast iron pipes. However, the reported results do not appear to describe the pipe metallurgy using ASTM standard methodology. Early work, such as that of Allen (Allen, 1933) deals only with pit cast pipe samples, while other authors (La Que, 1964, Sears, 1968, Jakobs, 1985) compare one form of grey cast iron pipe to ductile iron piping. Little work has been done to directly compare the two forms of grey cast iron pipe to each other. One British report (De Rose and Parkinson, 1985) that does present both forms of grey cast iron pipe in order to compare them to ductile iron pipe shows photomicrographs of vertical cast iron pipe that do not appear to be typical of those found in North America.

The work reported here is part of a larger American Water Works Association Research Foundation/National Research Council Canada project to develop a methodology to estimate the residual life of grey cast iron pipes. An overall description of the research project is given elsewhere (Rajani, B. and Makar, J., 1999, Rajani, et. al., 1999). In summary, the research approach used mechanical testing of pipes from 16 different North American cities in conjunction with fracture mechanics, corrosion rates and non-destructive examination to develop an approach to find safety factors for in-service pipes and to predict their expected residual life. The samples used in the study were exhumed from the ground by each water utility during scheduled repairs and replacement. It was apparent from the results of the mechanical tests that distinct differences existed between the mechanical properties of the pit cast and the spun cast pipes (Rajani, Makar and MacDonald, 2000). Further differences were observed between the mechanical properties of the majority of the spun cast pipes and those from the City of Winnipeg. These differences and the lack of a systematic comparison between the two classes of grey iron pipe based on ASTM standards led to the work described below.

While the results presented here are important for explaining the mechanical behaviour, they can also be directly applied by water industry professionals in two ways. First, samples from pipes can be examined to ensure that their age and type has been correctly recorded. While the precise age is impossible to determine, the approximate time period (pit cast versus spun cast) can readily be found. In general, such sampling should be used in cases where there are grounds for suspicion that the age attributed to the pipe is incorrect or unknown, such as anomalously high break rates, missing records and dates of road construction that differ from the recorded time of pipe installation. Knowing the correct age for the pipes will help the system operator to determine when rehabilitation or replacement should be scheduled. The second application is in explaining pipe behaviour that is far outside the expected bounds, especially in cases where pipes are much weaker than would be expected. Metallurgical examinations can indicate if the problem is due to the manufacturing of the pipes themselves. This type of examination therefore provides a means for determining if replacement of an entire section of pipe installed at the same time is warranted. Examples of both applications will be given below.

Cast Iron Metallurgy

Reviews of the metallurgy of grey cast irons in general can be found in the American Society for Metals (ASM) Metals Handbook series (American Society for Metals, 1985, 1988, 1990) and in the Iron Castings Handbook (Iron Castings Society, 1981). The manufacture of grey cast iron pipe is also described in detail in the Cast Iron Pipe Research Association's Handbook of Cast Iron Pipe for Water, Gas, Industrial and Sewer Usage (Cast Iron Pipe Research Association, 1952). The summary below is drawn from those texts.

Both steels and cast irons are composed of iron alloyed with relatively small percentages by weight of carbon. However, cast irons differ from standard steels by having significantly higher carbon (C) and silicon (Si) contents. Steel typically has less than 1.2 weight percent (wt. %) carbon and little or no silicon, while the carbon content in cast irons typically ranges from 2.5

to 4.5 wt. % C and 1 to 3 wt. % Si. Cast irons also often have higher sulphur (S) and phosphorus (P) contents, while manganese is an important additive in both metals.

The extra carbon and silicon in cast iron is added primarily to lower the melting point of the metal. As an example, steel made with 0.86 wt. % C has a melting point of approximately 1470^{o}C while a cast iron alloy with 4.3% C has a melting point of about 1150^{o}C. This difference and the enhanced fluidity of the metal that accompanies it is enough to make the cast irons easy to cast into complicated shapes such as pipes and fittings.

Sulphur, by contrast, is an unintentional addition to iron or steel and, especially in more modern pipes, is either removed or controlled by the addition of manganese. Sulphur without manganese tends to form brittle iron sulphide at the boundaries of the grains in the metal. This is more of a problem in steels, where the inclusions will cause cracks during rolling and other forming, but can also be detrimental to cast irons. When manganese is present manganese sulphide (MnS) is formed in the centre of the grains as inclusions instead and is relatively harmless.

Phosphorus, like sulphur, can be detrimental to the performance of steels and cast irons. It forms brittle iron phosphide (steadite) inclusions at the grain boundaries, but if more than about 0.5 wt. % phosphorus is present these inclusions can form a continuous, brittle network through out the metal. However, phosphorus can also have some beneficial effects on cast iron. It can be deliberately added to the molten metal in order to promote abrasion resistance. It also increases the fluidity of the molten metal, which means that casting temperatures can be somewhat lower than might otherwise be required. Modern manufacturing processes ensure that cast irons and steels have low phosphorus levels, except where special purpose products are being made. In the past, higher levels were more common.

The basic material of cast iron consists of metal and graphite flakes. The size and the shape of the graphite flakes and the exact type of metal depend on the manufacturing process. The metal in cast irons can be either ferrite (almost pure iron) or pearlite (alternating bands of ferrite and iron carbide in a single grain). Very slow cooling tends to produce very large graphite flakes and ferrite, moderate cooling produces pearlite and somewhat smaller flakes and very quick cooling produces ferrite and very fine flakes. The tendency to produce pearlite or ferrite is also affected by the alloying elements in the cast iron. The shape of the graphite flakes is also affected by the cooling rate and other processing.

The creation of graphite flakes as cast iron cools is unavoidable, but it is also detrimental to the strength of a pipe. Flat flakes act as natural crack formers, which means that grey cast iron tends to produce brittle fractures that travel along the flakes (Sun and Wang, 1990). The grey colour of alloy's fracture surface that gives it its name is produced by these flakes, not by the metal grains (American Society for Metals, 1985). Modifying the shape or size of these flakes can improve the material's mechanical properties. The most extreme example is ductile iron, where the addition of small amounts of magnesium causes the graphite to form small spheres rather than a continuous network of flakes. As a result ductile iron is both stronger and tougher than grey cast iron while still being readily castable.

The manufacture of cast iron pipes

Many older North American water distribution systems include pipes installed during the previous century. Two major shifts in the technology of casting iron pipes have occurred since that time (pit cast grey iron to spun cast grey iron to spun cast ductile iron) and there have undoubtedly also been many smaller improvements and changes between those shifts. These changes have been reflected in the various American Water Works Association standards

(American Water Works Association, 1908, American Standards Association, 1939a, 1939b, 1953 a, 1953b) governing the manufacture of cast iron pipes since the turn of the century. It is therefore necessary to examine not only the current state of the art, but also past practices, in order to understand the differences in the mechanical behaviour of cast iron pipes.

The earliest pipes in this study were pit or vertically cast. A series of upright sand molds were created in a pit, and the molten cast iron was poured into them. When the metal had cooled sufficiently, the molds were removed and the pipe rolled free, cleaned, inspected and tested (Cast Iron Pipe Research Association, 1952). The specifications 7C.1-1908 (American Water Works Association, 1908) and A21.2 (American Standards Association, 1939a) applied to the manufacture of pit cast pipe, while the recommended practice A21.1 (American Standards Association, 1939b) applied to its design. Other standards have also been issued over the years, frequently in the form of updates to the above.

The technology to produce what are known as spun or horizontally cast pipes was developed in 1914 (Longmuir, P., 1939) and was introduced commercially over the next two decades. The mold was made of sand or metal, with the outside of the metal molds being cooled to prevent damage from the molten metal that is poured into them to form the pipe (Cast Iron Pipe Research Association, 1952). In either case the mold lay horizontally and was spun as the metal was poured into it, with centrifugal force causing the metal to coat the inside surface of the mold, rather than pooling in its bottom. The pipes cast in metal molds initially have higher residual stress levels due to rapid cooling of the metal against the mold walls, but were heat treated to remove those stresses. It does not appear that heat-treating was used on those pipes made in sand molds. The recommended practices A21.6 (American Standards Association, 1953a) and A21.8 (American Standards Association, 1953a) and their updates cover the manufacture of spun cast pipe in metal and sand molds, respectively.

Experimental Details

Eighteen samples were cut from thirteen pipes for this phase of the examination. These pipes were chosen to represent a range of mechanical properties and geographical regions. A list of pipes, their tensile strengths and their fracture toughnesses is given in Table 1. Details of the test methods and a more extensive discussion of these properties in gray cast iron pipes will be given in a future paper (Rajani, Makar and McDonald, 2000). Each of the samples was approximately 10 mm (0.4 in.) long and wide and the same thickness as the pipe. They were mounted in plastic and polished for examination according to standard metallurgical practice. The samples were polished and microphotographed so that the type, form and size of the graphite flakes could be determined according to ASTM standard A247-67 (American Society for Testing and Materials, 1998a). The samples were then etched to expose grain boundaries and structure for analysis. The grain size of the samples with more than 50% ferrite was determined at this time according to ASTM E112-88 (American Society for Testing and Materials, 1998b) . It should be noted that cast iron samples can be difficult to properly prepare for examination, since the graphite flakes can be pulled out of the matrix by improper polishing techniques. Different etchants are also recommended depending on whether the sample is ferritic or pearlitic. Recommended procedures for preparing cast iron for examination are summarised in the Metals Handbook Desk Edition (American Society for Metals, 1985).

Metal from each sample was then analysed to determine its chemical composition. The method of analysis depended on the element that was being measured. Silicon was determined gravimetrically. A portion of each sample was dissolved by oxidative acid dissolution and the resulting silica was dehydrated by evaporation with perchloric acid. Silica (plus any impurities) was filtered and weighed. The silica was then volatilized with hydrofluoric acid and the impurities weighed, with the silicon determined from the weight difference. Magnesium, manganese and phosphorus contents were determined by using inductively-coupled plasma atomic emission spectrometry (ICPAES) following dissolution of the samples with a multiple acid digestion involving hydrochloric, nitric and perchloric acids. Carbon and sulphur were determined by combustion analysis using LECO instruments.

The final type of tests used on these samples was Vickers Microhardness measurements. This test was used instead of the Rockwell B tests called for in the AWWA standards for the manufacture of cast iron pipe as it allowed multiple tests to be made on the surface of the same small sample to check the variation in hardness from the inside to the outside of the pipe.

Results and Discussion

The samples have been divided into three groups as a result of the analysis. These include spun cast samples, pit cast samples and anomalous samples. The former two types have been identified both by the reported age of burial of the pipes and by common metallurgical behaviour. The anomalous samples represent pipes that do not appear to fit the typical characteristics of either group. With the exception of Figure 8, the photomicrographs shown in this paper are from the centre of the pipes, where the metallurgical behaviour is the most consistent and easily identifiable.

(a) Graphite flakes

All of the samples examined showed only flake graphite (ASTM form VII) (American Society for Testing and Materials, 1998a), with the exception of sample WN-1-A2, which may show temper graphite (form III) on its outside surface. Form VII graphite is composed of long, thin individual flakes. It is typical for grey cast irons and was expected to be observed in these pipes. If temper graphite is present in sample WN-1-A2 it may indicate that the sample was given a longer heat treatment after its initial cooling than the other spun cast pipes received (American Society for Metals, 1985).

While all of the samples showed the same flake form, the type of flakes varied consistently between spun cast and pit cast pipe. Table 2 shows the standard ASTM flake types, while Table 3 shows the forms, types and sizes of the flakes in the individual samples. Type D graphite is the most common form in the spun cast pipes and was consistently found in the central region of each sample (Figure 1). The majority of the outer and inner surfaces of these samples also showed type D graphite, although in some cases type A or C was also seen. The presence of type D graphite generally means that the metal has been rapidly cooled, which is exactly what would be expected in a spun cast pipe manufactured in a metal mold. Flake sizes in these pipes range from 4 to 8, but the largest flake sizes are generally on the inside surfaces of the pipes, where the metal would have cooled the slowest. The central area of the pipe usually has significantly smaller flake sizes (7 to 8).

In contrast, the pit cast samples did not show any evidence of type D graphite. The central regions of the pipes are either type A (Figure 2) or type C (Figure 3), while the exterior of the pipe can be A, B or C. The flake sizes in these pipes are also noticeably larger than those of the spun cast pipes, ranging from size 3 to 5 according to ASTM A247. The central area of the pipe has flakes of the same size as the rest of pipe (3 to 4). These flake types and sizes are likely to have been produced by the slower cooling rates experienced by the pit cast pipes during manufacturing.

An examination of the work done previously in the United Kingdom (de Rose and Parkinson, 1985) suggests that type B flakes are typical of pit cast grey iron pipes manufactured in that country. This is clearly not the case in North America, which indicates that there may have been differences in the manufacturing techniques used in each region.

The clear differences between metallography of the two classes of North American pipes suggest that this type of metallurgical analysis can provide a relatively simple method of discriminating between them where records are missing or suspect. An example of its use is for sample DN-3-1, which was recorded as being from 1894 (Figure 4). This sample has type D graphite with very small flakes in the pipe center. The appearance of this pipe indicates that it is really a spun cast pipe and that the records for the pipe may not have been updated when it was installed. The mechanical properties of this sample also correspond to those that would be expected from a recent, spun cast pipe.

The other two anomalous samples, MN-4-1 and WN-2-B2, do not clearly fit into either category of pipe. Both samples are dated to the time period when spun cast grey iron pipes were manufactured and both pipes show mechanical strengths typical of that period as well. However, MN-4-1 only shows type D graphite on the outside surface of the pipe (next to the mold), showing A in the central region and inside surfaces. The flake sizes are also anomalous, being size 8 on the outside, but sizes 5 to 6 on the inside. The small flake size and type D graphite on the outside of the pipe suggest that this pipe was cast in a horizontal mold, but the type A graphite with larger flake sizes indicates that the rest of the pipe metal may not have solidified as rapidly as the outside region. WN-2-B2 shows very large flakes, but in each region these flakes are type B, rather than A, C or D (Figure 5).

(b) Grain structure

Etching the samples to examine the structure of the iron grains showed that the metallic grains in the spun cast samples (including DN-3-1) were predominantly ferrite, with only occasional small grains of pearlite. Figure 6 shows a typical example of the etched surface of a spun cast pipe. The thin black lines between the grey metal are the boundaries of the individual grains. The etching process widens the apparent size of the graphite flakes in these microphotographs because the acid used preferentially attacks the graphite.

By contrast, all of the pit cast samples showed significant amounts of pearlite (Figure 7). In many cases the pearlite was common enough that the grain sizes in the sample could not be analysed by the LECO analyser. This instrument relies on the contrast between etched grain boundaries and the grain itself to measure the grain sizes. If a region of the sample does not have lower than 50% pearlite, grain size can not be accurately measured. These large amounts of pearlite are common in many cast irons. Table 4 shows which of the pit cast samples had so much pearlite that their grain size could not be measured (except WN-2-B2, where the presence of iron phosphide prevented the measurement). Table 4 also shows the measured grain sizes for the remaining samples. The grain sizes of the pit cast samples are larger than those of the spun cast samples, which would be expected since the latter type of pipe was cooled more quickly during casting than the former, allowing less time for the individual grains to grow in size.

The amount of pearlite and ferrite in an individual sample depends both on the initial matrix of graphite flakes and the cooling rate of the sample. During the cooling process, carbon atoms will diffuse through the metal to the graphite flakes. The very fine type D graphite matrix in spun cast grey iron permits most of the carbon in the surrounding metal to diffuse into the adjacent flakes before the cast iron completely cools. In these pipes the carbon is almost entirely removed from the metal grains and only ferrite remains. The initial graphite flakes in the pit cast pipes are both larger and more widely spaced. As a result carbon will diffuse primarily from the area immediately surrounding the flake, leaving some or all of the more distant grains as pearlite. This effect is seen in Figure 7. However, if the pipe cools very slowly, the carbon in the grains will still have time to enter the graphite flakes. The examples of the pit cast iron that have both bulk pearlite and ferrite present (such as MP-1-B or BS-2-B) are therefore the pipes with slowest cooling rates.

Cooling rates are also likely responsible for the structure of sample WN-2-B. While Type A and C graphites are produced by slow cooling rates and type D by very fast cooling rates, type B flake graphite is produced by an initial quick cooling followed by a rise in temperature as the molten metal starts to solidify (Loper, 1990). The result is very fine flakes at the centre of each rosette with the flake size growing towards the outside of the pattern. As is the case with the pit cast pipes, carbon is removed from the metal matrix into the graphite (Figure 8), leaving ferrite near the graphite with surrounding regions of pearlite.

An examination of another sample, WN-3-1, from the same city and approximate time period shows a similar rosette graphite pattern. In addition, the mechanical analysis of the spun cast pipes from this city[11] shows that they in general have a lower tensile strength than pipes from the other cities that contributed to the project. These observations suggest that the graphite structure is due to the standard procedures used by the pipe supplier, rather than an error during the manufacturing of a single pipe. One possible explanation for the metallography of this pipe is that it was made by spin casting using a sand mold rather than a metal mold.

The etched metallograph of the sample MN-4-1 revealed a different phenomenon. In this sample a high phosphorus content has produced an extensive network of iron phosphide. Figure

9 shows a scanning electron microscope image at high magnification. Other samples showed evidence of the presence of iron phosphide, but this was the only sample that showed a network of the material throughout the sample. The chemical analysis of the pipe metal (Table 5) shows a high phosphorus content. This percentage of phosphorus (0.62 wt. %) is often present due to the deliberate addition of the element to the molten metal to improve its fluidity. The high phosphorus content suggests that the metal in the pipe may not have been raised to as high a temperature as would normally be the case during the spin casting process, with the phosphorus being added to compensate for the lower temperature. The presence of the phosphorus is also likely responsible for the change in the flake type from D to A across the sample towards its inner surface, since phosphorus is effective in promoting the formation of graphite.

(c) Chemistry

The differences between the pit cast and spun cast samples are not as clear in Table 4 as they are from the microstructure results. With the exception of the sample CH-3, where the lowest carbon content of 3.39% is compensated for by the highest silicon content (3.31%), all of the samples have carbon contents between 3.68 and 4.2 percent by weight. The silicon variation is somewhat larger (1.39 to 3.31% by weight), but no real difference between the pit cast and spun cast samples can be seen. The same is also true of the sulphur, magnesium and manganese content in the samples. One alloying element that does vary more consistently between the two types of pipe is phosphorus, which is generally below 0.5% by weight for the spun cast pipes and above 0.6% by weight for pit cast pipes. The exceptions are the anomalous samples, MN-4-1 and WN-2-A, and one of the spun cast pipes, MN-1. It is noteworthy that MN-1 and MN-4-1, both pipes from the same city and with similar chemistry and ages, have different microstructures. If the pipes were supplied by the same manufacturer, these similarities would suggest that only a very slight change in chemistry or manufacturing technique may have significant effects on the microstructure and mechanical properties of a grey cast iron pipe. However, it may be impossible to determine if this is the case. While records exist of the basic manufacturing techniques, many municipalities do not have complete historical records of the source of their pipes. Many local pipe manufacturing companies no longer exist and the ones that do no longer produce this type of pipe.

(d) Vickers microhardness measurements

The microhardness measurements showed that spun cast samples were noticeably softer than the pit cast samples. Table 5 gives the average results for the 10 measurements made across each sample. The difference between the two types of pipe reflects whether ferrite or pearlite is predominant in each sample. While the presence of graphite flakes caused significant variations in the hardness measured across each sample, no consistent trends in hardness were seen.

Conclusions

Although a relatively small number of samples were examined, the results indicate that spun and pit cast pipes can be differentiated by their type of graphite flakes, the size of those flakes and the metallic matrix of the pipe. Spun cast pipes typically have type D flakes, a ferritic matrix and small flake sizes (7-8) in the central region. Pit cast pipe typically has C or A type flakes in the central region, a significant presence of pearlite, and large flake sizes (3-4) in the central region. Of the three samples originally labelled as anomalous, one, DN-3-1, was identified as a spun cast pipe that appears to have been incorrectly dated. The two remaining anomalous samples were both tentatively identified as being spun cast pipes that were produced by different manufacturing methods than the majority of this type of pipe.

There are significant differences between the strengths and fracture toughnesses of pit cast and spun cast grey iron. These differences are directly attributable to microstructure of the metal. The carbon flakes in grey cast iron act as crack formers, i.e., where cracks will initiate when the pipe is placed under stress. The much larger graphite flakes in the pit cast pipe make it easier for cracks to start and propagate through the metal, reducing the mechanical strength. Knowing whether the pipe is pit or spun cast can therefore provide a simple initial determination of its quality.

Metallography can also differentiate between typical and anomalous pipes. In the examples discussed above, one anomalous sample had excessive phosphorus content and a network of iron phosphide inclusions, while a second anomalous sample had large B type graphite flakes, which suggests that the pipe was cooled more slowly than standard spun cast pipes. The metallurgy of the latter pipe may explain the lower mechanical strengths of the pipes from the source city. Further work will be necessary to confirm these conclusions.

The examples demonstrate that metallurgical analysis can provide a tool for water utilities to understand the reasons behind grey cast iron pipe failures in their water distribution systems. In some cases the metallurgy of the pipes may be a major contributing factor along with external forces such as corrosion or poor installation practices. This understanding can therefore lead to better, more economical decisions on scheduling pipe replacement and on pipe repair and rehabilitation strategies.

Acknowledgements

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Sample id	Reported date of manufacture	Tensile strength (MPa)	Fracture toughness (MPa√m)
<u>Spun cast samples</u>			
WN-1-A-2	1973	157.2	11.9
OC-6-A-2	1960	159.8	12.2
MN-2-1	1970	304.9	14.9
TO-2-B	1930	221.6	12.8
MN-1-B	1957	285.7-300.9	14.8-15.1
DN-3-1	1895§	247.7	
<u>Pit cast samples</u>			
TO-3-7A	1910	102.8	9.7
MP-1-B-6	1885	67.8	7.9
CH-1-A	1910	110.2	8.5
BS-2-B-10	1893	146.2	8.6
CH-3-B	1889	107.9	8.9
<u>Anomalous Samples</u>			
MN-4-1	1954	225.8	14.8
WN-2-B-2	1955	198.1	14.0 (WN-2-A)

1 MPa = 145 psi; 1MPa√m = 0.92 ksi √in; §: date corrected to 1925
WN = Winnipeg, Manitoba, OC = Regional Municipality of Ottawa-Carleton, Ontario, MN= Moncton, New Brunswick, TO = Toronto, Ontario, DN = Denver, Colorado, MP = Minneapolis, Minnesota, CH = Chicago, Illinois, BS = Boston, Massachusetts

Table 1 – Mechanical properties of analysed samples

Flake type	Flake description
Type A	Uniformly distributed, apparently randomly oriented flakes
Type B	Rosette pattern of graphite flakes
Type C	Randomly oriented flakes of widely varying sizes
Type D	A very fine pattern of flakes surrounding areas without graphite
Type E	Graphite flakes have preferred orientation and appear in a quasi-regular pattern

Table 2 - Description of graphite flakes according to ASTM A 247.

Sample id	ASTM graphite flake type[1]			ASTM graphite form[2]			ASTM graphite Size[3]		
	Inner Edge	Centre	Outer Edge	Inner Edge	Centre	Outer Edge	Inner Edge	Centre	Outer Edge
Spun cast samples									
WN-1-A-2	C	C/D	-	VII	VII	III	4-5	7-8	7-8
OC-6-A-2	D/A	D	D	VII	VII	VII	5-6	7-8	7
MN-2-1	D/A	D	A	VII	VII	VII	6	8	7-8
TO-2-B (A)	D	D	D	VII	VII	VII	6	7	7
TO-2-B (B)	D	D	D	VII	VII	VII	7	7	6
MN-1-B (A)	A	D	D	VII	VII	VII	5	-	7
MN-1-B (B)	A	D	D	VII	VII	VII	5	-	7
Pit cast samples									
TO-3-7A	A	A	A	VII	VII	VII	3	3	3
TO-3-7B	C	C	C	VII	VII	VII	4	4	5
TO-3-7C	A	A	C	VII	VII	VII	3-4	4	3-4
MP-1-B-6	B	C	B	VII	VII	VII	4	4	4
CH-1-A	B	C	B	VII	VII	VII	4-5	3	4
BS-2-B-10	B	C	B	VII	VII	VII	4	3	5
CH-3-B (A)	A	A	A	VII	VII	VII	3	3	3
CH-3-B (B)	A	A	A	VII	VII	VII	3	3	3
Anomalous Samples									
DN-3-1	C/D	D	D	VII	VII	VII	4/8	8	7
MN-4-1	A	A	D	VII	VII	VII	5-6	5-6	8
WN-2-B-2	B	B	B	VII	VII	VII	4	3	5

[1]See Table 2 for flake type definitions.
[2]In ASTM A247 the flake form refers to the actual shape of the flake, which may be I) spheroidal graphite; II) imperfect spheroidal graphite; III) temper graphite; IV) compact graphite; V) grab graphite; VI) exploded graphite or VII) flake graphite. Pictures of both the flake types and forms can be found in the standard.
[3]In ASTM A247 the sizes refer to a range of values as measured at 100x magnification that vary geometrically from 1 mm to 128 mm. Size 3 corresponds to approximately 16-32 mm at this magnification, size 4 to 8-16 mm, size 5 to 4-8 mm, size 6 to 2-4 mm, size 7 to 1-2 mm and size 8 to 0-1 mm.

Table 3 - Cast Iron ASTM graphite flake type, form and size according to ASTM A247-67.

Sample id	ASTM grain size[1]	ASTM standard deviation	Grain size (mm)	Grain size standard deviation (mm)	Average Vickers Micro Hardness
<u>Spun cast samples</u>					
WN-1-A-2 inside	8.12	0.055	0.022	0.0001	140 (all)[3]
WN-1-A-2 outside	8.24	0.087	0.021	0.0002	-
OC-6-A-2	7.40	0.19	0.027	0.0007	162
MN-2-1	7.23	0.61	0.028	0.0023	179
TO-2-B (A)	8.99	0.110	0.016	0.0002	182 (all)
TO-2-B (B)	8.99	0.097	0.016	0.0002	-
MN-1-B (A)	9.72	0.05	0.012	0.0001	172 (all)
MN-1-B (B)	9.63	0.057	0.013	0.0001	-
DN-3-1[2]	7.73	0.32	0.024	0.001	160
<u>Pit cast samples</u>					
TO-3-7A					239 (all)
TO-3-7B					-
TO-3-7C					
MP-1-B-6 inside	6.98	0.62	0.030	0.0027	237 (all)
MP-1-B-6 outside	7.51	0.22	0.026	0.0008	-
CH-1-A					276
BS-2-B-10 inside	7.49	0.31	0.026	0.0011	213 (all)
BS-2-B-10 outside	6.43	0.46	0.036	0.0026	-
CH-3-B (A)					217 (all)
CH-3-B (B)					-
<u>Anomalous Samples</u>					
MN-4-1					174
WN-2-B-2					236

[1]According to ASTM standard E112, on a standard 100x magnification. Note that a smaller ASTM number means a larger grain size. The samples that do not have grain sizes shown had less than 50% ferrite content and could not be measured by the Leco Analyser.
[2]Considered to be spun cast pipe after microstructural analysis.
[3]Average values labelled "all" include the measurements made for all of the samples checked from the same pipe.

Table 4 - Average hardness and ferrite grain size

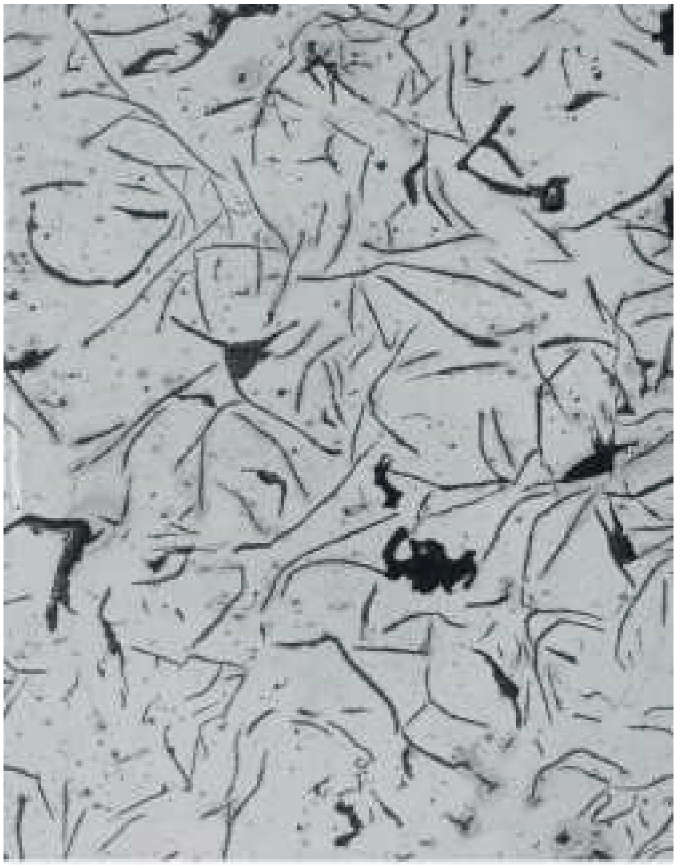
Sample id	Reported Date Installed	Carbon (% by weight)	Silicon (% by weight)	Sulphur (% by weight)	Phosphorus (% by weight)	Manganese (% by weight)	Magnesium (% by weight)
Spun cast samples							
WN-1-A-2	1973	4.20	1.39	0.018	0.057	0.35	0.0008
OC-6-A-2	1960	3.96	1.61	0.11	0.17	0.39	0.0006
MN-2-1	1969	3.78	2.41	0.077	0.22	0.49	0.0018
TO-2-B	1930	3.72	2.03	0.076	0.42	0.52	0.0008
MN-1-B	1957	3.76	1.93	0.099	0.80	0.25	0.0005
DN-3-1[1]	1895§	3.97	1.92	0.071	0.18	0.49	0.0006
Pit cast samples							
TO-3-7A	1910	3.91	2.32	0.090	0.74	0.49	0.0012
MP-1-B-6	1885	3.72	2.65	0.15	1.03	1.13	0.0052
CH-1-A	1910	3.74	1.96	0.046	0.82	0.91	0.0005
BS-2-B-10	1893	3.70	1.93	0.093	0.69	0.34	0.0004
CH-3-B	1889	3.39	3.31	0.089	0.77	0.21	0.0006
Anomalous samples							
MN-4-1	1954	3.79	2.19	0.095	0.62	0.30	0.0004
WN-2-B-2	1955	3.68	2.12	0.099	0.55	0.45	0.0012
Typical Values (reference 9)							
		2.5-4.0	1.0-3.0	0.02-0.25	0.2-1.0	0.2-1.0	Trace

[1]Considered to be spun cast pipe after microstructural analysis; §: date corrected to 1925
Note: all measurements accurate to four decimal places.

Table 5 - Chemical analysis of grey cast iron pipe samples.

Figures

1. Spun cast sample OC-6-A2 polished to show Type D graphite flake networks (100x magnification).

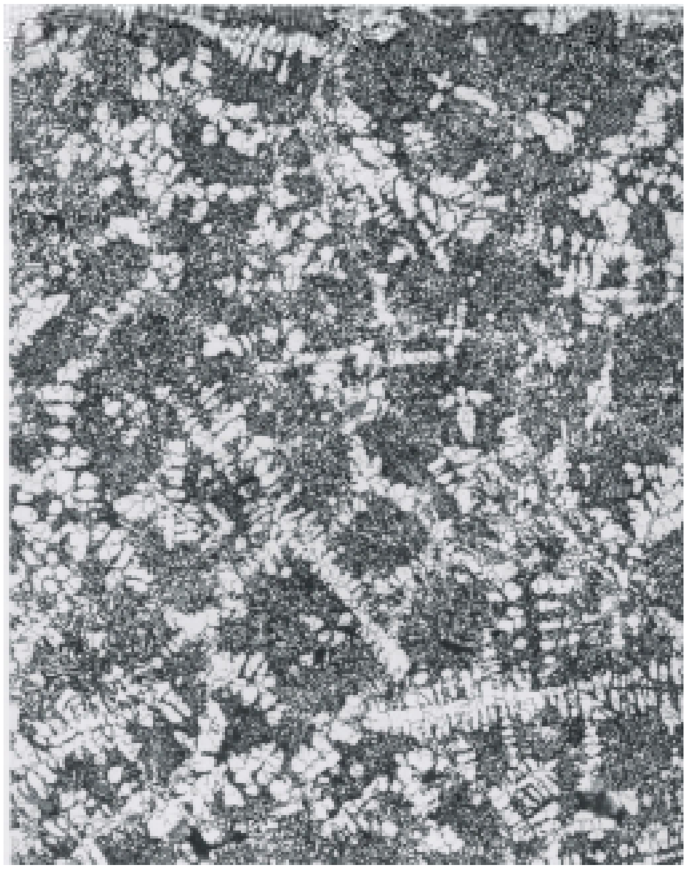


2. Pit cast sample TO-3-7 polished to show Type A graphite flakes (100x magnification).

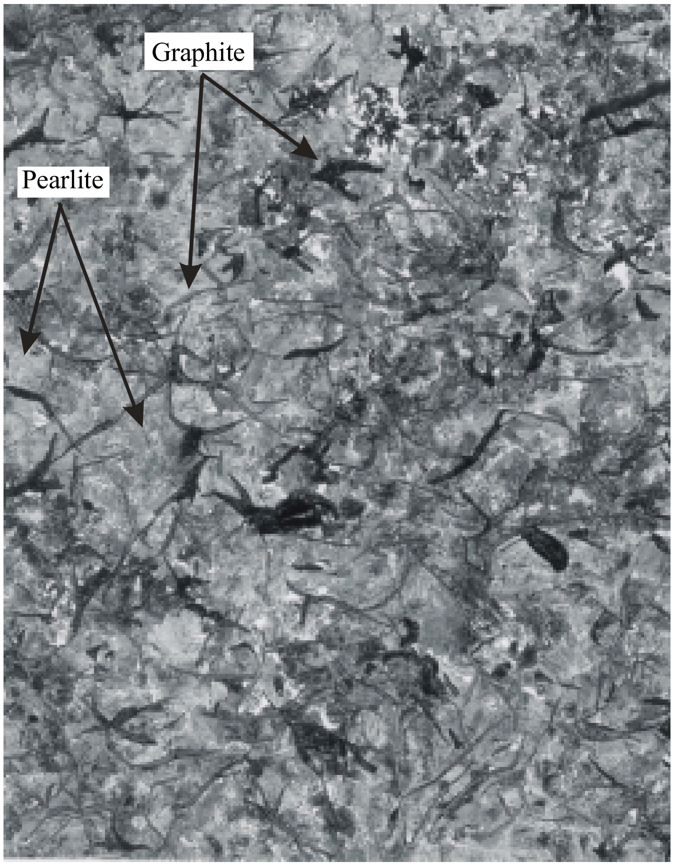
3. Pit cast sample BS-2-10 polished to show Type C graphite flakes (100x magnification).

4. Spun cast sample DN-3-1 polished to show graphite flakes (100x magnification).

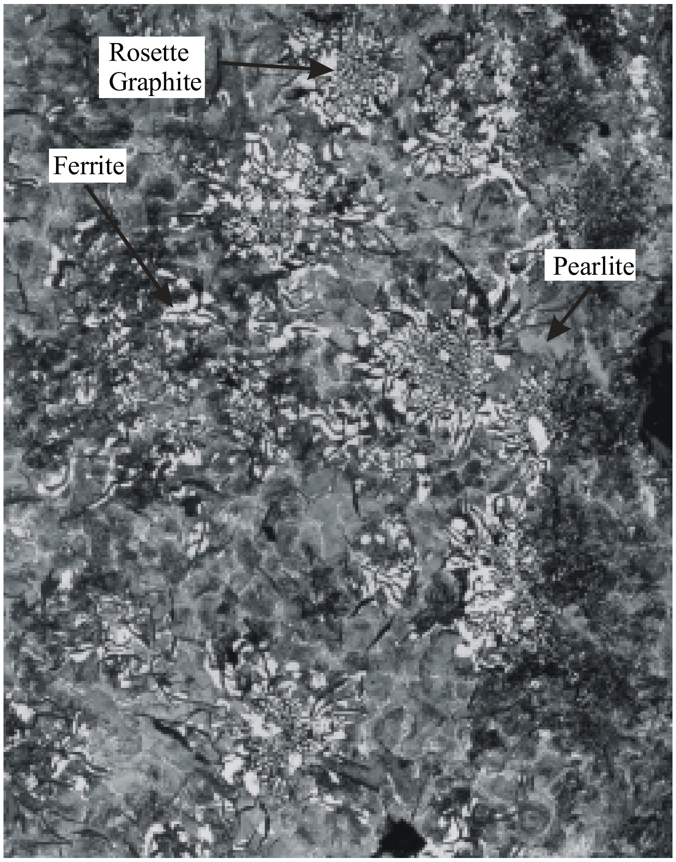
5. Anomalous sample WN-2-B polished to show graphite flakes (100x magnification).



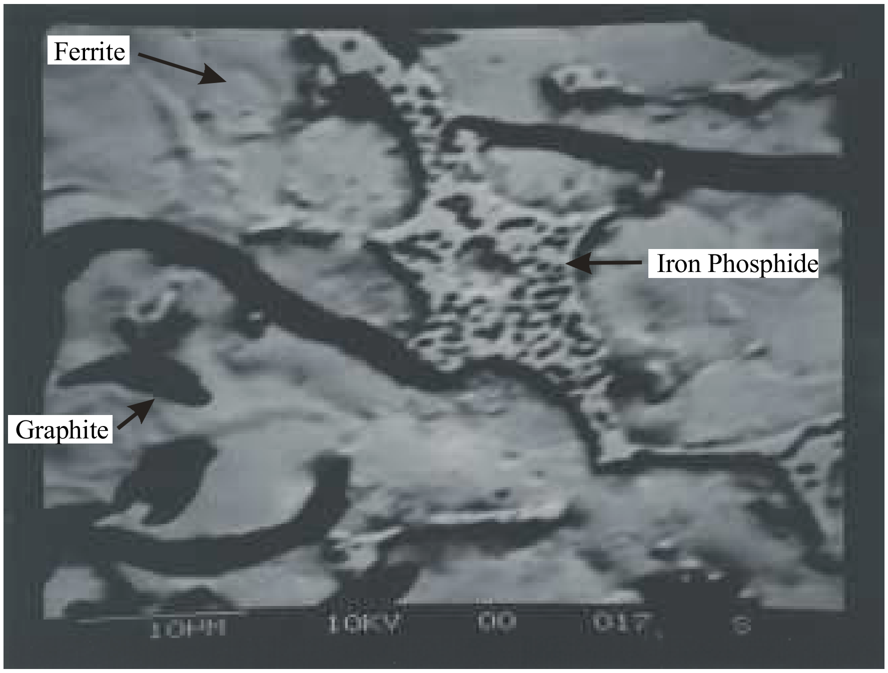
6. Spun cast sample DN-3-1 etched to show grain boundaries (100x magnification). Black areas are networks of graphite flakes, grey areas, including those within the graphite flake networks, are ferrite. The grain boundaries are the fine lines that divide the ferrite and indicate the edges of individual grains.



7. Pit cast sample TO-3-7 etched to show pearlite (100x magnification). Black areas are graphite flakes, grey areas are pearlite.



8. Anomalous sample WN-2-B etched to show pearlite (100x magnification, outside edge of sample). Black areas are etched graphite flakes, light grey areas are ferrite grains and medium grey areas are pearlite grains.



9. Scanning electron micrograph of sample MN-4-1. Dark areas are etched graphite flakes, background is ferrite grains, raised “porous” areas are iron phosphide. 2350x magnification