Characterisation of the fatigue properties of cast irons used in the water industry and the effect on pipe strength and performance

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Abstract. As part of an on going programme to characterise the residual properties and understand the failure mechanisms of in-service grey cast iron water pipes, the fatigue crack propagation behaviour of grey cast iron samples has been studied. Specimens were sourced from three ex-service pipes. For each pipe the microstructure and composition were characterised and the fracture toughness was determined. The fatigue behaviour was investigated in terms of the crack growth rate (da/dN) as a function of the applied stress intensity factor range. Clear differences in the fatigue behaviour of the samples from different pipes were observed. The result from these investigations, which indicate that microstructural differences play a role in mechanical behaviour, will support the development of asset management tools for use in the water industry.

1. Introduction
Cast iron is a material that still has significant usage in the water industry. In the context of the United Kingdom, although cast iron pipes are being phased out of distribution and mains systems, a significant portion of current pipe networks are still comprised of the aging cast iron infrastructure that can be up to 150 years old. This cast iron infrastructure is deteriorating at different rates [1-2], which are linked to the geology and other localised conditions. The problem is further complicated by the diversity in production quality as well as the range of diameters and wall thicknesses used. In order to develop a rehabilitation or replacement strategy for the industry, it is important not only to understand the mechanisms by which a pipe can fail, but also to use this understanding to develop tools for asset management. In order to better model these mechanisms and their contribution to service failures an understanding of the initiation and propagation of cracks is necessary. For example, sub-critical cracks could originate from inherent defects present ab initio from casting; be generated during installation or arise in service. If this hypothesis is true, any information on the rate of and the factors influencing fatigue behaviour is of relevance. The literature regarding the fatigue of gray cast iron is limited and inconsistent. These inconsistencies are likely in part to be a consequence of the microstructural differences between the gray cast irons used in these studies [3-5]. This is particularly relevant as little has been done by way of comparing the behaviour of different types of cast irons under the same condition.

In the present work the propagation of fatigue cracks in samples of different classes of cast iron were studied in order to investigate the possible role of the microstructure (in particular graphite morphology) on the fatigue behaviour of cast iron pipes. The structure of the paper is as follows. In the next section the test materials and test methods are described. Following this results are presented.
relating to the microstructure and fracture and fatigue behaviour. Finally the implications for service life are discussed.

2. Experimental Methods

2.1 Material characterisation
Samples were sourced from three water mains which had failed in-service. Three plates were taken from each pipe and test specimens were machined from these plates. Metallurgical examination was carried out to verify that the pipes were a grey cast iron material. Chemical compositions of the samples are given in Table 1.

Table 1 Chemical composition of grey cast iron mains (Wt %)

|        | C   | Si  | P   | S   | Mn  | V   | Mo |
|--------|-----|-----|-----|-----|-----|-----|----|
| Pipe1  | 3.23| 2.7 | 0.6 | 0.12| 0.6 | 0.08|    |
| Pipe2  | 2.75| 2.35| 1.2 | 0.08| 0.5 | 0.1 |    |
| Pipe3  | 3.2 | 2.36| 0.3 | 0.2 | 0.7 | 0.05| 0.01|

2.2 Microstructure characterisation
Samples of the full pipe wall thickness were cut from each pipe, mounted in conducting Bakelite and polished following a typical schedule to give a 0.25 \( \mu \)m surface finish. The specimens’ microstructures were then studied using a Zeiss Axiophot optical microscope. Initially, the samples were studied in the as polished condition; the samples were then etched with 2% Nital (a solution of nitric acid in methanol) and re-examined.

2.3 Fatigue and Fracture toughness testing
A single edge notch beam (SENB) configuration was chosen for fatigue testing. To ensure plane strain conditions the ratio of W/B (where B and W are breadth and width) has been chosen according to 1 < W/B < 2, whilst the minimum breadth of the specimens was chosen to satisfy the requirement of B > 2.5\( (K_{IC}/\sigma_{YS})^2 \). Specimens were obtained in the form of rectangular cross section bars cut from the plates of ex-service failed mains. To exclude the effects of corrosion, the specimens were machined to remove the surfaces. A notch, nominally 1/3 the width of the specimen was machined into each specimen. Fatigue testing was carried out using an Instron 8511 (servo-hydraulic machine) with an automatic data logger. A three point bending method was employed with a cycling stress ratio of 0.1 and the loading frequency of 10 Hz. At all stages, the requirements of ASTM E647-86a-00 protocol were followed. Specimens were pre-cracked prior to testing. A load shedding method was adopted to obtain a crack growth rate of the order of \( 10^{-3} \) and \( 10^{-5} \) mm/cycle for pre-cracking and fatigue respectively. Initiation and growth of cracks was observed with the aid of a travelling optical
microscope. Crack growth was also monitored with crack propagation sensors (CPA01, VISHAY Measurements Group). A pre-crack was grown, with the maximum cycling load corresponding to $\Delta K$ values of $10 \text{ MN/m}^{1.5}$, to an approximate length of 2 mm, at which time the test was stopped and micro-photographs of the crack were taken in order to determine the exact length of the generated crack. The test was continued with the maximum cycling load corresponding to $\Delta K$ values of $8.5 \text{ MN/m}^{1.5}$. A parallel series of experiments were carried out to determine the fracture toughness values of the pipes using an Instron 6025 (5500R) with a loading rate of 1KN/min and 40% sensitivity. At all stages the requirements of ASTM E1820-01 was followed.

3. Results and discussion

3.1 Microstructure analysis

Optical microscopy reveals differences in the microstructures of the specimens taken from different pipes. The microstructures of all pipes show a multiphase matrix of pearlite, ferrite, and phosphide eutectic with different graphite morphology. Microphotographs representing the microstructures seen in samples from pipes 1-3 are presented in figure 2. A summary regarding the graphite morphology (type, size, and form, with reference to ASTM A247-98) is presented in Table 2.

Table 2 Graphite flake identification (with reference to ASTM A247-98) observed in pipes 1-3

| The edges | The mid section |
|-----------|----------------|
| type      | distribution   | Maximum flake size/ | type         | distribution | Maximum flake size/ |
|           |               | mm                  |              |             | mm              |
| Pipel     | IIIV           | Between A (Random   | IIIV         | Between A (Random | IIIV           | Between A (Random |
|           |                | orientation) and B  |              | orientation) and B |                | orientation) and B |
|           |                | (Rosette)           |              | (Rosette)     |                | (Rosette)        |
|           |                | 3 0.3               | IIIV         | 2 0.45       |                | 2 0.45           |
| Pipe2     | IIIV           | A (Random orientation) | IIIV       | A (Random orientation) | 1 0.9         |
|           |                | 2 0.4               |              | 1 0.9        |                |                  |
| Pipe3     | IIIV           | B (Rosette)         | IIIV         | B (Rosette)  | 2 0.4           | B (Rosette)      |
|           |                | 2 0.4               |              | 2 0.4        |                |                  |

Figure 2 Digital photo-Microphotographs Representing the Morphology of Microstructure seen in Pipes 1-3

a: an example of type B ‘rosette’ graphite flake morphology observed at Pipe3, b: detail of a

C: an example of type A ‘scythe/sickle’ graphite morphology observed at Pipe2, d: detail of c

e: an example of mixture of type A and type B graphite morphology observed at Pipe1, f: detail of e
3.2 Fatigue results
The result of crack growth rate versus applied stress intensity factor of all samples is presented in Figure 3. From Figure 3b it is seen that the propagation of cracks in samples from Pipe 3 corresponds to relatively higher $\Delta K$ values than for the samples from the other two pipes. This is in agreement with the applied $\Delta K$ values for the crack initiation, which were 10.7, 10.2, and 11.4 MN/m$^{1.5}$ for Pipes 1 to 3 respectively. These differences are likely to be due to the microstructural variation of the specimens, which in turn gives rise to differences in the crack growth behaviour of the samples. Experimentally obtained values for fracture toughness also show a variation. The mean fracture toughness values of pipes 1-3 were 15.4, 15.1, and 16.1 MPa/m$^{\frac{3}{2}}$ respectively.

Figure 3 Fatigue crack growth rate of samples from pipes1-3. (a): as a function of $\Delta K$, (b): as function of $\Delta K/\Delta K_c$

Figure 4 presents micro-photographs taken during fatigue testing. From Figure 4a-b, a tendency for interlamellar propagation of the crack as well as crack branching phenomena at the low stress intensity factor regime is observed. The crack growth mechanism seems to vary throughout the fatigue life. At the early stage of the crack development, where $\Delta K$ value is near the threshold, the crack follows a preferential path induced by coalescence of the graphite flakes, which act as foci for stress concentration. As the crack grows, crystallographic slip directions seem to be favoured. The mechanism of the crack growth can still be described as the coalescence of the graphite flakes but this time via an intergranular induced path. At this stage, as $\Delta K$ increases - and so the crack tip plastic zone becomes sufficiently large - the formation of cracks parallel to the principal crack on planes near the crack tip is observed (Figure 4b-c). Figure 3a-b reveals a fluctuation on the slope of the lines particularly in the intermediate regime of $\Delta K$. This might be due to the structure-sensitive nature of crack growth, which depends on the grain size of the controlling phase. The fracture surface of the intermediate $\Delta K$ regime is seen to be smoother in this regime than in the higher $\Delta K$ regime (Figure 5). When $\Delta K$ increases to a value such that the fracture toughness is approached, the crack starts to grow unstably. The crack at this stage is a high energy one and it does not follow a preferential path. As a
result the crack growth occurs via the coalescence of graphite flakes by either a transgranular or an intergranular induced path or some combination of the two.

Figure 4 – Digital-microphotographs taken during the fatigue of Sample 17 pipe1 after, (a): 20,000 cycles; crack at an early stage, low ∆K regime, (b): 25,000 cycles an example of the main stream crack branching, (c): 37,500 cycles, example of the initiation of parallel cracks as ∆K increases, (d): 52,500 cycle, an example of graphite flake induced preferential path.

Figure 5 SEM Fractographs of sample4 pipe3 (a): Fatigue fractured surface of stable crack growth regime, (b): Detailed of a (c): Fatigue fractured surface of near failure (d): Details of c.
4. Application of Paris relation to model S-N behaviour of the pipes

An S-N model was developed from the fatigue experiment data using the Paris relationship. The fatigue crack growth behaviour of the material is given by the Paris relation as:

$$\frac{da}{dN} = A\Delta K^m$$  \hspace{1cm} (1)

Where $\Delta K = K_{\text{MAX}} - K_{\text{MIN}}$  \hspace{1cm} (2), and A and m are Paris components. The stress intensity factor, $K$, for a SENB bend specimen geometry is given by [6] as:

$$K = \frac{PS}{BW^{3/2}} f(a/W)$$  \hspace{1cm} (3)

Where $P$ is the max cycling load, $S$ is the span of the sample, $B$ and $W$ are the breadth and the width of the specimen respectively, and $f(a/W)$ is a function of the ratio of the crack length ($a$) and $W$ and is calculated according to:

$$f(a/W) = \frac{3(a/W)^{1/2}}{2(1+2a/W)(1-a/W)^{3/2}} \times [1.99 - (a/W)(1-a/W)(2.15 - 3.93a/W + 2.7a^2/W^2)]$$  \hspace{1cm} (4)

The Paris constants for the samples were obtained from log(da/dN)-log($\Delta K$) plot and averaged for each pipe. The number of cycles to failure for each pipe was obtained by using MATLAB to integrate numerically the Paris relation for various crack configurations of $a/W$.

$$N_f = \int_{a_i}^{a_f} \frac{da}{A(\Delta K)^m}$$  \hspace{1cm} (5)

It is worth emphasising that S-N plots obtained from the integration of Paris equation are based on the assumption that pipes already contain initial flaws which are either inherent or arise during service. Cast iron pipes most commonly suffer from localised corrosion such as corrosion pits. These corrosion pits can be regarded as flaws and hence estimating the remaining in-service fatigue life of the pipe becomes of great importance. Figure 6 presents two different crack length configurations under which the fatigue life modelling was developed. Figure 6a compares a situation where the flaw size is of the same order of magnitude as a graphite flake, thus modelling the case of an inherent flaw. It is seen that for a relatively low applied stress – such as normal service loading conditions - all three pipes are expected to show a fatigue life of approximately $10^7$-$10^8$ cycles, with Pipe 3 showing slightly better performance (this difference is more apparent at higher applied stresses). Figure 6b models the situation where the flaw in the pipe is $0.2W$ (width of the pipe), and in this case the larger remaining fatigue life of Pipe 3 is clearer. The model seems to be valid for intermediate and low applied stress levels (evident from experimental data) but for higher stress levels there are some doubts as to whether the model remains valid.
Figure 6. S-N model developed for pipe 1-3, a: the flaw size is small (the order of microstructure features) b: the flaw size is large (fifth of the width of the pipe)

5. Concluding remarks
Fatigue of grey cast iron pipes shows microstructural dependent behaviour. In the case of grey cast iron pipe with graphite flake, morphology of the graphite seems to be a key parameter in characterising this behaviour. Further investigation will consider the environmental effects on crack growth mechanisms. Future work will also focus on crack opening displacement and whether this will have pronounced effect on the obtained S-N curve.

Acknowledgment
The authors would like to thank Mr Antony Scratt (Struers Ltd), Mr Anton Chitty (VISHAY measurement groups Ltd UK), Dr. B. Le Page, Mr. C. Burt, Mr. M. Parker, and Mr. P. Haynes for their contribution to the work. The authors would like to acknowledge the support of Thames Water during the course of this work and, in particular, many helpful discussions with Dr Hal Belmonte and Mr Jeff Farrow. The opinions expressed in this paper are those of the authors and are not necessarily endorsed by the University of Surrey or Thames Water.

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