CONVENTIONAL VS CLOSURE FREE CRACK GROWTH IN NODULAR IRON

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Abstract

This investigation deals with the fatigue properties and material parameters for a silicon alloyed nodular cast iron. The material follows the Swedish standard SS 140725. The objectives for this investigation where to evaluate properties of the material in a fracture mechanic sense of view. In this first part, the attention was paid to the basic fracture mechanic properties, i.e. da/dN-curves and Paris law parameters. It also include R-dependence behaviour evaluated for R-values from R= 0 to R= 0,8. The main incitement for using the closure free approach is that it produces the fastest crack propagation rate that can be found at given conditions and load levels. This paper is the first part of the investigation of the silicon alloyed nodular iron SS 140725 and will be followed by subsequent parts. The investigation in total is a part of the nordic project "Cast Design 2005".

Introduction

Nodular iron is a material that is widely used for heavy construction equipment. The material has a number of attractive properties that makes it convenient for instance in the automotive industry. The properties are in general similar to grey iron but with a far better toughness. This makes the material suitable for all the same applications as grey iron but also for application that requires resistance against shock loadings. It is also relatively easy to found, an important property with respect to productivity. As being used for moving structural parts, it will also be exposed for fatigue. The issue of fatigue strength for cast materials is mainly governed by the presence of cast defects, Nadot *et al.* [1]. The main reason for this is that cast defects generally have an irregular, sharp interior geometry that facilitate crack establishment. The notch effect of those defects is often so severe that the initiation phase can be more or less disregarded, thus leaving the fatigue life for the fracture mechanics [1]. Normally the initiation phase constitute a main part of the fatigue life, so by losing it one will miss a great deal of the service life for a component. Under those conditions, it became extra important to manage the fracture mechanic tool in order to perform reliable forecasts.

One of the themes of this work is to relate the crack growth that will occur during closure free conditions to the crack growth rate that can be expected under closure. It is a quite interesting note that during closure free conditions the highest crack growth rate is expected to take place in a certain material provided equal load level. This is valid also for internal cracks, there are only some more conditions to consider. For example the stress field and the stress intensity take another appearance, but the most significant difference from surface cracks is that they are developed under vacuum which imply other crack propagation rates, closure effects etc. [1]. The presumption is, for all cases, that once the closure free crack growth rate for a material is known, all other fatigue conditions will result in an equal or minor crack growth rate. By the use of the closure free crack growth rate, one will therefore produce only conservative fatigue life times. It is then, if desirable, possible to develop empirical correction factors for different load conditions. The approach is particular suitable for nodular iron because of the widely spread crack growth parameters that have been reported in the literature [1], Lindeborg, B, Nilsson, J [2], Sundström, B *et al.* [3].

$$\frac{da}{dN} = C * \left(\Delta K\right)^m \qquad (1)$$

The evaluation of the fatigue behaviour is made by LEFM, Anderson, T. L [4]. For the fracture mechanic characterisation the standard form of Paris law was used, Eq. (1).

Specimen

The most common specimen type for mode I crack analysis is maybe the CT-specimen. It has some advantageous properties such as single determined crack path, reliable compliance behaviour, it is easy to pre-crack and have an extensive crack length. However, despite those good points, one can object that not many components have a shape similar to the CT-specimen. Much more common are the scenario with some kind of centre crack in the component. On top of that, since this investigation is about cast material, the probability is substantial that a fatigue crack will start at a cast defect below the surface of the component, and an initiation point in the bulk will not form a crack development similar to the CT-specimen crack. Instead, a centre crack specimen design was applied, furnished with a central stress concentration. The geometry of the specimen is shown in Fig. 1.

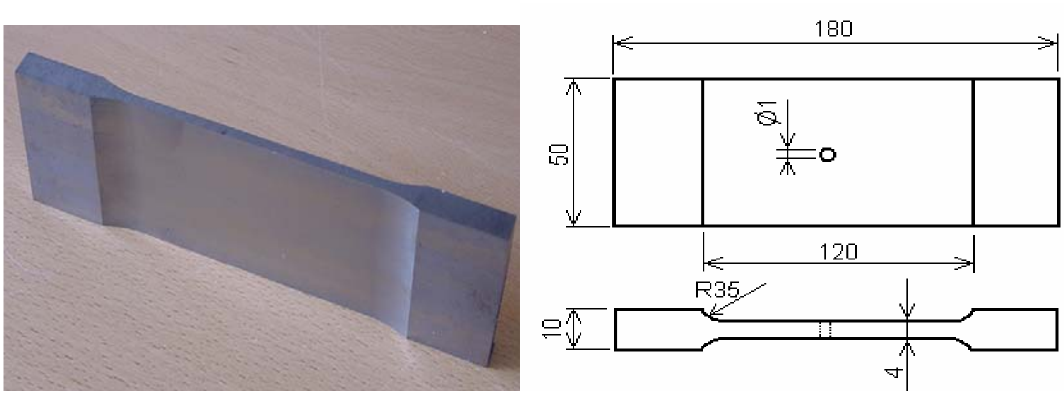

Figure 1. Specimen appearance and geometry

Width of the specimen was chosen to 50 mm in order to compromise between uniform stress distribution in the specimen, available raw material and the desire of having as long crack path as possible. The thickness was chosen to 4 mm in order to have minimal influence from bending forces causing non-uniform stress levels at different sides of the specimen. This demand should be balanced against the influence of plain stress that will become more accentuated for a thin specimen. For example, the ASTM E647 [5] states that the thickness is allowed to be as small as W/20 which, translated to the current specimen, corresponds to a thickness of only 1.25 mm. That indicates that it should be fair enough with the thickness 4 mm, but it should be noted that according to the theoretical requirements of LEFM [4] the thickness should be larger to achieve plain strain as a primary condition. Material properties published in this report can therefore possibly be affected by the thickness of the specimen, thus underestimating the crack growth rate at R-values lower than the crack closure level.

TABLE 1. Chemical composition of the material.

C	Si	Mn	P	S	Mg
3.30%	3.7%	0.25%	0.05%	0.02%	0.06%

The chemical composition of the material is shown in Tab. 1. The material SS140725, SIS [6] is a nodular cast iron with high silicon content. It is a rather new material standard that not yet have been widely used for construction components although it has been available besides the material standards for quite some while. The base material is ferritic, a phase that normally exhibits low strength and extensive toughness. The high amount of silicon will harden the ferrite by a solution hardening mechanism. This is the explanation of the excellent strength despite the ferrite base material. Because of the ferritic base, it is also less brittle than the traditional ferrite/pearlite base. It will also, in opposite to the traditional ferrite/perlite base, exhibit uniform toughness and hardness thanks to the single-phase matrix. Despite the excellent strength, the tooling properties remain almost the same as for ferritic material, a very important point considering productivity issues.

TABLE 2. Material properties.

	E (Gpa)	$Rp_{0.2}$ (MPa)	Rm (Mpa)	A_5 (%)	HB
Typical values*	173	422	523	15	195
SS 140725-00**	160-175	360	500	10	185-215

*) Typical values from cast components

**) Lower limits and intervals established in standard

Numerical model

The specimen was modelled in finite element as a half-model utilizing symmetry. Two cracks where supposed to emanate from the stress riser, perpendicular from the load and from the lengthwise direction of the specimen. The cracks could be propagated independent of each other in order to model any non-symmetric behaviour of the cracks. The symmetry plane needed for the model where created by locking the lengthwise degree of freedom at the midsection. The axial load was emulated by stress acting at the end area of the model and finally all degrees of freedom but the lengthwise was locked at the grip tabs.

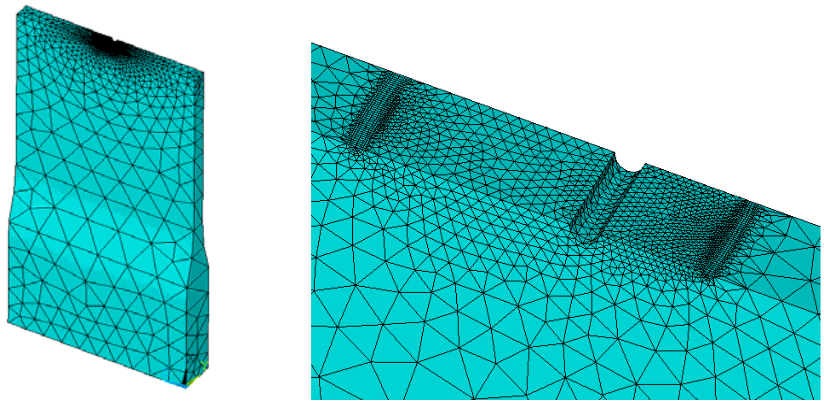

Figure 2. Half model of the specimen and a close up at the notch and the crack fronts

The tests was carried out in a servo-hydraulic test rig which had a diameter of the spindles of about 70 mm. Compared to the dimensions of the specimen waist (4 mm of thickness) the test rig can be considered as infinitely stiff. Therefore it has been no compensation made for any flexibility or load-induced displacement of the boundaries in the finite element model. The correctness of this was confirmed by measurements with strain gauges during the testing.

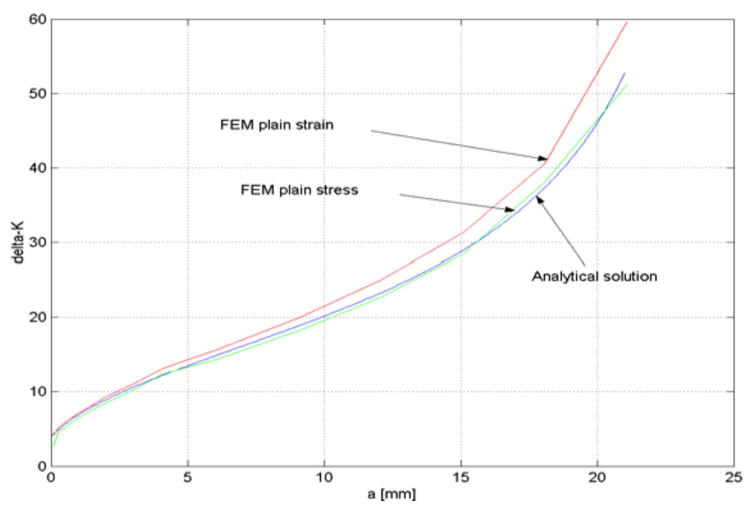

Figure 3. Stress intensity as a function of crack length for FEM vs. analytical solution for σ_0=100 MPa

The finite element calculations where made in the software ANSYS. The K-solutions where calculated by built-in routines utilizing wedge formed singular crack tip elements with displaced node locations (1/4th position) [4]. Stress intensity factors for both plain stress at the surface and plain strain in the bulk of the specimen where calculated.

Experimental procedure

The testing was performed in a servo-hydraulic test machine of type Schenck Hydropuls PSB. The load capacity for the machine was 50 kN. Sinusoidal curve shape at frequencies between 20 and 30 Hz where used during the testing. All tests where made in air at room temperature. Great efforts where paid to have a smooth start of the test sequences in order to avoid over- and under loads.

To measure the propagation during the testing a travelling microscope was used. Estimated accuracy was ±0.02 mm in total.

Constant load was used during all tests; accordingly the crack tip was exposed for strict increased stress intensity. The procedure helps to avoid accumulation of residual stresses at the crack tip, thus creating as little as possible of crack closure, Suresh, S [7]. The constant load condition is also the most usual for real components, often combined with a load spectrum. Since a spectrum load tend to demolish the residual stresses at the crack tip, it is even more important not to use a test sequence that promote the build-up of residual stresses. All testing was conducted step-by-step in small increments with reading in between. The crack increments were typical from 0.05-0.1 mm of length at the beginning of the propagation and up to 1-2 mm at the end of the crack path just before rupture. The stress intensity and the da/dN-values where then calculated as mean values over the current crack increment.

In this investigation no attention was paid to the initiation phase. The crack initiation was established by cycling the specimens between $\sigma_{0=}$225 Mpa and $\sigma_{0=}$–25 Mpa, thus at R= -0.11 for approximately 30-35000 cycles. Corrected for the effect of the notch, the stress would become +675 Mpa to –75 Mpa at the initation site, i.e. 1.6 times the yield stress. This will explain the low cycle count for crack initiation. At complete crack initiation, the cracks where about 0.2-0.3 mm of length.

$$r_p = \frac{1}{\pi}\left(\frac{K_1}{\sigma_y}\right)^2 \tag{2}$$

The first part of the propagation was disregarded because of the remaining plastic zone after initiation cycling at high stress level. The extension of the plastic zone was estimated according to the Irwin approximation for plane stress, Eq. (2), [7]. This is the condition which produces the largest plastic zone size and the situation that is predominant at the surface where the observations of the propagating crack where made. Assuming an average size of 0.3 mm for the initial crack, the size of the plastic zone was calculated using the stress intensity from the initiation cycling. The crack was then propagated beyond the plastic zone using the same load level as for the subsequent testing before any crack rate measurements where made.

Initiation site establishment from machining

Even if the initiation phase was not at focus for this investigation, it is interesting from an engineering point of view to have some knowledge about factors that affect the initiation. The presence of initial defect at the walls inside the hole is one such issue. Macroscopic fatigue cracks often initiate in microscopic flaws. The material around boltholes are usually pretensioned by the mounted bolts and consequently stress released. Under such conditions, the surface smoothness inside the holes is not crucial. In other cases, when the holes are to be free from clamp loads during service, the surface character inside the holes can be of vital importance. Note that it can be of great difference how the holes are manufactured. In this investigation drilled holes are considered, but it is likely that an inclination for micro crack development due to machining is general for a certain material.

The circumference surface inside the hole was examined in 31 experimentally drilled holes of diameters 1.5, 2.5 and 3.5mm. The holes where drilled in three small test specimens, see Fig. 4, all of which where cut out from one of the nodular iron specimens. The holes were drilled under different conditions such as sharp drill and low feeding, sharp drill and high feeding and finally blunt drill and medium feeding. The test specimens was moulded in plastic and then grinded and polished and after that microscope examined in 2D, showing the presumptive initiation points as cracks and flaws originating in the drilling operation.

The grinding and polishing procedure was then repeated, generating a new 2D section to examine. Totally four 2D hole sections of each test specimen was examined, i.e. 124 hole sections in total.

Figure 4. Test specimens for investigation of machined surfaces inside holes

The range of flaw size that is of interest was estimated to be from 10-20 μm and upwards. In contrast to steel, Björkblad, A [8] this ferritic nodular iron does not give rise to any initiation flaws inside bored holes. The average numbers of flaws where less than one per section an no one of the rare flaws that were found was bigger than 20 μm. The only present type of surface braking cracks where at the nodules that was located near under the surface. That type of cracks are still not menacing as they end up in a nodule with a radius at bottom, and therefore can be placed on an equal footing with all other surface braking nodules. All other irregularities that where found was only embrace the surface.

This sub investigation shows that this material is not sensitive to crack initiation emanating from machining operations. Only the surface from bore operations has been investigated, but it is likely, most because of the tough character of the material and the large amount of nodules that will cut off the chips, that the characteristics is the same for other machining operations.

Results

The results that have been achieved so far are mainly the Paris parameters m and c. These are for R=0: m=5.5, c=1.5e-12 and for R=0.8: m=5.5, c=7e-11 provided da/dN in [mm/cycle] and ΔK in [Mpa(m)$^{1/2}$]. The middle curve in Fig. 5 (Ref) is an average curve for R=0 [2] for a ferrite/perlitic nodular iron. Paris data for that curve are m=5 and c=2.5e-11.

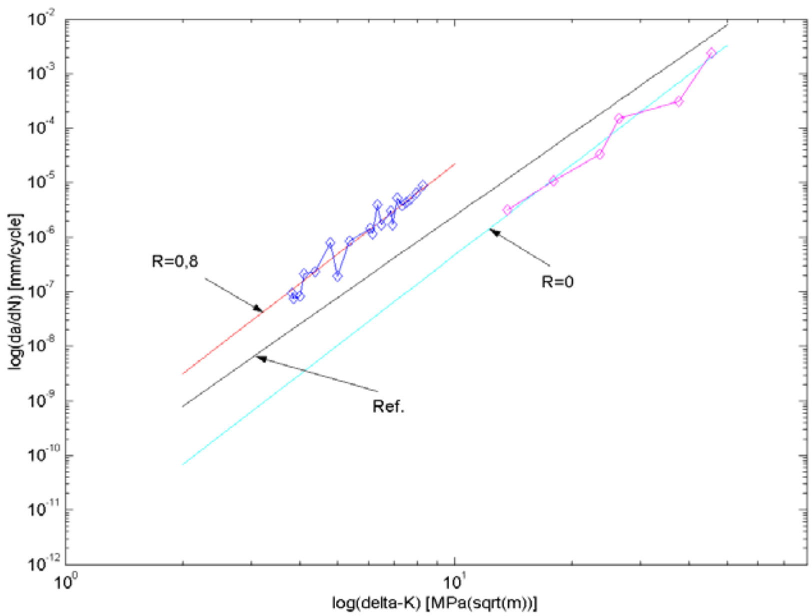

Figure 5. Obtained da/dN-curves for SS 0725 and one example of another nodular iron (Ref)

Conclusions

The fatigue material properties for nodular iron SS 140725 where investigated. The investigation is based on stress intensities from FE-calculations and fatigue testing of a center crack specimen.

The general conclusions that can be drawn are the as follows:

- Stress intensity solutions from FEM are in good correlation with analytical solutions
- The material shows a smooth and uniform crack rate behavior, thus indicating uniform microstructure and hardness
- The difference in crack rate between R=0 and R=0.8, i.e. propagation with respectively without crack closure, is substantial
- The testing shows a Paris law slope that are equal for different R-values
- No sensitivity for crack establishment from machining can be discerned

Discussion and further work

This is a part report from an ongoing work. Because of a test system breakdown, the schedule has not been possible to follow and the whole investigation is delayed. The testing is not yet concluded and the evaluation will be supplemented by tests of other specimen designs.

It is too early to evaluate the results at this stage; this will be done in the following report at the subject.

Acknowledgement

The author would like to thank Jack Samuelsson, Volvo CE, and Kenneth Hamberg, Chalmers Lindholmen, for being sources of inspiration and for supervision. Further, Kjell Eriksson, Volvo CE, for material investigations. Last, but not least, Nordic Industrial Found (NI), National Council for Technical Research and Vehicle Engineering (PFF) and Volvo for founding.

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