Geometrical Size Effect in High Cycle Fatigue Strength of Heavy-walled Ductile Cast Iron GJS400: Weakest Link vs Defect-Based Approach

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Abstract

Fatigue strength is known to decrease with increasing dimension of the component. This is due to a technological size effect, related to the production process, and to a geometrical size effect, due to a higher probability of finding a large defect. To investigate the latter, an heavy-walled component made of Ductile Cast Iron (DCI) has been trepanned and a fatigue test plan has been carried out using 4 different specimen geometries. An attempt has been made to relate the resulting fatigue strength using a weakest-link approach based on the effective volumes and surfaces. This approach seems to work well only in cases of different specimen’s lengths. Some of the fracture surfaces were analyzed by means of SEM and the initiating defects were identified and measured. An approach in which the defects population can be randomly distributed in the specimen has been tried. Virtual fatigue tests have been carried out by considering pure propagation of the worst defect. The resulting fatigue curves showed that this approach is promising but needs further description of the initiation phase.

Keywords: high cycle fatigue; probabilistic; weakest-link; ductile cast iron.

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1. Introduction

It is a well known phenomenon that the fatigue strength of material decreases with increasing the size of the component [1-3]. In most materials, fatigue initiates from discontinuities, that may be considered as micro-cracks. In a simplified approach as proposed by Murakami [4], the fatigue strength inversely depends on the area of the defect, projected on a plane normal to the damaging stress field. The link between the size of the component and the size of the initiating defect is of two types: technological and geometrical. By increasing the volume of the component, the production process becomes less controllable and generally leads to a population of bigger defects. In heavy-walled cast iron castings, for example, large mass results in large solidification times, which are related to bigger grains, graphite particles, porosities (technological size effect). Moreover, the larger the volume (or the surface) subjected to a given damaging stress, the larger the probability of finding a defect of a size which will result in a failure (geometrical size effect). This paper is focused on the latter.

2. The fatigue test plan

To investigate the matter, a component made of Ductile Cast Iron (DCI) EN-GJS-400-18 was trepanned in an area with a wall thickness of about 400mm. Fatigue specimens of 4 different geometries were machined in order to test different volumes and surfaces (see tab. 1). Effective volumes and surfaces cover two orders of magnitude. The transition radii and the gauge length were chosen in order to keep the working stresses in a ±2% of the nominal stress. Since it is known that material properties vary with the cooling curve and hence the position within the casting, great care was taken in mixing up the locations of the specimens, in order to avoid any bias due to technological size effect.

The results were analyzed using the Bi-conditional Fatigue Model [5] with a 3-parameter Weibull distribution on the fatigue strength at infinite number of cycles.

Table 1. Fatigue test details. The strengths values have been normalized to the 50th percentile of the fatigue strength of the #047 serie.

| Specimen ID | Gauge diameter (mm) | Gauge length (mm) | Relative Volume | Relative Area | Fatigue data points | Weibull scale parameter | Weibull shape parameter | Weibull location parameter | Median Fatigue Strength |
|-------------|---------------------|-------------------|-----------------|---------------|---------------------|------------------------|------------------------|--------------------------|------------------------|
| #048        | 10                  | 12                | 0.2             | 0.2           | 28                  | 1.16                   | 17.26                  | 0.02                     | 1.21                    |
| #047        | 10                  | 69                | 1               | 1             | 51                  | 0.41                   | 7.43                   | 0.61                     | 1                      |
| #045        | 20                  | 37                | 2.1             | 1.1           | 36                  | 1.16                   | 17.26                  | 0.02                     | 1.15                    |
| #046        | 32                  | 160               | 21.4            | 10.8          | 24                  | 0.83                   | 19.45                  | 0.15                     | 0.96                    |
3. The initiation defects analysis

Part of the specimen were analyzed by means of optical and S.E. microscope in order to identify and measure the initiating defects. The $\sqrt{\text{area}}$ of the defects were analyzed using the Gumbel distribution for each data set, fig.2. It is worth notice that, despite the fact that the material is the same and that the volume/surface is lower, the larger defects are found in the #047 and #48 series. In the author’s opinion, this may be related to the diameter playing some role in the initiation phase. Also the larger defects are always agglomerates of degenerated graphite.

4. Weakest Link approach

In the W-L approach, the component is modeled as a serial system in which failure is defined as any of the link fails. When it is used in conjunction with a 3-p Weibull distribution, the following applies:

$$\sigma_i(P) = \alpha_0 \cdot \left[-\ln(1 - P)^{1/\beta_0}\right]^{1/\beta_0} + \lambda_0; \quad I_i = \int_S \left(\frac{\sigma(x,y,z)}{\sigma_{\text{max}}}\right)^{\beta_0} dS \quad \text{or} \quad \int_V \left(\frac{\sigma(x,y,z)}{\sigma_{\text{max}}}\right)^{\beta_0} dV$$

where $\alpha, \beta, \lambda$ are the scale, shape and location parameter of the Weibull distribution and $\sigma_{\text{max}}$ is the local maximum in stress.
Fig. 3 shows that the prediction is acceptable only within the #045-#046 and #047-#048. The surface-based weakest link performs slightly better than the volume based one.

5. Explicit defect approach

The steps of this approach are the following: 1. starting from an appropriate measure campaign, define a probabilistic distribution of defects in terms of dimension, shape and position; 2. define a failure process (example: defects are treated as cracks and only propagation is considered); 3. perform a Monte Carlo analysis by running n sets of defect distributions.

The routine written for this work is a simpler version of the P•FAT software [6]. In fig. 4 it is possible to see that the main features of the experimental data has been captured in the numerical approach.

6. Conclusions

1. The fatigue tests carried on 4 different specimen geometries shows that the dependence of the HCF strength to either surface or volume is not monotonic. In particular, the diameter seems to play a role.
2. The fracture surface analysis revealed that larger initiating defects are found in the specimens with smaller diameter. The larger defects were always agglomerates of degenerated graphite.
3. When surface and volume based Weakest-link approach was applied to fatigue strength, satisfactory results were obtained only within the series with small and large diameter. The surface –based approach performed slightly better than the volume one.
4. Using a simple version of an approach in which the defect population is randomly distributed inside the specimens seems to properly catch the main features of the experimental data.
5. A further improvement is needed to include the observation at point 2.

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