Fatigue 2010

Application of quantitative image analysis of graphite structures for the fatigue strength estimation of cast iron materials

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Received 25 February 2010; revised 11 March 2010; accepted 15 March 2010

Abstract

The characteristic formation of graphite microstructures defines the physical and mechanical properties of cast irons. The graphite morphology of cast iron structures can be classified according to their shape, arrangement and size using as reference the structure micrographs specified in the standards ASTM A 247-67 and DIN EN ISO 945. These specific values do not provide any mathematical correlation between microstructure and mechanical properties. The application of quantitative image analysis in microstructure investigations allows a statistically reproducible evaluation method. Although cast irons were quite often focus of research works in this sector, the graphite morphology classification has been mainly handled devoid of any quantitative correlation to material properties.

In this article an interrelation between the fatigue strength of cast iron materials and a quantitative characteristic of the graphite microstructure was established. Thereby it is necessary to identify the largest graphite precipitates, which can be statistically considered as potential crack initiation sites. In this context three different cast iron materials were investigated: EN-GJL-270, EN-GJV-450 and EN-GJS-700.

Keywords: Cast irons; graphite morphology; quantitative image analysis; fatigue strength

1. Introduction

The different graphite precipitation forms in cast iron have a decisive influence on the physical and mechanical properties of this material group. The internal notch effect, as a result of the geometrical form of the graphite inclusions, is qualitatively well known. The fatigue strength reflects this effect very clearly. Therefore an appropriate quantitative evaluation of the graphite morphology should be able to identify an evident interrelationship with the fatigue strength. The aim of the present investigation was to correlate the fully reversed fatigue strength $\sigma_{\text{f,FR}}$ of different cast iron grades with the correspondent statistically biggest defect in the highly stressed material volume according to Murakami using quantitative image analysis. As a basis for the statistical evaluation of the image analysis results, the extreme value statistics according to Gumbel were used. The study was carried out with a lamellar (EN-GJL-250), a vermicular (EN-GJV-450) and a nodular (EN-GJS-700) cast iron grade.

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1877-7058 c⃝ 2010 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
doi:10.1016/j.proeng.2010.03.139
2. Experimental Procedure

2.1. Cast Iron Grades

The mechanical properties of various members of the cast iron family are influenced both by the morphology of the graphite and the characteristics of the surrounding matrix structure. The graphite morphology can be manipulated in several ways. The most frequently applied method to adjust the graphite formation is alloying with magnesium (Mg). The chemical composition of all three investigated cast iron grades is listed in Table 1.

With the objective to reduce the matrix structure influence in this study, all three analysed cast iron grades were kept mainly (ca. 95%) pearlitic. Fig. 1 (unetched) and Fig. 2 (etched) show representative microstructural images taken from the investigated cast iron materials at the same magnification.

Table 1. Chemical composition

|        | C   | Si  | Mn  | P   | S   | Cu  | Sn  | Mg  |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| EN-GJL-250 | 3.340 | 2.080 | 0.654 | 0.039 | 0.090 | 0.275 | 0.059 | <0.001 |
| EN-GJV-450  | 3.613 | 2.393 | 0.334 | 0.016 | 0.011 | 0.680 | 0.063 | 0.009 |
| EN-GJS-700  | 3.740 | 1.850 | 0.521 | 0.037 | 0.006 | 0.579 | 0.007 | 0.014 |

Fig. 1. Unetched microstructure of the investigated cast iron grades - (a) EN-GJL-270; (b) EN-GJV-450; (c) EN-GJS-700

Fig. 2. Etched microstructure of the investigated cast iron grades - (a) EN-GJL-270; (b) EN-GJV-450; (c) EN-GJS-700
2.2. Determination of the Fatigue Strength

The fully reversed fatigue strength $\sigma_{zW}$ is an important parameter for the fatigue design of components and was used to compare the cyclic load-bearing capacity in this work. To this end, unnotched cylindrical specimens according to Fig. 3 were cut from cylinder blocks cast to the desired microstructure. For a statistically secured determination of the fatigue tests, 25 fatigue specimens were used in each test series with runouts beyond $10^7$ cycles.

Fig. 3. Fatigue specimen geometry

The statistical evaluation of the fatigue tests was carried out using the software SAFD [1], in which a logarithmical distribution of the stress levels in the transition zone from the High-Cycle-Fatigue (HCF) to the Long-Life-Fatigue (LLF) was assumed.

For the cast iron grade EN-GJL-270 (lamellar cast iron) a fatigue strength $\sigma_{zW} = 71$ MPa was evaluated for a failure probability of $P = 50\%$, Fig. 4.

Fig. 4. S-N-curve for cast iron grade EN-GJL-270

After the statistical evaluation of the fatigue tests for the cast iron grade with vermicular graphite precipitations (EN-GJV-450), a fatigue strength of $\sigma_{zW} = 177$ MPa was obtained for a failure probability of $P = 50\%$, Fig. 5. The vermicular cast iron shows a fatigue strength value already more than twice as high as the lamellar cast iron.
The cast iron grade with nodular graphite EN-GJS-700 shows the highest fatigue strength value among the three grades, $\sigma_{z_{FD}} = 289$ MPa for the same failure probability, $P = 50\%$, Fig. 6.

Fig. 6. S-N-curve for cast iron grade EN-GJS-700

2.3. Image Analysis

The 2-dimensional quantitative image analysis has gained importance in materials science and engineering. Several research studies have been successfully carried out using image analysis as an efficient instrument for the
evaluation of microstructure characteristics. This methodology provides a reliable and reproducible statistical procedure for the classification of different microstructural features, [2-7]. The aim of this study was to establish a correlation between the graphite morphology and the fatigue strength avoiding the use of standard series images according to ASTM A 247-67 and DIN EN ISO 945. Table 2 summarizes the technical data used for the microstructure evaluation.

Table 2. Technical data of the image analysis system

| Parameter                              | Characteristic                                      |
|----------------------------------------|-----------------------------------------------------|
| Light optical microscope               | Leica DM 4000 M                                     |
| CCD-camera                             | Jenoptik ProgRes 3012                               |
| Image analysis software                | A4i Aquinto - Version 5.1                           |
| Camera resolution                      | 3.072 x 2.320 (7,12 MPixel)                         |
| Magnification                          | 100:1                                               |
| Evaluation criterion                   | Particle size > 3.79 \( \mu \text{m}^2 \) (> 20 Pixel) |
| Image size                             | 1,338 x 1,010 mm                                   |
| Measuring area per foto                | 1,352 mm\(^2\)                                     |
| Total measured area (35 images)        | 47,32 mm\(^2\)                                     |
| Analysed objects per specimen          | ca. 34,000 for EN-GJL-270                           |
|                                       | ca. 20,000 for EN-GJV-450 and EN-GJS-700            |
| Non-evaluated objects                  | Boundary cut objects                               |
| Objects density                        | ca. 720 / mm\(^2\) for EN-GJL-270                  |
|                                       | ca. 425 / mm\(^2\) for EN-GJV-450 and EN-GJS-700  |

The investigations using image analysis were carried out with specimens which were tested in the transition zone from the High-Cycle-Fatigue (HCF) to the Long-Life-Fatigue (LLF) area. This way both failures and runout-specimens were taken into account. The samples for the image analysis were extracted from the middle area of the fatigue specimen, where the fatigue cracks occur. From each fatigue specimen, 5 slices with ca. 2 mm thickness were cut out and subsequently metallographically prepared. From each slice, 7 image fields were recorded, so that 35 images for each fatigue specimen could be evaluated. In total, 15 fatigue specimens of the cast iron grade EN-GJL-270, 14 of grade EN-GJV-450 and 16 of grade EN-GJS-700 were analysed.

3. Evaluation Using the Gumbel Distribution

The influence of small-sized material defects and non-metallic inclusions on the fatigue strength of engineering materials was evaluated by Murakami. In this work the size of a defect was defined as \( A^\circ \), where \( A \) is the area of the defect in a metallographic cross section, Fig. 7 [8]. Only the largest defect in each image of a large series of parallel images is included in the evaluation according to Gumbel's statistics of extreme [9].

![Fig. 7. Primary characteristics for the image analysis of microstructures](fig7.png)
In this study, the major dimension of a graphite precipitation $F_{\text{max}}$ was selected as defect characterizing parameter. For each fatigue specimen, the biggest defect of all 35 images was identified and evaluated with the Gumbel distribution. The probability density function $f(x)$ of the Gumbel distribution is defined for the characteristic $x$ by eq. 1:

$$f(x) = \frac{1}{\delta} \exp\left(-\exp\left[-\frac{x-\lambda}{\delta}\right]\right) \cdot \exp\left[-\frac{x-\lambda}{\delta}\right]$$

(1)

The characteristic $x$ represents the size $F_{\text{max}}$ of the 35 largest graphite precipitations, $\lambda$ is a characteristic size of the largest graphite precipitations and $\delta$ the distribution spread. $\lambda$ indicates the position of the distribution maximum point, $\delta$ characterizes the width of the distribution curve. The cumulative distribution function or cumulative frequency can be described using eq. 2:

$$F(x) = \exp\left(-\exp\left[-\frac{x-\lambda}{\delta}\right]\right)$$

(2)

Substituting $F(x)$ in equation (2) by an estimated probability $P$ and taking twice the logarithm, a linear correlation between the size of the largest graphite precipitations $x$ and the term $-\ln(-\ln P)$ can be obtained, eq. 3.

$$-\ln(-\ln P) \approx \frac{1}{\delta} x - \frac{\lambda}{\delta}$$

(3)

Using a linear regression of the term $-\ln(-\ln P)$ the parameters $\lambda$ and $\delta$ for the distribution function can be determined. In this study the probability $P$ was estimated using eq. 4, where $i$ is the a ranking of increasing $F_{\text{max}}$ of the graphite precipitations and $n = 35$ is the number of image fields.

$$P = \frac{i-0.3}{n+0.4}$$

(4)

Fig. 8 shows, by example for one fatigue specimen of each cast iron, the correspondent major dimensions of the largest graphite precipitations from 35 analysed fields. The intersection between the regression line and the x-axis defines the characteristic size $\lambda$. 

![Gumbel distribution for the biggest graphite particles for one fatigue specimen of each analysed cast iron grade](image-url)
The evaluated characteristic size $\lambda$ for all three cast iron grades differ significantly from each other. While the lamellar cast iron grade shows a $\lambda$-value of almost 300 $\mu$m, the vermicular graphite cast iron material has roughly half that value with $\lambda \approx 170$ $\mu$m. As already expected, the nodular cast iron exhibits the smallest $\lambda$-value, one fifth that of grade EN-GJL-270 and one third that of grade EN-GJV-450.

In Fig. 9 the fatigue strength at $P = 50\%$ failure probability is plotted versus the more than 10 $\lambda$-values of the three cast irons each. EN-GJL-250 shows comparatively the largest scatter of the $\lambda$-values under all three materials analysed in this study. The smallest variation of $\lambda$-values was observed for nodular cast iron (EN-GJS-700). Both the evaluated fully reserved fatigue strength $\sigma_{zdW}$ and the $\lambda$-values for the vermicular cast iron grade (EN-GJV-450) are located between both other investigated cast iron materials. The $\lambda$-values of the three grades do not overlap in spite of the scatter.

![Fig. 9. Correlation between fully reversed fatigue strength $\sigma_{zdW}$ and the characteristic size of the largest graphite precipitations $\lambda$.](image)

There seems to exist a linear correlation between the fully reversed fatigue strength $\sigma_{zdW}$ and the corresponding mean $\lambda$-value, so that the average $\lambda$-value could characterize the fully reversed fatigue strength $\sigma_{zdW}$ for cast iron materials within the limit of the $\lambda$-scatter bands.

Since the fatigue strength extrapolates to zero at a defined $\lambda$-value, further studies going into more detail are necessary to modify the linear relationship found here.

4. Conclusion

The dependence of the fully reversed fatigue strength $\sigma_{zdW}$ on the graphite morphology could be correlated to the microstructure analyzing the graphite size of three different pearlitic cast iron grades with lamellar, vermicular and nodular graphite inclusions.

A linear correlation was established between the fully reversed fatigue strength $\sigma_{zdW}$ and a characteristic size $\lambda$ of the largest graphite precipitation using image analysis as an instrument for the evaluation of the microstructure.

Gumbel’s statistics of extremes proved to be a suitable instrument to characterize the graphite morphology in the most often used cast iron grades simply by a size parameter.

The linear correlation between the average $\lambda$-value of the largest graphite precipitations and the fully reversed fatigue strength $\sigma_{zdW}$ has a very high correlation coefficient and suggests the applicability of this method for the estimation of the fully reversed fatigue strengths $\sigma_{zdW}$ for pearlitic cast iron grades within the limits of $\lambda$-scatter.

In the same way, it is plausible to apply this methodology for the estimation and characterisation of further mechanical properties and possibly also for physical properties of cast iron materials. The analysis must, however, include more structural variations to finally make it a viable tool for educated guesses.
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