

Fatigue Assessment of Nodular Cast Iron with Material Imperfections

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ABSTRACT

For the design of thick-walled nodular cast iron components, fatigue assessment, especially in the context of local imperfections in the material, is a challenging task. Not only the cyclic material behavior of the sound baseline material, but also the cyclic behavior of materials with imperfections, such as shrinkages, dross and chunky graphite, needs to be considered during the design process of cast iron components. In addition to this, new materials, such as solid solution strengthened alloys, offer new possibilities in lightweight design, but need to be assessed concerning their fatigue strength and elastic-plastic material behavior. If a safe and reproducible fatigue assessment for any component cannot be performed and a secure usage is therefore not given, the cast components are generally rejected, leading to a loss of additional material, energy and money for recasting the component. In this context, four nodular cast iron materials are compared with reference to their cyclic material and fatigue behavior as well as their potential for a lightweight design, based on stress- and strain-controlled tests both for sound and defective material. However, to develop an optimal and individual fatigue design method for cast components with local material imperfections present, the component's local fatigue strength needs to be combined with information from non-destructive testing (NDT), since a removal of specimens is generally not possible. For this purpose, as an example, a method is described that uses information from ultrasonic and X-ray analysis as well as the given fatigue strength of the baseline material to conduct a fatigue assessment of local shrinkages in nodular cast iron components. The method is based on the reproducible measurement of the local density by NDT and its correlation with the local fatigue notch factor, enabling a safe and local assessment of the allowable fatigue strength when shrinkages are present.

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INTRODUCTION

To reduce the output of carbon dioxide and to preserve resources, the usage of more efficient thick-walled cast iron products has become increasingly important, especially for applications in wind energy and heavy industries, where solutions for a better material saturation for a lightweight design are needed. However, the machine's availability and safety are further crucial points that cannot be neglected.

To design such components properly, the cyclic material behavior of the nodular cast iron grade in a sound condition and in the presence of local material imperfections, such as shrinkages, needs to be known properly. Of similar importance is the detection of fatigue-relevant material imperfections, especially in thick-walled components. Therefore, measures for determining the influence of local material imperfections through non-destructive testing are desired, in order to prevent the rework or even the rejection of the heavy cast components. Presently, thick-walled cast iron components are assessed by certain severity levels e.g. [1, 2], indicating the influence of material imperfections on fatigue life depending on the results of NDT. However, these measures do not offer possibilities for an appropriate fatigue evaluation, since a correlation between the severity levels and the local fatigue strength is presently not given and the usage of the severity levels are statistically and experimentally not assured. Initial attempts to assess the local fatigue

strength of material defects in thick-walled nodular cast iron grade GGG-40 were pursued by [3] by determining S-N curves for the shrinkages classes according to [4]. However, the results are not proven for other nodular cast iron grades and cannot be used if an X-ray analysis cannot be performed on the thick-walled components. Further investigations on shrinkages in steel castings [5, 6, 7, 8] were performed to determine a local fatigue notch factor K_f for the shrinkages by using FEM and X-ray analysis, leading to large scatter bands for assessing K_f . Furthermore, the results are not transferable to thick-walled cast iron components due to a demand for a high resolution of the local shrinkage of only a few 10 μm , which cannot be offered by X-ray and ultrasonic tests on cast components having a wall thickness of several 100 mm.

Nevertheless, new methods of non-destructive testing, such as the ultrasonic technique, Sampling Phased Array, provide new possibilities for involvement in the design process enabling the determination of a local density and a three dimensional view of the shrinkages in the components [9, 10]. To investigate the fatigue strength of thick-walled nodular cast iron and to find a method for an assessment of thick-walled components made of nodular cast iron based on NDT methods, four different nodular cast iron materials, EN-GJS-400-18U-LT, EN-GJS-450-18, EN-GJS-700-2 and ADI-800, were investigated based on strain- and stress-controlled fatigue tests.

Through ultrasonic investigations with the measurement technique Sampling Phased Array, a design concept is discussed linking the local component's density measured by Sampling Phased Array and the fatigue life of the sound material with the local fatigue strength of the shrinkage-affected material.

MATERIALS AND FATIGUE SPECIMEN

The investigations were performed on cast blocks of ferritic EN-GJS-400-18U-LT, ferritic, solid solution strengthened EN-GJS-450-18, pearlitic EN-GJS-700-2 and ausferritic ADI-800. To achieve micro-structures comparable to those of thick-walled cast components, the blocks were cast with wall thicknesses d between 120 and 250 mm. In the case of EN-GJS-400-18U-LT, EN-GJS-450-18 and EN-GJS-700-2, large shrinkage volumes were generated inside the cast blocks by means of a controlled solidification. For ADI-800, only macroscopically sound material was investigated. Examples of the cast block of EN-GJS-400-18U-LT with 230 mm thickness and the Y-cast block for ADI-800 are shown in [Figure 1](#). The chemical compositions of the materials and the mean results of three tensile tests performed on specimens removed in the rim zone of the cast blocks are shown in [Table 1](#) and [Table 2](#). Compared to the other materials, EN-GJS-450-18 has, at 3.18 %, the highest silicon content to achieve a solid solution strengthened matrix. The results of the tensile tests show high values for the breaking strain A_5 of the solid solution strengthened EN-GJS-450-18 compared to EN-GJS-400-18U-LT. This can be related back to the much higher wall thickness of the cast block of EN-GJS-400-18U-LT and, thus, to the better material parameters of EN-GJS-450-18U-LT, having only half of the wall thickness.

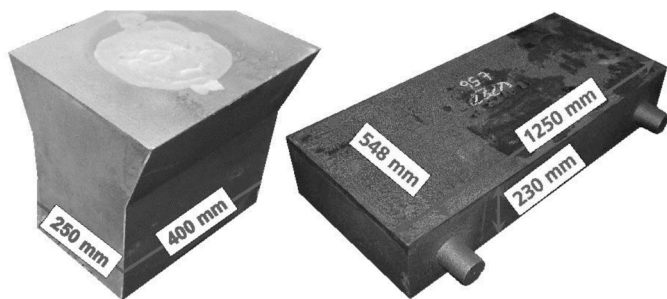


Figure 1. Cast blocks (ADI-800 (left) and EN-GJS-400-18U-LT (right))

Table 1. Chemical composition of the tested materials

Material	Chemical Composition (in %-weight)				
	C	Si	Mn	S	Mg
EN-GJS-400-18U-LT	3.410	2.200	0.172	0.006	0.049
EN-GJS-450-18	3.320	3.180	0.160	0.008	0.051
EN-GJS-700-2	3.700	2.410	0.500	0.006	0.051
ADI-800	3.540	2.120	0.283	0.007	0.053

Table 2. Quasi-static material data of the tested materials

	Temperature	EN-GJS-400-18U-LT	EN-GJS-450-18	EN-GJS-700-2	ADI-800
Tensile strength R_m [MPa]	RT ¹⁾	351	443	713	782
Yield strength $R_{p0.2}$ [MPa]	RT ¹⁾	235	325	537	614
Breaking strain A_5 [%]	RT ¹⁾	13.6	20.4	1.9	2.5
Wall thickness d [mm]		230	120	200	250
RT ¹⁾ – room temperature					

Additionally, the parameters of the microstructure were determined for all materials on polished sections. The results for graphite form, graphite size and nodularity, according to [11], are given in [Table 3](#), as well as an example of an etched section for each material. Further investigations concerning the microstructure for specimens removed from the shrinkage volume in the cast blocks of EN-GJS-400-18U-LT, EN-GJS-450-18 and EN-GJS-700-2 are discussed in [12].

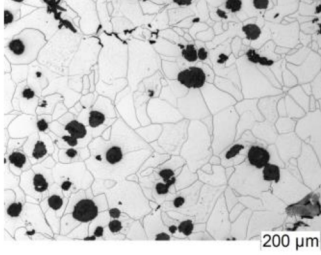
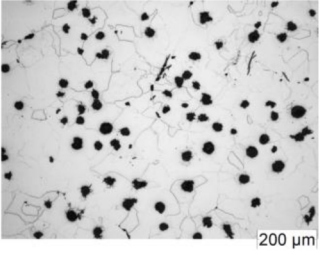
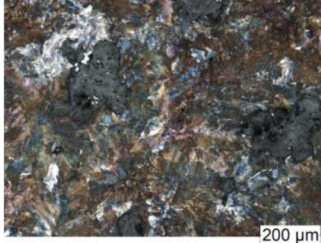
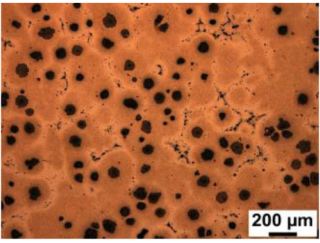
NON-DESTRUCTIVE TESTING

X-Ray and Ultrasonic Testing

All cast blocks were investigated non-destructively by ultrasonic measurement techniques, especially by Sampling Phased Array, and the blocks of EN-GJS-400-18U-LT, EN-GJS-450-18 and EN-GJS-700-2 were additionally X-ray analyzed [9, 10, 12]. The ultrasonic technique Sampling Phased Array was particularly used and further developed to detect the shrinkages in the cast blocks, to determine the three dimensional geometry of the shrinkages present and their density according to [9, 10]. Shrinkages were found only in the cast blocks of the ferritic and the pearlitic materials. The block of the ADI-800 was completely sound, according to the ultrasonic inspection. As an example, [Figure 2](#) shows the result of the shrinkage volume detected in the cast block of EN-GJS-700-2. The resolutions of the detectable structures are dependent on test frequency and material and are in the range between 0.3 and 6.0 mm [9, 10].

Also the specimens, being removed from the cast blocks, were X-ray analyzed, according to the German standards for X-ray analysis [13, 14] and the shrinkages were categorized in the classes Cc-1 to Cc-5 according to [4]. The parameters for the X-ray testing are exemplified in [15].

Table 3. Parameters of the graphite according to [6]

Material	
EN-GJS-400-18U-LT	EN-GJS-450-18
	
etched by using 3 % Nital	
Graphite form acc. to DIN EN ISO 945-1 [11]	
V + VI (88 %)	V + VI (97 %)
Graphite size acc. to DIN EN ISO 945-1 [11]	
4 + 5 + 6 (92 %)	4 + 5 + 6 (95 %)
Nodularity	
51 %	67 %
Hardness (HBW2.5/187.5)	
139.3	159.2
Material	
EN-GJS-700-2	ADI-800
	
etched by using 3 % Nital	
etched by using Murakami	
Graphite form acc. to DIN EN ISO 945-1 [11]	
V (94 %)	V + VI (94 %)
Graphite size acc. to DIN EN ISO 945-1 [11]	
3 + 4 (89 %)	4 + 5 + 6 (91 %)
Nodularity	
58 %	81 %
Hardness (HBW2.5/187.5)	
284.4	295.4

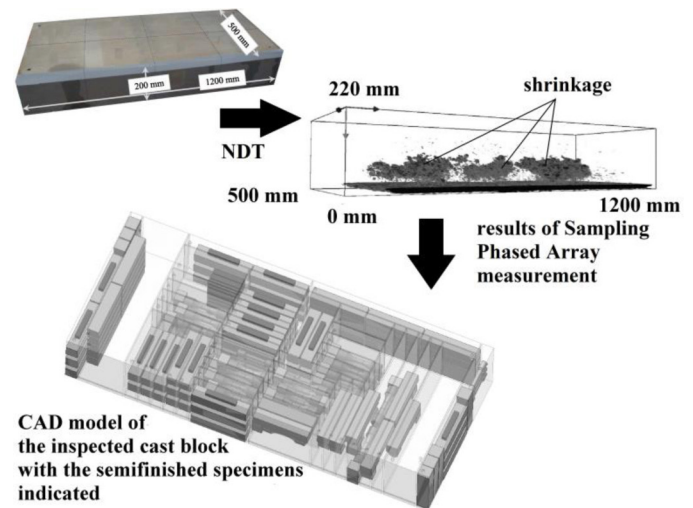


Figure 2. Cast block, result of ultrasonic testing technique Sampling Phased Array and removal plan for the EN-GJS-700-2

DETERMINATION OF THE VIRTUAL YOUNG'S MODULUS

From investigations on steel castings [5, 6, 7, 8, 16] that measured the stiffness of the specimens with shrinkages by an extensometer during stress-controlled fatigue tests [5, 6, 7, 8] or tensile tests [16], it is known that the material's stiffness is influenced by the shrinkages present. According to these prior investigations, the so-called virtual Young's modulus E_f was also determined for the specimens with shrinkages for EN-GJS-400-18U-LT, EN-GJS-450-18 and EN-GJS-700-2 that were removed from the cast blocks. The measurement was performed on servo-hydraulic test rigs, Figure 3. The specimens were loaded with a force and the resulting strain ϵ was measured by means of an extensometer. The extensometer had a gauge length of $l = 25$ mm and covered the complete length of the test volume. The measurement was repeated four times for each specimen, moving the extensometer by an angle of 90° around the specimen. Based on the measurement of the strain ϵ and the applied load, the evaluation of the so-called virtual Young's modulus E_f was performed according to [17], who compared different methods of determining the Young's modulus E and finally suggested a hyperbolic approach. The determined Young's modulus is subsequently referred to as the so-called virtual Young's modulus E_p , since the expression Young's modulus is normally reserved only for the sound material condition. During the evaluation, the shrinkages in the specimens were neglected and the load was related to the nominal cross section. Thus, the resulting stresses are nominal stresses.

For metallic materials, it is known that a higher density ρ is generally accompanied by a higher Young's modulus E . To see whether this is also valid for the specimens with shrinkages, the test volumes of all specimens were cut off after the fatigue test, Figure 4. Both remaining pieces were weighed and the density ρ_w determined. The correlation between the measured density ρ_w and the measured virtual Young's modulus E_f is shown in Figure 5 for the materials