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Microporosity and statistical size effect on the fatigue strength of cast aluminium alloys EN AC-45500 and 46200

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A R T I C L E I N F O

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A B S T R A C T

This paper investigates the fatigue strength of two cast aluminium alloys, EN AC-45500 and 46200, dealing with the influence of microporosity and the statistical size effect. Small-scale round specimens are extracted from cylinder heads and crank cases as typical cast components in automotive industry. Uniaxial fatigue tests under alternating tension/compression loading are performed. Local microstructural properties, such as second dendrite arm spacing and microporosity, are characterized by means of metallography, fracture surface analysis utilizing scanning electron microscopy, and X-ray computed tomography. The measurements reveal significant differences in microporosity and microstructure depending on the extraction position and specimen type. These findings are reflected by the experimental test results showing that the microporosity majorly affects the fatigue behaviour with a maximum difference in fatigue resistance at ten million load-cycles of up to 39% in case of the EN AC-45500 specimens. Additional experiments involving two different EN AC-46200 specimen types exhibiting unequal highly-stressed volumes demonstrate a reduction of the high-cycle fatigue strength by 8% caused by the statistical size effect. Fatigue strength assessment incorporates the application of the model by Tiryakioğlu based on the extreme value distribution of the micropore sizes by Gumbel, as well as the √area approach by Murakami. The evaluated results agree well to the fatigue tests enabling a local fatigue strength assessment under consideration of manufacturing process dependent material characteristics.

1. Introduction

Casted Al-Si-Mg alloys are widely utilized for high-performance, lightweight parts within mobility sectors [1], and especially in automotive industry [2] due to their advantageous castability and comparably beneficial strength to weight ratio. Although advanced casting technologies [3] are facilitated, the resulting microstructural and mechanical material properties strongly depend on casting process parameters as well as specific material compositions [4]. Such material discontinuities strongly affect the fatigue life of cyclically-loaded parts causing failure by microporosity-induced defects [5–7] and microstructural inhomogeneities [8–10]. Focus of this work is laid on the effect by micropores as primary influence factor on the fatigue strength of casted Al-Si-Mg alloys [11] utilized in complexly-shaped lightweight automotive components, such as internal combustion engine EN AC-45500 cylinder heads and EN AC-46200 crank cases, see Fig. 1.

A study in [12] investigating Al-Si cast alloys concludes that variations in fatigue strength may be obtained even by testing an increased number of specimens, which is mainly caused by the statistically distributed occurrence of micropores. Hence, a comparably huge number of samples are essential to obtain a meaningful mean value and scatter index of manufacturing process dependent fatigue strength characteristics. Such a testing scheme is basically a rather time-consuming and expensive process. In order to cover the statistical distribution of casting defects, an incorporation of Weibull statistics [13] and microstructural parameters [14] within the fatigue analysis of Al-Si cast alloys is suggested in [12]. Furthermore, a weakest link concept based on a Weibull distribution function in [15] concludes that the fatigue strength distribution of weak links is different from the micropore size distribution, though fatigue crack initiation is predominantly associated with pores. Another work [16] presents that a log-normal distribution model may act as best fit to the statistical distribution of fatigue initiator sizes enabling a quantitatively correlation with the fatigue life of the experiments. However, a comparison of different statistical distributions for fatigue strength assessment is provided in [17]. Among them, one well suitable model for Al-castings [18] is based on an extreme value distribution of the micropore sizes introduced by Gumbel [19]. Thereby, the cumulative probability P for a certain

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Nomenclature

area	projected area of micropore	N_T	number of load-cycles at transition knee point of S/N-curve
B, m_1	parameters of fatigue life model by Tiryakioğlu	P	cumulative probability
C_0, k_0	constants for crack initiation model	P_f	probability of failure
C_1, C_2, m_2	parameters of fatigue approach by Murakami	P_S	probability of survival
DAS	second dendrite arm spacing	R	stress ratio
d_{equ}	equivalent defect diameter	T_S	stress-based scatter index
HV	Vicker's Hardness	UTS	ultimate tensile strength
k	constant for crack initiation model and Weibull parameter	V	highly-stressed volume
k_1, k_2	slopes of S/N-curve	α, β	constants for crack initiation model
k_σ	stress concentration factor at micropore	δ	scale parameter of extreme value distribution
N	number of load-cycles until burst fracture	$\varepsilon_{equ}{}^{p}$	equivalent plastic strain
N_i	number of load-cycles until crack initiation	σ_a	nominal stress amplitude
		σ_R	alternating fatigue resistance at ten million load-cycles
		λ	location parameter of extreme value distribution

equivalent defect diameter d_{equ} is given in Eq. (1) involving a micropore size distribution depended location λ and scale parameter δ.

$$P(d_{equ}) = \exp\left[-\exp\left(\frac{d_{equ}-\lambda}{\delta}\right)\right] \tag{1}$$

A study in [20] investigating the relationship between defect size and fatigue life distributions of Al-Si castings based on numerous experimental data sets shows that the equivalent diameter d_{equ} is well suited to statistically analyze fatigue-initiating defects. It equals the diameter of a circle, which features the same area as the corresponding defect, see Eq. (2).

$$d_{equ} = \sqrt{\frac{4\cdot area}{\pi}} \tag{2}$$

Fig. 2 represents a typical crack-initiating shrinkage pore at a scanning-electron-microscopy (SEM)-analyzed fracture surface of a tested EN AC-46200 specimen as well as the corresponding depiction of the area-value. In addition to this method, micropore sizes can be characterized on the basis of X-ray computed tomography and metallography [21]. Especially X-ray computed tomography, as non-destructive technique, experiences an increasing practicability due to developments regarding scan quality, such as improved resolution to properly measure complexly-shaped shrinkage pores, and efficiency [22]. Applying such elaborated methods facilitates a fatigue strength assessment involving a three-dimensional evaluation of microporosity [23] and enables an enhanced damage tolerant design of casted components [24].

Based on the extreme value distribution by Gumbel [19], a fatigue model to assess the limit value of failure probability P_f for a certain lifetime until burst fracture N is presented by Tiryakioğlu [20], see Eq. (3).

$$P_f(N) = 1 - \exp\left(-\exp\left(\frac{\lambda}{\delta} - \frac{2}{\delta\cdot\sqrt{\pi}}\cdot\left(\frac{N-N_i}{B\cdot\sigma_a^{-m_1}}\right)^{\frac{2}{2-m_1}}\right)\right) \tag{3}$$

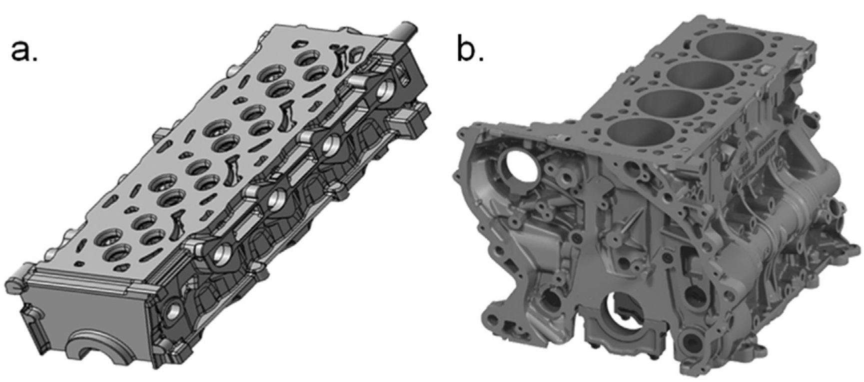

Fig. 1. Cylinder head manufactured of cast aluminium EN AC-45500 (a) and crank case made of EN AC-46200 (b).

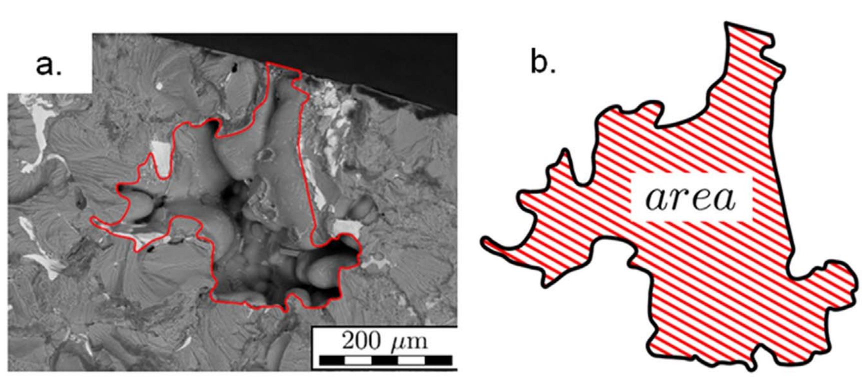

Fig. 2. SEM analysis of micropore at fractured surface of EN AC-46200 specimen (a) and evaluation of corresponding micropore area (b) according to [25].