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Through process Modeling applied to the fatigue design of cast A356-T6 components

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ABSTRACT

The optimization of cast aluminum alloy components is proposed using a Through Process Modeling (TPM) methodology applied to the fatigue design. A full manufacturing process simulation of a cast aluminum alloy A356 component is described. The modeling strategy presented in this paper is able to simulate the defect size, microstructure size and thermal history during the casting process. The microstructure and defect simulated are the Secondary Dendrite Arm Spacing (SDAS) and maximum pore size, respectively. Based on the Defect Stress Gradient approach (DSG) published in a previous work, the fatigue limit is predicted as a function of the SDAS and defect size. Tension fatigue tests have been performed on bespoke prototype cast component samples with various SDAS and defect size. The comparison between experimental results and the TPM simulation shows good agreement in terms of simulated heat transfer rates, defect size, SDAS and fatigue limit except for defect sizes greater than 500 µm.

1. Introduction

Cast aluminum alloys are widely employed in the automotive industry for a wide range of applications such as wheels and engine cylinder heads. These alloys are used because of their excellent castability and lightweight. A major concern in the production of cast aluminum alloys components is the occurrence of casting defects such as pores and oxides. Pores form due to either an inability to compensate for material contraction during solidification or the presence of dissolved gas in the casting [1–6]. A number of studies [7–11] have investigated the effect of casting defects and microstructure (such as the Secondary Dendrite Arm Spacing (SDAS)/ the Dendrite Arm Spacing (DAS), the eutectic silicon, and the intermetallic) on High Cycle Fatigue (HCF) behaviour of cast aluminum alloys. To aid casting designers in developing components, numerical models capable of predicting the formation of porosity and microstructure in the casting after solidification have been formulated. These models may in turn be used to improve the fatigue behaviour of cast aluminum components.

HCF studies on cast aluminum alloys have shown [11,12] that the effect of defect size is in competition with other microstructural features such as SDAS/DAS to limit fatigue life. It has been clearly observed that casting defects have a detrimental effect on the fatigue strength above a critical size [13,14]. In addition, the influence of microstructure defined by DAS or SDAS on the fatigue behaviour of cast aluminum alloy cannot be neglected [15–18]. It has been demonstrated [16] that the eutectic phase can cause micro-cracking due to strain accumulation in proximity to Si-particles. As reported in [11], for small defect sizes, there is a prominent

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Nomenclature

a_{∇}	material parameter describing the type of defect and its influence on the fatigue limit (μm)
f_s	solid fraction
l_{diff}	thickness of the diffusion boundary layer approximated as the defect radius (μm)
m_H	moles of hydrogen (mol)
r_p	defect radius (μm)
r_0	initial pore radius (μm)
t	time (s)
t_f	solidification time (s)
A	material elongation (%)
C_l	hydrogen concentration in the cast during solidification (mol/m^3)
C_{lp}	hydrogen concentration at the liquid/pore interface (mol/m^3)
C_l^X	concentration of the alloying elements in the melt, in the case of cast A356 X = Si, Mg, Fe, Zn, Na, Sr (wt)
D_l	diffusivity of hydrogen (m^2/s)
E	Young modulus (GPa)
K_L	equilibrium constant for hydrogen solubility (mol/m^3/atm$^{1/2}$)
P_a	atmospheric pressure (Pa)
P_g	melt pressure (Pa)
P_h	pressure due to the metallic head (Pa)
$R_{p0.2}$	yield stress (0.2% strain offset) (MPa)
R_m	tensile strength (MPa)
R_g	ideal gas constant (J/K/mol)
R_σ	load ratio $R_\sigma = \sigma_{min}/\sigma_{max}$
T	temperature (°C)
T_l	liquidus temperature (°C)
T_s	solidus temperature (°C)
V_g	defect volume (μm^3)
γ	surface tension (N/m)
φ	impingement factor
ρ	density of the melt (kg/m^3)
λ_2	Secondary Dendrite Arm Spacing (SDAS) (μm)
σ_D	fatigue limit for 10^6 cycles (MPa)
σ_{max}	maximum stress (MPa)
σ_{min}	minimum stress (MPa)
$\sigma_{eq\nabla M}$	DSG equivalent stress at point M (MPa)
$\sigma_{eq,cr}(\infty)$	Crossland equivalent stress far from the defect (MPa)
$\sigma_{eqcr,max}(M)$	maximum Crossland equivalent stress at the surface of the defect (MPa)
$\sqrt{area}$	defect size parameter defined as the projection of the defect on the plane perpendicular to the direction of the maximal principal stress (μm)

interaction between defects and microstructure affecting the fatigue limit of cast A356-T6 aluminum alloy. Therefore, the simulation of defect size and microstructure within a cast aluminum alloy component are critical inputs for fatigue design.

In this context, several studies [19–26] have proposed mathematical models to simulate the solidification process and the formation of pores. A number of models combine the shrinkage pressure and hydrogen concentration to describe the formation of pores. In these models the defects were explicitly assumed to be spherical [27–29]. Atwood et al. [22] assumed that during solidification, due to solid-liquid balance, pore shapes become complex as they grow between grains or between dendrite arms. Several studies [19,30] have suggested that it is more appropriate to consider an equivalent pore size rather than trying to characterize the complex 3D shape. This assumption is useful in simplifying the fatigue life predictions for casting aluminum alloy components.

In some studies [19,21–24,26], the effects of pressure, cooling rate and the distribution of hydrogen in the casting on the formation of pores has been studied. Yao et al. [19] have shown that the distribution of hydrogen in the liquid phase of the melt depends on the cooling rate, which affects pore growth: the pore volume decreases when the rate of solidification increases. In the same context, Carlson et al. [23] developed a model to predict the evolution of porosity during solidification phase. This evolution depends on hydrogen diffusion during solidification. It was shown that, at high cooling rates and low pressure, shrinkage and gas pore formation are more pronounced at low hydrogen concentrations.

From this literature summary, the important points that should be considered to predict defect size include the cooling rate, hydrogen diffusion and local pressure in the melt during solidification. When modeling aluminum alloy casting processes, there are several ways to simulate microstructure formation. Experimental observations have shown that the cooling rate is the major factor affecting dendritic structure [31,32]. The microstructure of a cast aluminum alloy can be quantified by the SDAS calculated as a function depending on the solidification time or the cooling rate [20,21,31,33].

The aim of the current work is to present a Through Process Modelling for the fatigue design of cast A356 components. This model will be applicable to gravity die cast components. The whole process contains 4 steps: (i) simulation of cooling history during solidification, (ii) SDAS prediction based on cooling rate, (iii) shrinkage and pore size prediction based on hydrogen diffusion and solidification time, and (iv) fatigue strength assessment in a multiaxial loading condition. The fatigue strength is predicted using the Defect Stress Gradient (DSG) model which takes into account the defect size, the microstructural variation (SDAS) and the mean stress effects [11]. It is worth noting that the numerical framework developed in this study can be easily extended to any Al-Si-Mg cast aluminum alloy. In this study, a purpose built mold was developed in order to vary the SDAS and casting defects with cooling rate and fatigue specimens were extracted from casting. Tension fatigue tests were carried at two stress ratios: $R_\sigma = 0$ and $R_\sigma = -1$. Finally, a comparison was carried out between experimental and simulated fatigue strength at 10^6 cycles in order to evaluate the prediction of the Through Process Modelling methodology applied to fatigue design.