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The effect of hot isostatic pressing on the fatigue behaviour of sand-cast A356-T6 and A204-T6 aluminum alloys

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ABSTRACT

The effect of the hot isostatic pressing (HIP) process on the fatigue resistance of sand-cast A356 (Al–Si–Mg) and A204 (Al–Cu–Mg) aluminium alloys was studied by means of rotating bending tests. Many solidification defects, such as gas pores and shrinkage cavities, were present in both alloys in the sand-cast before HIP. The HIP process had a negligible effect on microstructural features (such as grain size, SDAS, and intermetallic compounds), whereas it significantly reduced the solidification defects. The non-HIP processed A204 alloy showed a slightly lower fatigue resistance than the A356 alloy, due to the presence of many branched shape shrinkage cavities, especially along grain boundaries. For both aluminium alloys, the HIP process led to a reduction in fatigue data scattering and an increase in fatigue resistance, equal to about 40% for A356 and 70% for A204. In the HIP processed condition, when the alloys can be considered pore-free, the A204 showed a 20% higher fatigue resistance than the A356 alloy.

1. Introduction

Cast aluminium alloys of the 300 series are widely used in the automotive industry, for example for cylinder heads and engine blocks, and in aerospace and general industries, because of their excellent castability, good corrosion resistance and high strength-to-weight ratio. Many studies have investigated the effect of casting defects (such as porosity, cavity shrinkages and oxides) and other microstructural features (secondary dendrite arm spacing SDAS, eutectic silicon morphology, shape and composition of intermetallic compounds) on the fatigue behaviour of aluminium alloys (Wang et al., 1995; Wang and Càceres, 1998; Wang et al., 2001a,b; Ran et al., 2006; Jan et al., 2006; Li et al., 2004a,b; Ceschini and Morri, 2003; Paray et al., 2000). Since the size of the casting defects is generally larger than that of microstructural features, defects mainly impact on the fatigue behaviour of cast aluminium components. Several studies correlated the size of the defects or the SDAS with the cycles to failure and the scatter of the cyclic properties of cast materials, using both statistical analysis and linear elastic fracture mechanics (Wang et al., 2001a; Kobayashi, 2000; Buffière et al., 2001; Mayer et al., 2003). On the other hand, cast aluminium alloys of the 200 series have been less investigated and consequently few data are available on the relation between microstructure and their fatigue behaviour.

This paper compared the fatigue behaviour of sand-cast A356 (Al–Si–Mg) and A204 (Al–Cu–Mg) aluminium alloys and

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Table 1 – Nominal chemical composition (wt.%) of A356 and A204 aluminium alloys

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr	Ni	Al
A356	6.5–7.5	≤0.70	≤0.10	0.25–0.40	0.40–0.60	≤0.10	≤0.10	0.014–0.020	0.1–0.2	Bal
A204	≤0.15	≤0.15	4.20–5.00	≤0.10	0.20–0.40	≤0.10	0.20–0.30	–	≤0.05	Bal

studied the effect of the hot isostatic pressing (HIP) process on the microstructure of the alloys and consequently their fatigue resistance. Since the HIP can reduce or eliminate casting defects (such as cavity shrinkages and gas pores) (Wang and Càceres, 1998; Wang et al., 2001a,b; Ran et al., 2006), the aim of the study was to compare the size and distribution of casting defects on the non-HIP processed and HIP processed alloys and consequently to evaluate their influence on alloy fatigue behaviour.

2. Experimental

Cast aluminium alloys A356 (Al–Si–Mg) and A204 (Al–Cu–Mg), with the nominal chemical compositions given in Table 1, were used under the following conditions: (1) sand-cast and T6 heat treated; (2) sand-cast, HIP processed and T6 heat treated, according to the processing conditions in Table 2. For each alloy and each condition, two sets of fatigue specimens obtained from the same sand mould were used.

The microstructural characterization of the samples was carried out by optical microscopy (OM) also under polarized light (POL). Image analyses were carried out on optical micrographs using Image Pro-Plus software to evaluate SDAS, grain size and the size of casting defects (such as porosity and cavity shrinkage). The SDAS was obtained by a linear intercept method where the line was chosen to intersect a series of well-defined secondary dendrite arms. The metallographic samples were mechanically ground and coarse polished using a grinding disc, then polished with 9 μm and 1 μm diamond paste and finally chemically etched with Keller's reagent or electrochemically etched at 20 V for 30 s, using Barker's solution to reveal the grain structure. The tensile tests were carried out according to UNI-EN 10002 (UNI-EN, 2004) using tensile specimens with a gauge length of 30 mm, a gauge width of 10 mm and a thickness of 3 mm. The fatigue tests were carried out using a rotating bending fatigue testing machine, according to UNI 3964 using the stair-case methodology with 15 specimens (UNI, 1985). Cylindrical fatigue specimens with the geometry and dimensions shown in Fig. 1 were used. All the fatigue specimens were machined and then longitudinally polished with 1000 grade emery paper, so that polishing marks were in the longitudinal direction. After fatigue tests, the fracture surfaces were examined using a scanning electron microscope (SEM) to investigate the influence of casting defects on the mechanisms of failure for the two alloys.

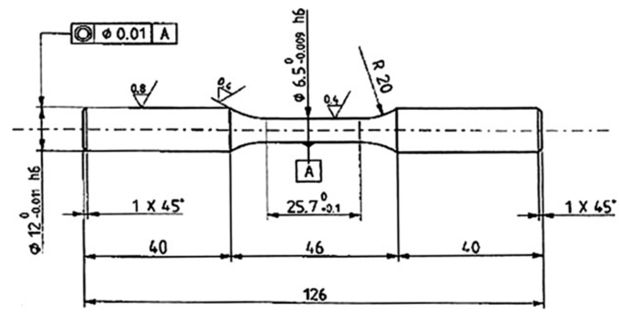

Fig. 1 – Shape and dimensions (mm) of the rotating bending fatigue specimens.

3. Results and discussion

3.1. *Microstructure*

Microstructural analyses of both the HIP processed and non-HIP processed A356 samples showed the typical hypoeutectic microstructure of Al–Si casting alloy, characterized by primary aluminium dendrites, separated by interdendritic Al–Si eutectic (Fig. 2a). The mean value of the secondary dendrite arm spacing (SDAS) was 42 μm, a typical value for sand-cast aluminium alloys. The eutectic silicon showed a globular shape (Fig. 2b) due to the modification effect of Sr addition. Observation of electrochemically etched samples under POL (Fig. 2c) disclosed the grains ranging in size from 0.3 mm to 0.8 mm. Iron-based intermetallic compounds were also observed (Fig. 3), as β-plate (Al–Fe–Si), π-phase (Al–Fe–Mg–Si) and α-plate (Al–Fe–Mn–Si) (Wang et al., 2001b; ASM International, 2004; Wu et al., in press). It is well known that the size and distribution of both dendrites and eutectic particles are dominated by the solidification conditions, while the morphology of eutectic silicon and Fe-based intermetallic compounds is mainly influenced by the chemical composition of the alloy.

Pores represent the most deleterious microstructural feature for the fatigue behaviour of cast aluminium alloys. Pores can be due to hydrogen adsorbed by the melt dur-

Table 2 – Processing condition of A356 and A204 aluminium alloys

Alloy	Set of samples	HIP	Heat treatment
A356	A1, A2	–	535 ± 5 °C for 10 h, water quenching, aging at 165 ± 5 °C for 8 h
	AH1, AH2	520 °C 2 h 100 MPa	535 ± 5 °C for 10 h, water quenching, aging at 165 ± 5 °C for 8 h
A204	B1, B2	–	530 ± 5 °C for 9 h, water quenching, aging at 170 ± 5 °C for 7 h
	BH1, BH2	520 °C 2 h 100 MPa	530 ± 5 °C for 9 h, water quenching, aging at 170 ± 5 °C for 7 h