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The Effects of Microstructural Characteristics and Casting Defects on the Mechanical Failure of Al-based Alloys

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Mechanical performances of materials are largely influenced by the presence of macro- and micro-imperfections (e.g. internal, surface and sub-surface defects, porosity, etc.) introduced during different phases of production, managing and finishing process.
In this paper, a study from morphological and mechanical point of view, of Al-based alloys is presented, with the aim of finding a relationship between some parameters and the mechanical failure of such components. Selected samples are studied and the evolution of surface conditions are compared to those of alloys after T6 thermal treatment. Conventional methods have been used for the materials characterization. Macro- and micro-structural inspections of the metallic alloy have been carried out by Optical and Scanning Electron Microscopy. The position and the nature of the defects have been established. The crack morphology in different regions of the material has been observed. Qualitative compositional analysis has been performed on the alloys by EDS technique, comparing non damaged and damaged areas. The axial fatigue resistance has been evaluated and after tests, fracture surface analysis has been carried out as well, by means of SEM.
The results show that there is a good correlation between the microstructural characteristics and the casting defects of the alloys and their fatigue failure.

Keywords: *Aluminium alloy, microstructure, porosity, fatigue failure.*

1. Introduction

In many industrial application the weight reduction and, as a result, fuel saving grow to be an important feature. Casting aluminium alloys have received much more attention as structural materials together with the amplified tendency to employ them in automotive application for the production of cylinder heads, brake rotors, engine blocks, for manufacturing aircraft components and marine engines, etc. [1, 2]. In such critical areas is important to have a complete data on the properties of the alloys employed and to find a relationship between the microstructural characteristics, including the presence of defects and mechanical behaviour constitutes [3-5].
The most common defects found in Al-Si casting alloys are represented by the presence of voids or cavities which are created within a casting during its solidification, caused by the volume contraction (shrinkage), the non correct feeding system and/or gas (prevalently hydrogen) development. Generally, interdendritic shrinkage pores, inclusions, secondary dendrite arm spacing are privileged crack initiation sites, independently of the loading conditions. These parameters are directly connected to the mechanical performances of the alloy leading to a reduced strength and ductile properties, irregular crack development and finally can cause the materials failure [6-8].
In this context, failure analysis and prevention have a central functions in material science, since determining the cause of failure can prevent future occurrence and improve the performances of the components or structures.
The present study aims to investigate the effects of microstructural characteristics (presence of brittle phases, slip bands), and casting defects (mainly porosity) of the A356 Al alloys on their fatigue failure. The study has been carried out considering two significant positions inside the same components of an automotive engine. Both samples have been considered in as cast state and after T6 heat treatment. The relationship between their microstructure and mechanical performances and their fracture surface has been investigated.

2. Experimental procedure

The present studies have been performed on A356 Aluminium alloys sample, extracted from cylinder heads produced by semi permanent gravity die casting process at Teksid Aluminium Srl, Carmagnola, Italy), where the moulds are of steel and the cores of ceramic material. Some of the selected samples have been subjected to T6 heat treatment (530°C for 6 h, water quenching to T= 80°C and then ageing at 165°C for 5 h).The chemical composition of the alloys has been reported in Table 1.

Table 1 *Chemical composition (% wt) of the A 356 alloy*

Elements	***Si***	***Mg***	***Cu***	***Zn***	***Ni***	***Fe***	***Mn***	***Ti***	***Pb***	***Sn***	***Al***
%Min	6.50	0.25	0.00	0.00	0.00	0.00	*0.00*	*0.10*	0.00	0.00	Bal.
%Max	7.50	0.45	0.10	0.10	0.05	0.15	0.10	0.20	0.05	0.05	Bal.

The samples employed for the microstructural analysis have been prepared by standard metallographic technique involving mounting and polishing procedures. On the transversal sections of the aforementioned samples metallographic analysis has been considered for the measurements of size and microstructural constituents, such as Secondary Dendrite Arm Spacing (SDAS) and porosity, by means of Optical Microscopy (OM, MeF4 Reichart-Jung), supported by an image analysis software (UTHSCSA Image Tool for Windows Version 3.00) in order to evaluate the average porosity percentage on the whole surface of the samples. Compositional analysis has been performed by Energy-Dispersive X-ray Spectrometry (EDS, Oxford microprobe). The components have been cut into pieces to obtain cylindrical fatigue samples according to the Standard ASTM E466-72. The high-cycle axial fatigue tests at room temperature have been carried out employing Rumul TESTRONIC 100KN apparatus with a tension to compression ratio of –1, in order to obtain the fatigue S-N Wohler curves in the different conditions. These curves have been obtained firstly by estimating the fatigue resistance (50 % level of probability of survival) with Staircase method (10^7 as reference number of cycles). Other fatigue proofs have been performed at different stress amplitudes, with the aim to approximate the characteristic straight line of the finite endurance zone by means of a linear interpolation of the experimental data. For each condition three curves have been drawn concerning 10%, 50% and 90% probability of survival produced. After fatigue tests, the fracture surface has been observed by Scanning Electron Microscopy (SEM, Leo 1450VP). It allows for all samples to determine the nucleation site of the cracks and the principal cause to their failure.

3. Results and discussion

Generally, the mechanical failure of the Al-Si casting alloys has been controlled by the microstructural characteristics of the alloy, including the presence of intermetallic phases, slip bands and SDAS and also casting defects related principally to the presence of porosity.

For the study, different pieces from some significant positions of the components have been extracted by cutting procedures and further analyzed, in order to compare their performances.
The sample, referred to A, is situated close to the combustion region of the engine unit, while the sample B is placed perpendicularly on the aforementioned ones and nearly to the valve region.
The microstructures of both samples (A and B, respectively) manufactured by gravity die casting process, in as-cast state and after T6 heat treatment are given in Figure 1. The liquid phase solidified as a dendritic structure and the presence of α-Al grain surrounded by the Al-Si eutectic phase can be evidenced. Table 2 reports some information concerning the dimensions of the dendrites (D), values of SDAS, which is defined as the distance between the protruding adjacent secondary arms of a dendrite, and the percentage of the porosity for the considered samples.

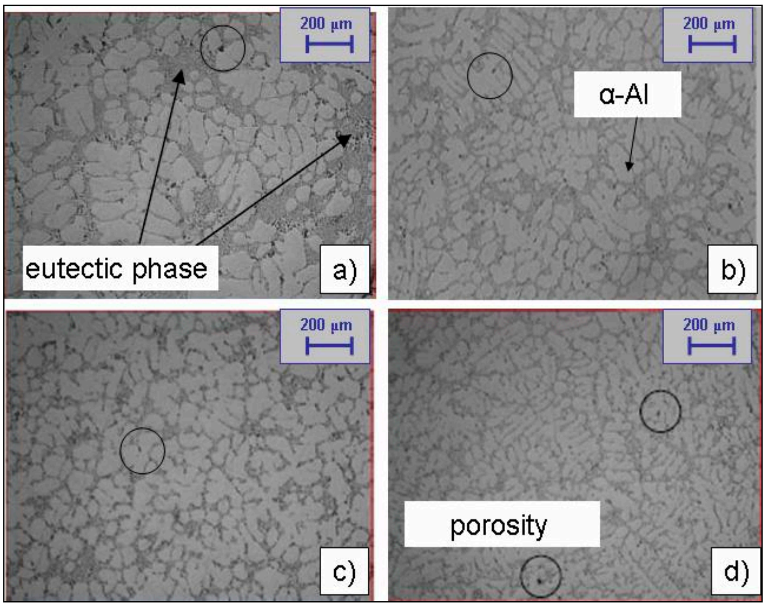

Fig. 1 *SEM micrographs of the A356 alloys obtained by gravity die casting process: (a) Sample A-as cast, (b) Sample B-as cast, (c) Sample A T6-treated, (d) Sample B T6-treated*

Castings having a finer microstructure explain better fatigue properties and, mainly for cast aluminium alloys, this improvement is related to a lower SDAS value.

Table 2 *Average grain size (D), SDAS and percentage of porosity measured for sample A and B, in as-cast state and after T6 heat treatment*

	D [µm]	S.D.A.S. [mm]	[%] POROSITY
Sample A_as cast	263	52	0.037
Sample B_as cast	176	31	0.014
Sample A_T6 treated	238	51	0.030
Sample B_ T6 treated	160	38	0.022

The smaller the SDAS value, the smaller the size of defects present during eutectic solidification, such as segregation, micro-shrinkage and gas porosity. The highest level of porosity and SDAS value can be detected for the sample A, in addition to the wide areas of liquid phase segregation.
The parameter that controls this detail is the solidification rate during the manufacturing process: sample A, in direct contact with the metallic die, solidified earlier than the other one (Sample B) located near to the ceramic cores. According to the literature [9, 10] and as can be observed also in Table 2, decreasing the cooling rate during solidification SDAS decreases become finer leading to obtain more homogeneous and more dense microstructure. Generally mechanical properties increase

as well. Additionally, T6 heat treatment contributes to decrease the differences, from microstructural point of view, between the two samples A and B. The variation between the SDAS values of the as-cast samples A and B is about 40%. After the thermal treatment this value reduces to 25%, as reported in Table 2.
The presence of impurity elements, such as Fe, leading to the precipitation of brittle phases (Chinese script intermetallic compounds) can influence the fatigue life of the alloy. The intermetallic phases have been identified by EDS analysis and are mainly constituted by Al-Si-Mg-Fe-Sr and Al-Si-Sr (Figure 2) and can influence the matrix stiffness.

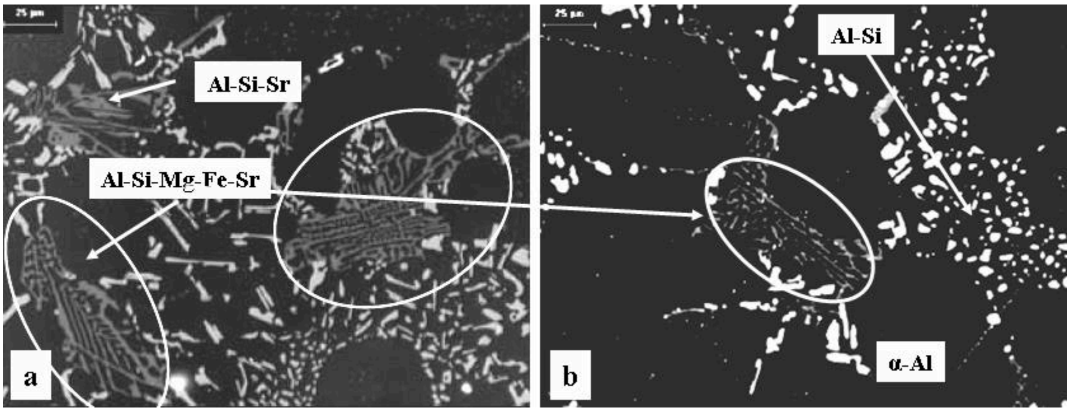

Fig. 2 *Optical micrographs showing the presence of intermetallic compounds: a) sample A-as cast state and b) sample A-T6 heat treated*

These intermetallic compounds form areas of elevated stress concentration and as a result can facilitate the crack nucleation and their further propagation. As can be observed in Figure 2 the T6-heat treated 356 alloy reveal a much more refined structure compared to the as-cast sample, leading to amplify the fatigue life of the alloy, as will be further illustrated.

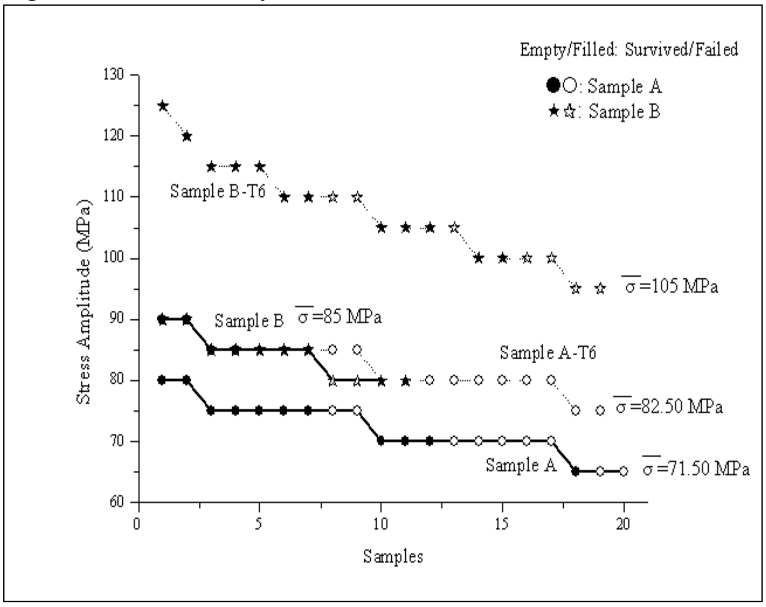

Fig. 3 *Fatigue test results of A356 alloy samples, in as cast state and following T6 heat treatment*

High-cycle fatigue test has been carried out according to ASTM standard E466-96 at room temperature. For an estimation of the fatigue limit, stair case method has been used, according to the Italian Standard UNI 3964, where the former sample is tested at the estimated fatigue limit of the material and the other samples are tested successively, decreasing or increasing the test stress amplitudes for each samples depending on whether the previous sample fails or survives inside the pre-determined number of cycles which is correspond to 10^7 cycles. For all samples the test has been conducted considering an incremental step of 5 MPa. The fatigue resulted, obtained for the as-cast and T6 heat treated samples, is illustrated in Figure 3.

The figure reports the number of the survived and failed samples and the average of fatigue resistance for all considered samples. Sample B reveals a superior fatigue limit with respect to Sample A, due to its minor SDAS value and porosity level, i.e. more finer microstructure. After T6 heat treatment the fatigue life for both samples has been increased. T6-heat treated Sample B has demonstrated a superior fatigue strength, but also higher standard deviation, probably due to the presence of some defects originated by an inaccurate casting process of the components.

The morphology of the fracture surface of some samples, after fatigue test, was observed by SEM analysis, in order to study the crack initiation site and its propagation and to identify some of the principal reason of the materials failure.

Figures 4a and 4c show a general feature of the fracture surface realised on both samples in as-cast state, illustrating the crack initiation and propagation regions, while Figures 4b and 4d highlights more in detail the different origin of the fractures in these cases. Generally, it was found that in as-cast state for the Sample A shrinkage porosity acts as fracture initiation points. As can be seen in Figure 5b the fracture path preferentially goes through the areas containing localized shrinkage porosity and also some fractured silicon and brittle intermetallic particles. Examining the fracture surfaces of the as-cast Sample B, it was established that in 95% of all observed samples, the fracture takes places along the persistent slip bands. Figure 4d demonstrates the features of the failed samples where the areas of high stress concentration have been detected, then contributing to reduce the fatigue limit of the alloy.   Following T6 heat treatment the endurance limit of the samples has been increased by about 20% with respect to the as-cast state. Analysing the fracture surface of these samples it was found that fatigue failure generally starts due to the presence of slip bands and the fracture has been propagated by a rapid crash of the surface.

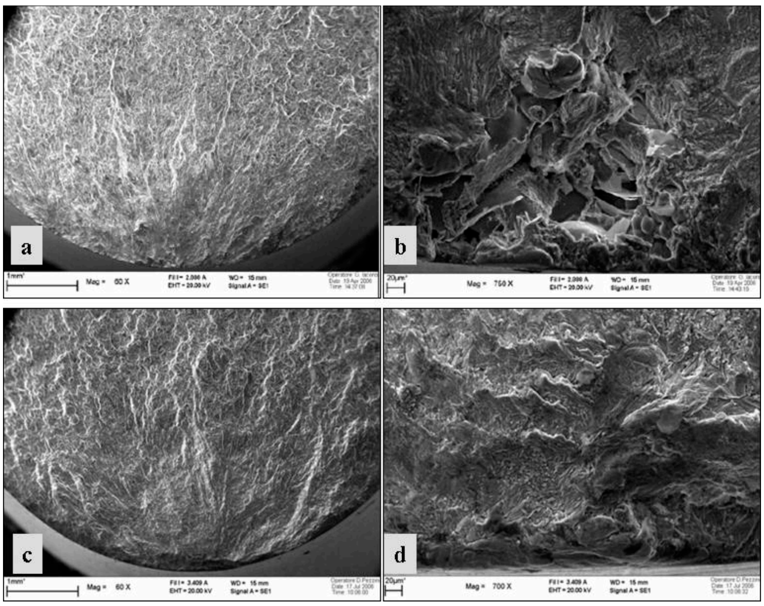

Fig. 4 *SEM micrographs of the fatigue fracture surface of the as-cast samples: a) Sample A and b) Sample B*

Ductile fracture is predominant, with the presence of some brittle phases (intermetallic compounds and Si particles) in few regions. The presence of dimples is also observable, in both cases, and intergranular fracture occurs.

4. Conclusions

In this paper the effects of microstructural characteristics and casting defects of the A356 Aluminium based alloy, produced by gravity die casting process, on their fatigue failure were investigated. In the study two important positions of the cylinder heads in as cast state and after T6 heat treatment were considered and the correlation between their microstructure and mechanical performances and the fracture surface has been presented. It was found that the solidification rate during the manufacturing process played a key function in the properties of the produced alloys. In fact, decreasing the cooling rate during solidification more uniform microstructure was obtained and increased mechanical properties result.

The results showed that the fatigue properties of an Al-based casting alloy are strongly influenced by the presence of casting defects. The reduction of the fatigue strengths is more accentuated in the presence of shrinkage porosity than those obtained in the presence of persistent slip bands only. As expected, the alloy performance is improved by T6 heat treatment.

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